UNIVERSITY OF STIRLING

School of Biological and Environmental Science

Modelling climate change and socio-economic impacts within three regions of Scotland, 1970-2100

By

Alan Kenneth Parnell

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Declaration

I hereby declare that this thesis is entirely original and where the work of any other thesis has been used it has been fully referenced in the text.

This thesis extends to 88,901 words

Alan Parnell

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Abstract

There is a consensus of scientific thought that human activities are altering the gaseous composition of the atmosphere and leading to global climate change. This thesis addresses the question of how this global climate change will manifest itself at the regional level. In particular, a dynamic simulation model integrating both climate change and climatically sensitive socio-economic activities will be developed. This model will explore the regional variations in both climate change and socio-economic activity. Three Local Authorities in Scotland were chosen for this study, Argyll on the west coast, Stirling inland and Fife on the east coast. This provides a west/east transect across central Scotland.

Meteorological data, covering the period 1970-1998, was collected from twelve sites spread across these regions. These data were analysed in order to provide a climatic profile of each of the regions, and to identify any evidence of climate change in the form of trends in the data. Data relating to socio-economic factors was taken from a variety of sources. Where possible this covered the same period in time as the climate data. Both sets of data were examined to determine evidence of climate sensitivity in the socio-economic data using suitable statistical techniques.

A simple, yet thermodynamically sound, dynamic climate model was developed and calibrated for each region using the data from the previous analysis. This model allowed increasing levels of atmospheric carbon dioxide (CO_2) to directly affect the mean surface temperature of the three regions. Precipitation changes from the UKCIP02 regional climate model were included. This allowed seasonal temperature and precipitation totals to be simulated, on a regional basis, under different climate change scenarios. Simulations, calibrated on data from 1970-1998, were run forward to 2100. The climate results were similar to the output from the UKCIP02 model.

Six sectors of a socio-economic model were constructed: population, employment, land use, water resources, housing and emissions. Where statistically significant relationships between climatic and the local socio-economic variables were found, these were included in the model. Simulations, for the period 1970-2100, were run under four different climate change scenarios, and that of constant climate, in order to assess their impact on the six sectors at the regional scale.

The results indicate considerable regional variations in the impacts both of climate change and the associated climatically sensitive activities. Argyll in the west, for example, could benefit from increased tourism and the potential for agricultural expansion. If in-migration is allowed to offset labour shortages, then the west sees a reversal of the population decline of previous decades. Climate change has little impact on the economy of the inland and eastern regions. However, a problem does emerge with water resources in the east. Summer droughts are seen to increase in frequency, suggesting that both the costs and benefits of climate change will be unevenly distributed. The implications of these results for the management of change are then discussed along with future research needs.

Chapter 1 A Background to the Thesis

1.1. Introduction

There exists a consensus of scientific opinion that human activities are indeed influencing the global climate (IPCC 1996). There is also a firm understanding of the main factors causing this climate change, human activities which are altering the gaseous composition of the planet's atmosphere. The most significant factors relate to industrial activities, fuelled by the burning of fossil carbon and land use changes. These activities are responsible for the increases in CO_2 and CH_4 which are the most important of the greenhouse gasses. In addition there is an increase in N_2O, the release of CFC's and related chemicals, all of which add to the warming of the atmosphere. The growth in the human population and the drive for improved standards of living in both the developed and developing countries have led to a growth in the activities which cause the release of greenhouse gasses. There is little prospect of these trends being reversed. One major uncertainty however is the rate at which changes to the gaseous composition of the atmosphere, and hence climate change, will occur (IPCC 2000).

Understanding the global picture does not have a great deal of relevance to individuals or communities who are interested in how their lives, or the lives of their children, will be affected. Given that the global climate is set to change in the coming decades two major questions arise. Firstly, how will these changes manifest themselves at the local level, and secondly, how will the changing climate affect the lives of the local population. Of central importance here is the question of their ability to adapt or respond by changing lifestyle or developing new skills to take advantage of changing opportunities.

This thesis aims to provide a demonstration that it is possible to have some forewarning of changes at the local level, both in the physical environment and social spheres, thus enabling the management of changes to proceed in a proactive rather than reactive way.

1.2. Aims and objectives

This is an interdisciplinary study of the socio-economic impacts of global climate change on three Local Authority areas (referred to as regions in the text) within Scotland. The main aim is to develop a dynamic model which allows the impacts of projected changes in temperature and precipitation to be assessed with respect to their effects on the local economy, population and land use patterns. This will be achieved by combining a simple climate model with a multi-sector model of local socio-economic structures and then running the model through simulated time, covering the period from 1970-2000 then with simulations from 2000-2100.

The objectives of the study are:

1. To identify evidence of climate change in the meteorological records from the regions of the study.
2. To investigate the cause of any changes in the climate of the regions which might be found.
3. To construct a model which will generate simulated temperature and precipitation which accurately matches the empirical records.
4. To construct a multi-sector socio-economic model for each of the three regions of the study.
5. To identify where climate impacts exist and build connections between the climate and socio-economic models.

6. To run the model through simulated time from 1970 up to 2100 and examine the potential socio-economic changes under a range of climate change scenarios.

1.3. Epistemological considerations

The interdisciplinary nature of this project involves the collection and analysis of data from a range of sources, and the establishment of trends in, and relationships between, variables. These variables are measures of phenomena relating to both the natural and social spheres. It is the interaction of these two systems, the natural and human systems which is of interest here and this raises certain questions relating to methods. Figure 1-1 illustrates the area of interest, where natural events create resources which human society can utilise, and at the same time generate hazards with which human society has to contend. The nature of this interaction is not fixed or defined by any constant set of principles, but is subject to changes resulting from cultural responses and adaptations (Kirk 1963). What represents a resource can change through time, the inhabitants of a particular region may utilise features of the natural environment in quite different ways, depending on technological or cultural factors. The presence of copper ore bearing rocks would have little significance to Neolithic farmers, yet the presence of such a resource would have been a source of wealth for their descendants once the cultural shift to metal working had been made. In more recent times the availability of crude oil has fuelled the development of much of the industrial world. Initially the cost of this resource was measured by the costs of extraction and refinement; it is only recently that the continued unregulated exploitation of this resource has begun to be perceived as a potential hazard. This is recorded as the growth of greenhouse gas concentrations in the atmosphere, such as carbon dioxide. The level of this gas has increased from approximately 324 parts per million (ppm) in 1970 to 365 ppm in the year 2000 and continues to rise. Our concerns with this in effect represent a change in the cultural filters which define our perception of the natural world.

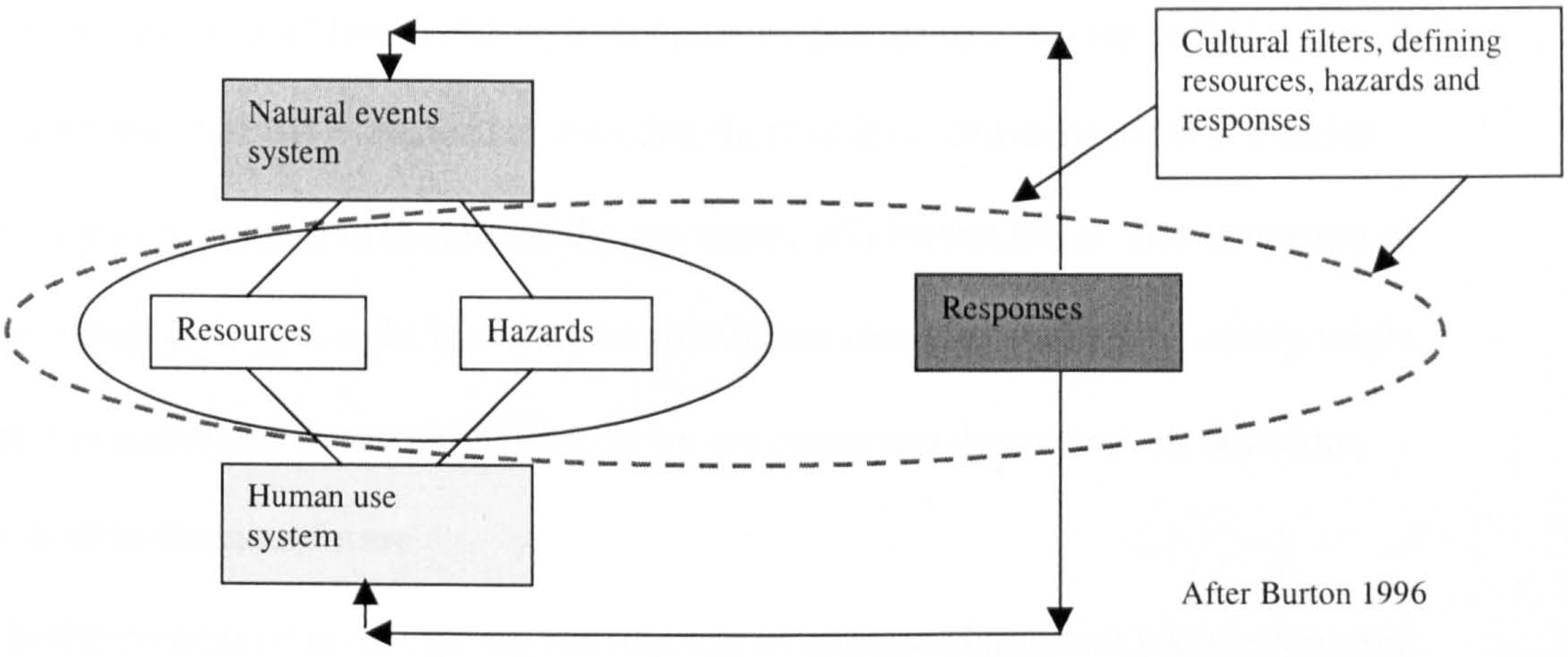


Figure 1-1 The interaction of the natural events system and the human use system.

Our current understanding of the natural world has been shaped by the successes of the natural sciences. The confidence in this area has led to the development of "Laws" of nature, examples being Newton's laws of gravity or the laws of thermodynamics. These laws essentially refer to patterns in the behaviour of the natural world which are predictable and independent of the point of view of the observer, replication of experiments to define these laws being an important prerequisite for scientific knowledge. In the context of this study the climate system is taken as a natural phenomenon about which a great deal of understanding has been obtained, and to which certain laws can be applied. This allows mathematical models of the climate system to be developed, and although certain aspects of this system are still to be understood fully, it allows forecasts to be made with a reasonable degree of confidence. This confidence stems from the belief that the physical "laws" will operate in the future as they have in the past.

The extension of scientific methodology to the social sphere has had less success than in the physical sciences. One major reason for this is the nature of the subject matter under consideration. Systems which include human actors are subject to change and information concerning the consequences of past actions feeds back to influence future behaviour. In this way a "law" relating to societal responses to a certain problem may be evident from the analysis of historical data, but there is less confidence that if similar problems are encountered in the future the responses will be the same. The extension of past trends may give an insight into the possible future directions which a society might take, but it is important to recognise that future scenarios are dependent on decisions taken now or in the near future.

In the context of investigating the impacts of climate change on socio-economic structures these decisions have even greater significance. This results from the fact that the projections made regarding the physical system are themselves subject to factors arising from the human decision-making process. Future scenarios regarding increases in greenhouse gasses are subject to uncertainty, arising from the lack of ability to predict factors such as the rate of growth of the global population, or the priority given to reducing greenhouse gas emissions by technological or other developments (IPCC 2000).

Given this structure, where forecasts are heavily dependent on a range of factors which are subject to the decision-making process, it is necessary to develop a methodology which can deal with change and is flexible enough to accommodate a range of possibilities. This will be addressed in chapter 3.

1.4. On Risks and Hazards

The systematic study of risks and hazards has been a relatively recent phenomenon. Early classical writers, notably Hippocrates, drew a link between the location of dwellings and the incidence of disease. However, it was Gilbert White, writing in the 1930's and 1940's, who was influential in bringing attention to this field and is attributed with initiating the modern study of both natural and man made hazards.

It was during the 1970's that this area of study was more fully developed, due to several factors. One was the growth of the environmental movement, with the publication of Rachel Carson's "Silent Spring" (Carson 1963) drawing attention to the hazards relating to the reliance on pesticides of the agricultural sector.

The greater prominence of the impact of extreme events and disasters, of both man made and natural origins, during the 1970's, led to developments in the field of risk assessment. This can be seen as partly due to the growth of communications, allowing television pictures to relay the impacts of disasters around the world, raising awareness of the existence of these events. The rapid growth of human populations around the globe during the 20th century meant that large numbers of people settled previously sparsely inhabited regions. This brought them into contact with hazards which had previously been experienced by relatively few individuals. When an extreme event, such as drought or tropical storm affected the area, the impact was experienced by a far greater population.

The 1970's also saw a number of man made disasters, among them the explosion at the chemical works at Flixborough in 1974, Seveso in 1976 and the nuclear accident at Three Mile Island in 1979. These events brought the existence of hazards to the publics attention along with a desire to minimise the risks.

The study of such events leads to a distinction between hazards and risks. The former represents naturally occurring or human induced processes which have the potential to create loss, either of human life or economic resources. The risk is defined as the actual exposure to a hazard and involves the combination of the probability of an event actually occurring and the extent of loss which can be expected (Smith 1996).

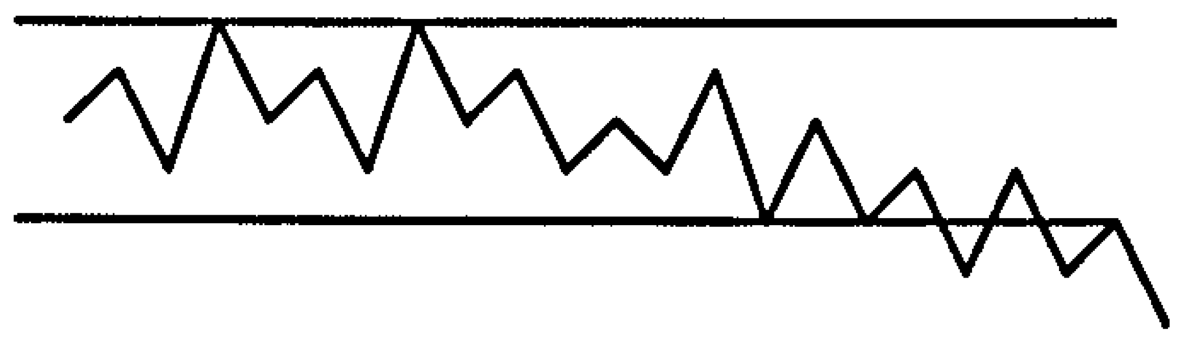
Natural hazards have long been described as "acts of God" and are still referred to as such in insurance documents. The randomness implied by this is in contrast to the ability to predict with some certainty the likelihood of such events, either their frequency or geographical location. Many disasters occur because humans misperceive the threat, choose to ignore it, or have no alternative but to accept it.

The line between natural and man made disasters is somewhat blurred. Floods may result from extreme meteorological events but the role of human activities often plays a part with deforestation or other land use practices acting in parallel with the natural process. Thus many problems can be described as hybrid hazards, as they involve the overlap between environmental, technological and social processes.

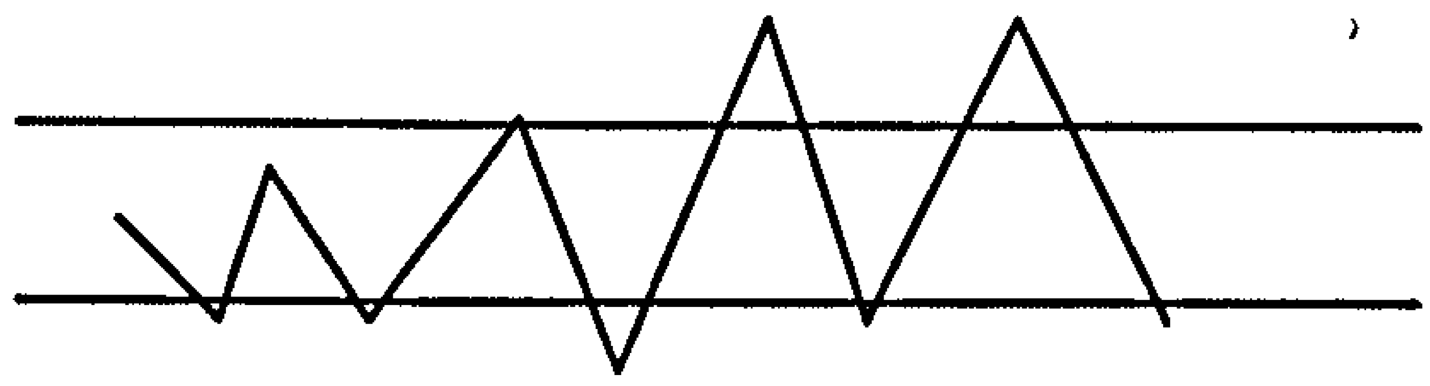
Hazards can be seen as resulting from the conflict between natural events and the human use system, with subjective assessments as to the balance between risk and benefits being crucial in determining the level of risk which is acceptable to a society or community (Ashby 1978).

An important part of the process of assessing risk is the expected norms to which people are exposed. Adjustments are made over time to minimise the dangers, whether this is in the form of architecture, such as the traditional use of light building materials in earthquake prone regions, or the building of dwellings on stilts in areas prone to flooding. As long as the events are within the range of expected values there is no need for further adjustments to be made. However, risks can increase as a result of several factors. Figure 1-2 illustrates the possible ways in which events can interact with social factors to increase the perception of risk.

1. Constant band of tolerance, change in mean value.



2. Constant band of tolerance, increased variance



3. No change in variable, tolerance decreases

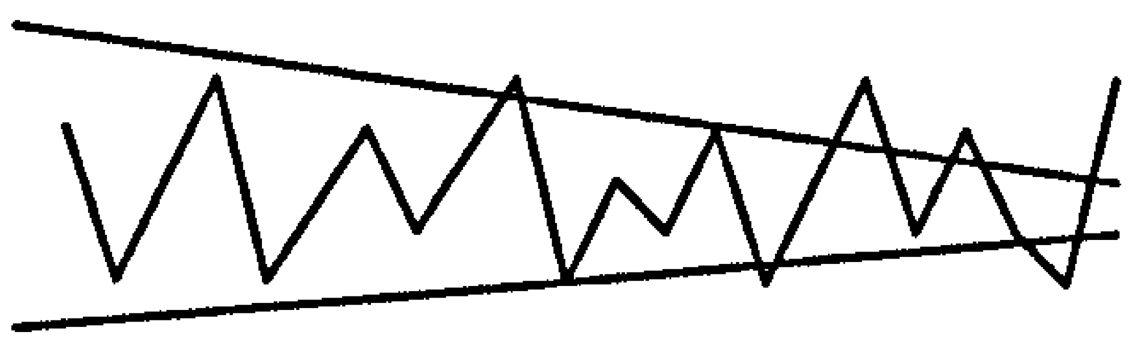


Figure 1-2 Bands of tolerance and environmental variables.

In terms of climate change the first two of these categories are relevant, as both mean values of climatic variables, as well as their variability are likely to change. An increase in material wealth could be seen as reducing tolerance to climatic factors, as the same event may produce significantly greater loss.

What is apparent from these diagrams is that risk cannot be assessed purely from the statistical or objective assessment of the events themselves, but involves consideration of the subjective perception of tolerance and risk by the people involved. Studies have shown (Slovic 2000) that the majority of citizens rely on intuitive risk judgements, influenced by friends, family, work colleagues and respected public officials. This is often at odds with the objective risk, as defined by the average fatalities per year for a given activity or hazard. The concept of risk can therefore mean different things to different individuals or groups.

Similarly the adjustments which might be required in the face of the changing nature of a hazard are subject to the perception of risk, as well as consideration of what is possible given social and political considerations.

The choices which are available fall into two main categories, purposeful adjustments and incidental adjustments (Burton, Kates, and White 1993). Incidental adjustments may involve simply discounting loss, accepting the risk and the consequences.

Purposeful adjustments involve a range of options summarised below in Figure 1-3 (after Burton 1993).

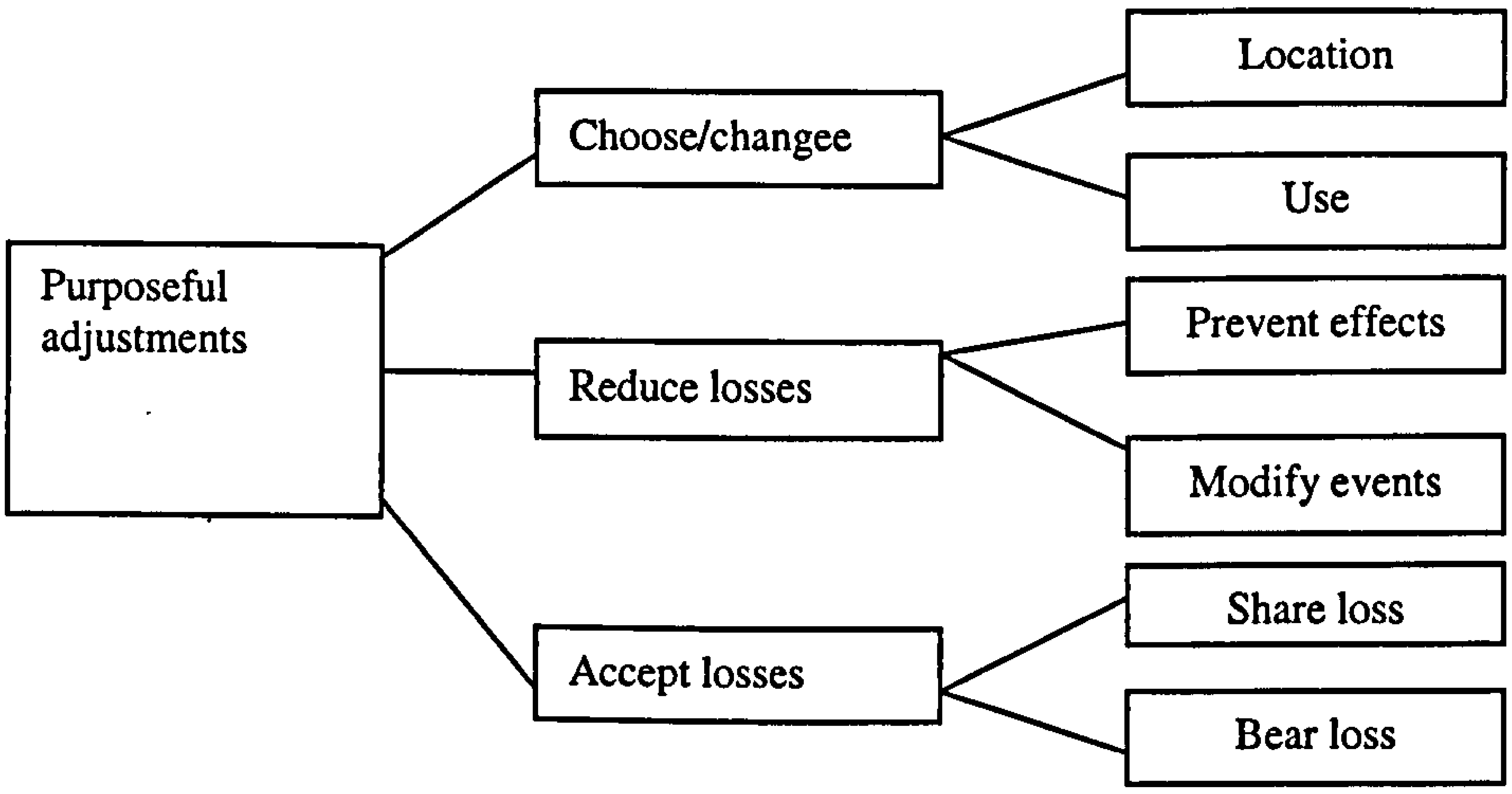


Figure 1-3 Options for purposeful adjustment.

Of these options the most radical involves the change of location, or the change of use of a given region. Reducing losses involves the prevention of damaging affects through warning systems, control works, building design or perhaps cropping practices, to make production less vulnerable to external factors. Sharing loss involves such factors as insurance, which spread the loss from one affected area to a broader base.

Various factors influence the decision making process, primarily an assessment of the nature of the hazard. The appraisement of the hazard lies in the realm of scientific examination, the results of which have to be disseminated in a comprehensible form to those involved in the decision process.

An appraisal of the various economic alternatives is also required in order to judge the consequences of each possible action. Figure 1-4 illustrates how different responses relate to different hazards.

States of Nature					
	Alternative actions	E_1	E_2	....	E_n
Economic Alternatives	A_1	response			
	A_2		response		
	A_n		.		response

Figure 1-4 States of nature and responses

Factors influencing the choice of responses include prior experience, and an understanding of the nature and severity of the event. The degree of material wealth is also important, poverty often being associated with greater risk taking. Personality traits are influential, as is the role of the individual in society, and how close they are to the decision making process.

This represents the main theoretical model of hazard research, known as the behavioural approach, and sees the nature of impacts of the natural environment being strongly affected by the nature of human adjustment (Smith 1996).

There have been criticisms of this method, largely due to the individualistic approach to responses, which are seen as a rational response to the available information by individuals or groups (Smith 1996). The importance of individual and governmental responses is seen as masking the reality of everyday existence in which socio-economic factors largely determine the range of possible responses. This method is also seen as favouring a high tech solution to problems, relying on experts and authoritarian social structures which function to organise and inform in a very top down manner. There is an implicit faith in technology and the effectiveness of disaster plans and military style emergency responses.

The alternative view takes a wider view of adjustments and responses, recognising the constraints on individual actions by more powerful institutional forces. This structuralist approach recognises the importance of socio-economic factors. In particular, it sees disasters in less developed countries as being strongly influenced by the workings of the global economy. The necessity of dealing with daily survival prevents the poorer sections of society from preparing for possible hazards, and their lack of resources further compounds this. Adjustments which are imposed from above often ignore local knowledge and understanding, and are seen as further reinforcing the marginalisation and underdevelopment which exists (Burton, Kates, and White 1993).

Both approaches have positive aspects, the former being more appropriate in the immediate response to the impact of some extreme event. The long term planning of potential responses and adjustments to natural hazards needs to recognise the structural constraints on individuals and governments. It also has to recognise that local knowledge and practices have to be taken into consideration when future plans are being formulated, with a more bottom up approach being adopted (Smith 1996).

1.5. The Concept of Sustainable Development.

A major development in the relationship between mankind and the natural environment has been the emergence of the concept of sustainability. Of central importance to this has been the recognition that mankind as a modifier of nature is in danger of disrupting the natural processes which sustain life.

The development of the concept has taken place mainly over the last three decades of the 20th century in response to growing concerns about the impact of human activities and populations on the natural ecosystems of the planet. There have been several important milestones in the emergence of the concept and numerous contributors to the debate. This has produced a variety of definitions (Moffatt 1996) which have a number of common themes running through them. These can be described broadly as principles relating to problems of ecology, ethics, economics and equity.

The United Nations Stockholm conference in 1972 was one of these significant milestones in that it helped to bring about a global perspective on the future of human development. The momentum generated by the Stockholm conference carried forward and helped to establish in 1983 of the World Commission on Economic Development, headed by Gro Brundtland. Through a process of consultation and discussion this commission helped to firmly establish the concept of sustainable development on the world stage. The widely quoted definition of sustainable development which emerged from this states that development should "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987).

The Rio summit in 1992 continued this theme and produced a set of 27 principles for sustainable development contained in the Rio Declaration. The signatories to this declaration, which included most national governments in the world, committed themselves to uphold these principles in order to achieve a more sustainable world in the 21st century. The principles covered a wide range of issues which are broadly categorised as environmental, economic and social (Moffatt 1996).

The concept of sustainable development draws on a number of different themes. There is the scientific evidence which quantifies pollution and loss of biodiversity and critically studies the impact of mankind as the modifier of nature. There is the evidence from the social sciences which describes the impact on human societies of the stresses brought about as a result of inequities in the distribution of wealth and access to resources, as well as the overexploitation of these resources. This is in a sense the study of how society is in part determined by the environment which mankind has created.

As a final step there is an ethical framework which encompasses the pursuit of sustainability, central to which is the notion that a harmonious balance must be established between mankind and nature if future generations are to have the same opportunities as the present generation. Thus mankind in harmony with nature is seen as an ultimate goal.

The pursuit of sustainability can be seen as a significant development in the relationship between mankind and nature. It requires an appreciation of the complex interrelationships which exist between natural ecosystems, human economic activity, socio-political factors and ethical and moral considerations. Previous cultural attitudes have tended towards one dominant view of the relationship between mankind and the natural environment. Some have emphasised the role of the natural environment in constraining human activities and determining the options available. The view of mankind as having a role in altering and even controlling the environment has been of great importance, as has a recurring desire to put mankind in harmony with the natural world. Each, individually, tends to see the relationship as unidirectional, where A acts on B to produce a resulting state. The major shift in thinking, which can be traced back to the influential works of 19th century writers, notably the early writings of Karl Marx from the period around 1844 (Marx 1975) and Charles Darwin's The Origin of Species from 1859 (Darwin 1998) and developed by many others in the 20th century, has been the view that there exists an interdependence between mankind and nature. This is portrayed by Marx as a dialectical process and by Darwin as the web of life, where complex interactions take place that cannot be explained by simple cause and effect relationships. This notion of interdependence and feedback within systems is discussed in Chapter 3.

1.6. The Area of the Study

Scotland is the most northerly part of the British Isles and is situated at the convergence of polar, subtropical, continental, and oceanic air masses. This gives variability to the climate though it is the dominance of the westerly airflow of oceanic origin which dominates the weather of Scotland. The circulation pattern of the Atlantic Ocean is responsible for transporting considerable amounts of heat northwards via the Gulf Stream and North Atlantic Drift. This raises temperatures across the whole of north West Europe well above those of other areas of similar latitude. The prevailing westerly winds, blowing across a relatively warm ocean serve to transfer this heat energy from the oceans to the landmasses.

Two major fault lines running roughly from south west to north east separate Scotland into three main geological zones. North and west of the Highland boundary fault lie the Highlands, a largely mountainous area with a landscape clearly indicative of it's glacial past. The central lowlands are relatively flat and contain the majority of the population of Scotland, mainly within the Forth and Clyde valleys. To the south lie the Southern Uplands, extensive upland areas with fertile valleys between.

The area chosen for the study comprises three local authority areas which form a rough transect across Scotland running just north of Glasgow and Edinburgh, the main centres of population. These are Argyll on the west coast, Fife on the east coast and Stirling in a central location.

Within the study area there are a number of contrasts between the west and east. Geologically the west is dominated by igneous and metamorphic rocks which are hard, impermeable and tend to degrade to produce acidic soils. In contrast, much of the east of the study area lies on sedimentary rock formations which are softer, and hence more eroded, as well as being permeable, and degrade to form more base rich soils. The east has considerable coal deposits which have been worked for centuries and have allowed industrial activities to develop, in contrast to much of the west of the area of the study.

The west is exposed to the prevailing winds, which tend to originate in moist and relatively warm oceanic air masses. The mountainous relief of the west combines with this to generate heavy rainfall, which decreases on a west/east gradient. The presence of warm waters off the west coast tends to moderate temperature extremes, the range of temperature experienced in the west being less than the range experienced in the central or eastern areas.

All of this has consequences for the natural vegetation of the areas as well as the uses to which the land has been put in the different regions. Argyll, in the west, is dominated by rough grazing and forestry, with limited arable and dairy farming. The eastern areas of Fife and parts of Stirling are largely arable with intensive grazing on improved grassland.

These contrasts in the physical attributes of west and east have produced a considerable contrast in the distribution of the human population, with the west being sparsely populated and the east developing more densely populated areas, particularly around the sites of industrial development.

The three regions of this study have been chosen to reflect these contrasts, and, by providing a rough west/east transect across Scotland, cover a considerable amount of the variations which characterise Scotland as a whole. The following sections provide some information relating to the regions of Argyll, Stirling and Fife, all of which have had their boundaries altered during the local government reorganisations of 1973 and 1996, but have for the most part remained very similar to their present form.

Figure 1-5 shows the location of the three regions in relation to the rest of Scotland.

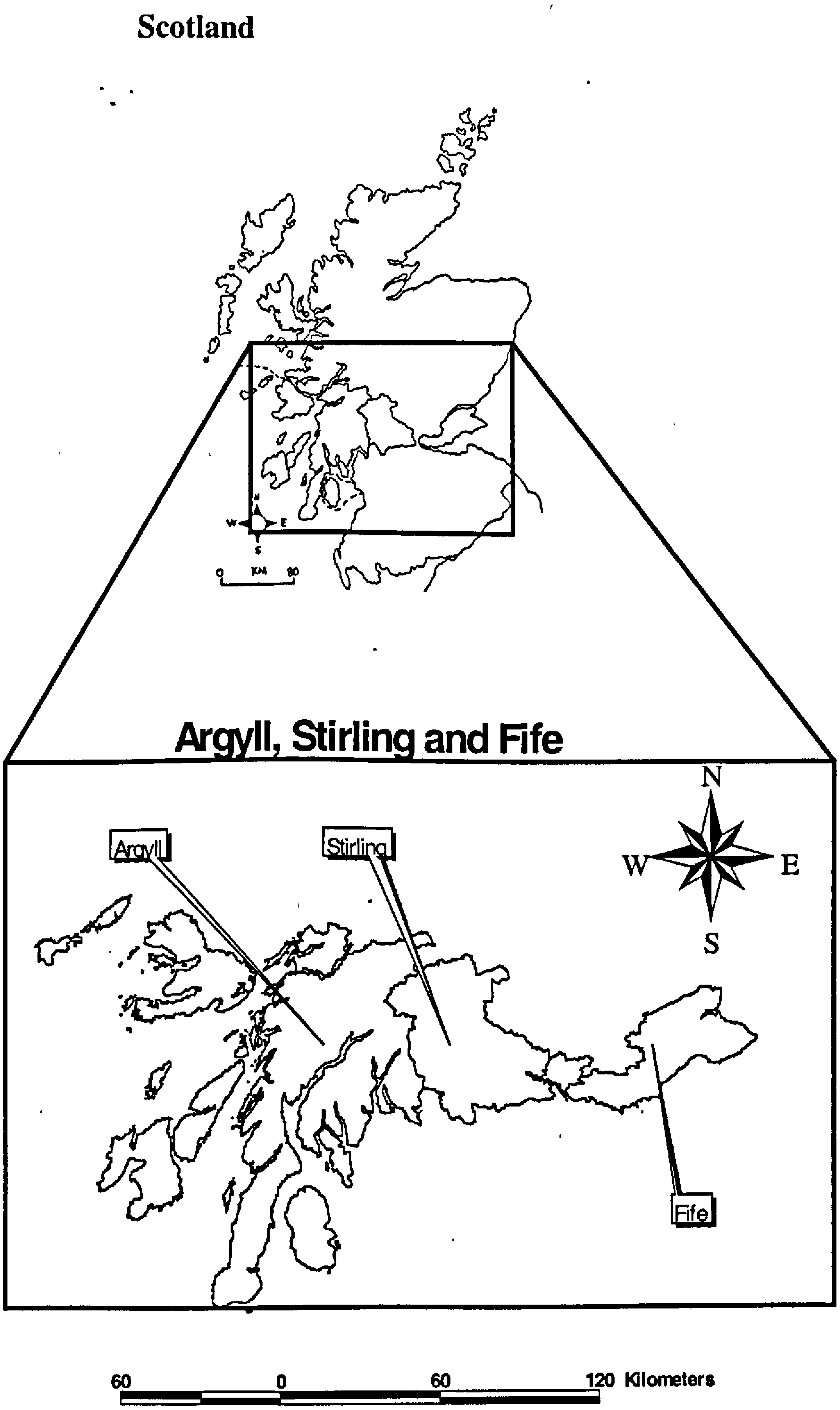


Figure 1-5 The three regions of the study.

Argyll and Bute

The population of Argyll has been in decline over the past 3 decades. The reorganisation of local government in 1996 added a significant part of West Dunbartonshire, which increased the population from around 60,000 to approximately 90,000 persons. In order to maintain some continuity in the records and avoid a sudden increase, the population was backdated by scaling the previous figures for Argyll by the appropriate factor of 1.43, representing the ratio of the new population to the old in 1996. Thus population figures in the model from 1970 onwards represent the population of Argyll according to the new boundaries.

Figure 1-6 shows the topography of the region. To enable a comparison, the scale used for the heights is the same as in the maps of Stirling and Fife. It can be seen that there is a lot of high ground, particularly on the mainland, but that a considerable amount lies between 0m and 300m above sea level, particularly on the islands and coastal regions. This is by far the largest of the three regions with an area of 702,300 hectares and, as can be seen from the map, has an extensive coastline.

The distribution of the urban areas is illustrated in Figure 1-7 along with the main road network. It can be seen that there are few large settlements and the population is scattered mainly along the coastal fringes of the region. The population of the entire region is 88,790 (in 2000) giving a population density of approximately 13 persons per square kilometre.

Much of the land is devoted to rough grazing, 470,000 hectares in the year 2000 which represents 67% of the land surface. In addition there is extensive forestry, much of which is composed of recent plantations of exotic species, mainly Sitka spruce. The extent of this forestry is illustrated in Figure 1-8.

This map was created from ordnance Survey data available through Digimap (Edina 2003). Figure 1-8 gives a clear picture of the extent of tree cover in Argyll, and gives an indication of the importance of forestry to the economy of the region.

Tourism plays an important role in the economy of Argyll, the spectacular coastal and mountain scenery being one of the major attractions for visitors. The proximity of the region to major centres of population in the central belt of Scotland makes this a popular destination for short breaks and day trips. This area also attracts a considerable number of visitors from within the rest of the UK, over 90% of the bed nights sold are to UK residents, making home grown tourists by far the most important sector of the market.

A useful source of general information concerning this region can be found on the Argyll and Bute Council website (Argyll council 2003).

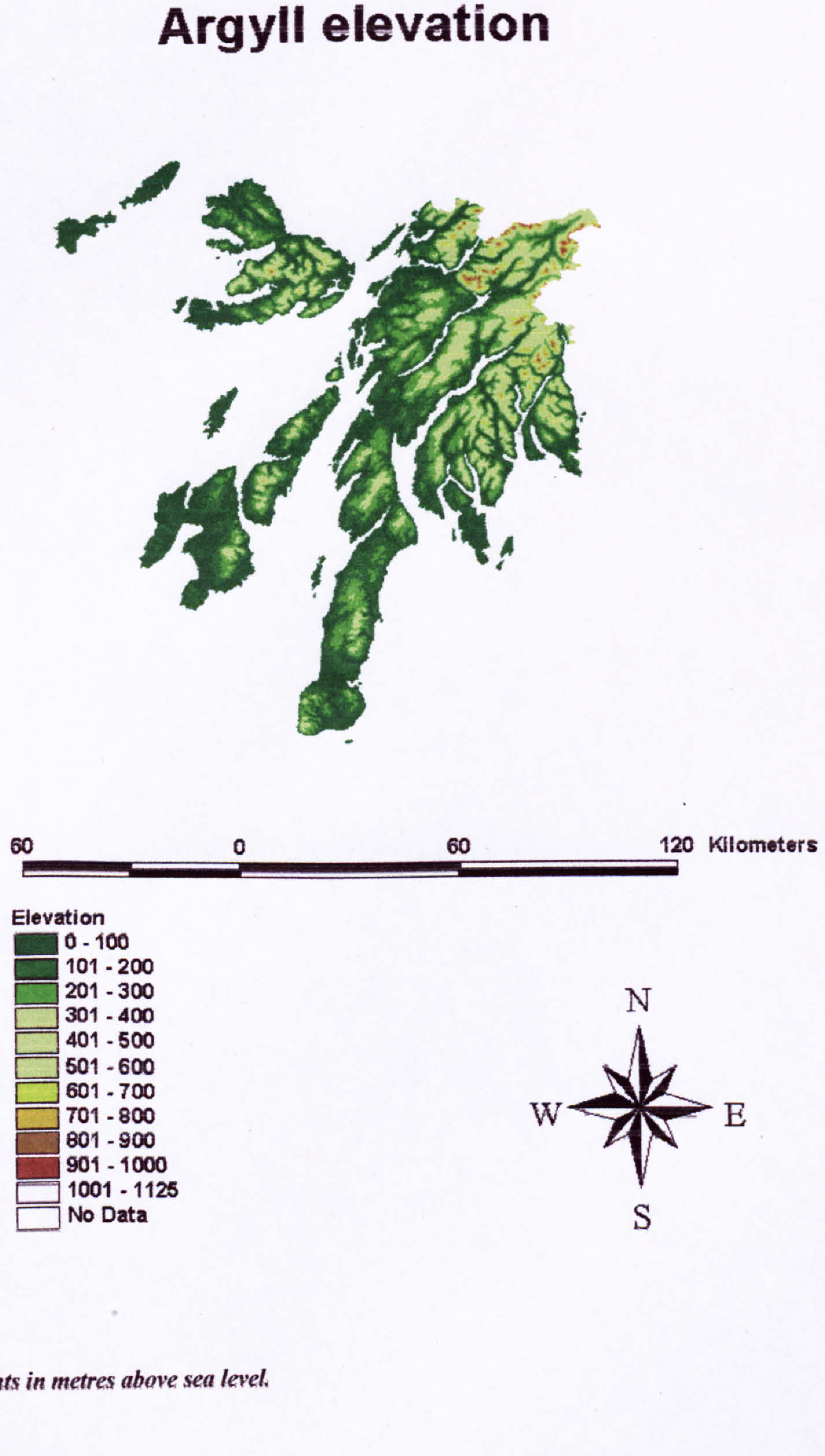


Figure 1-6 Argyll; heights in metres above sea level.

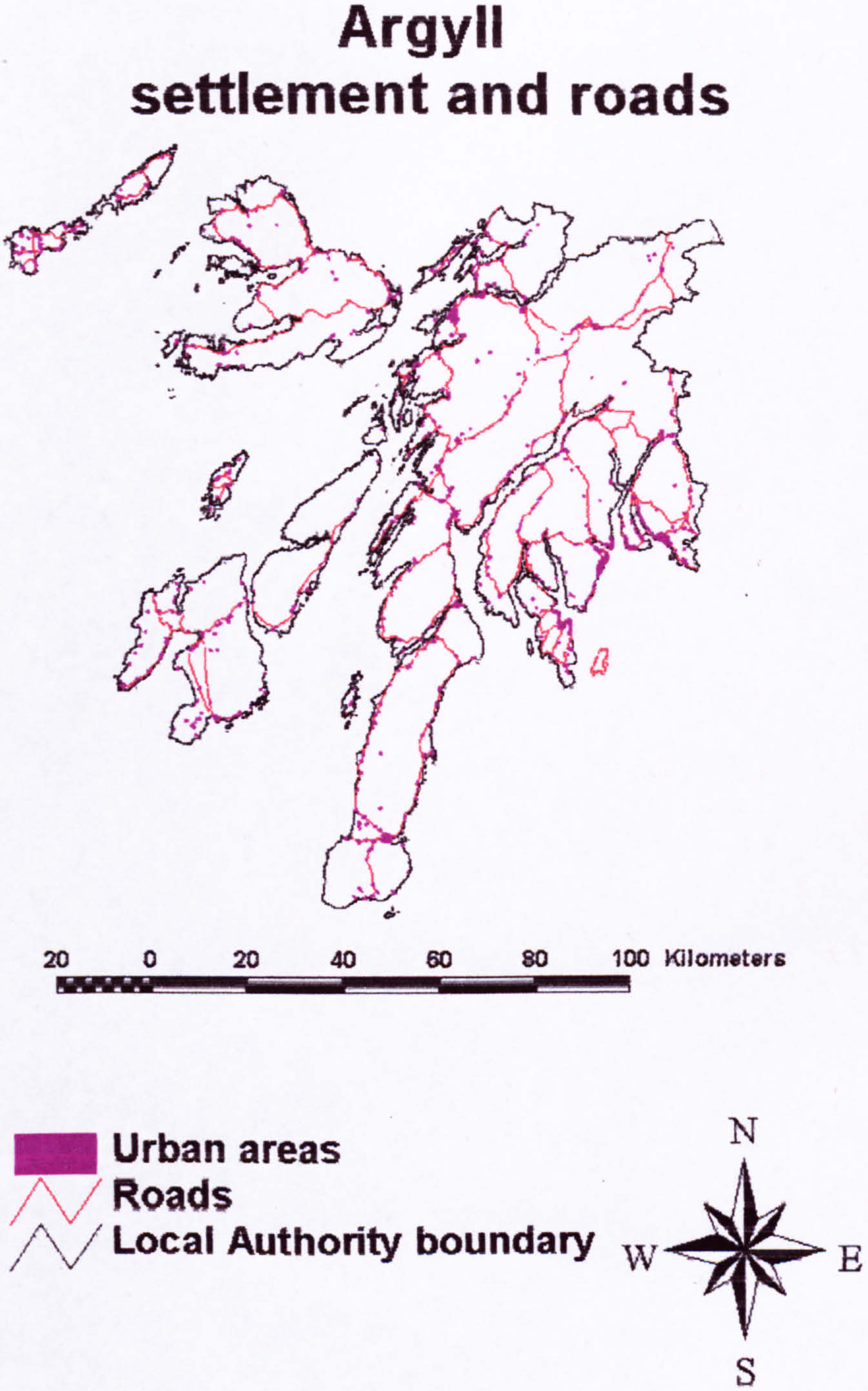


Figure 1-7 Argyll; Urban areas and main road network.

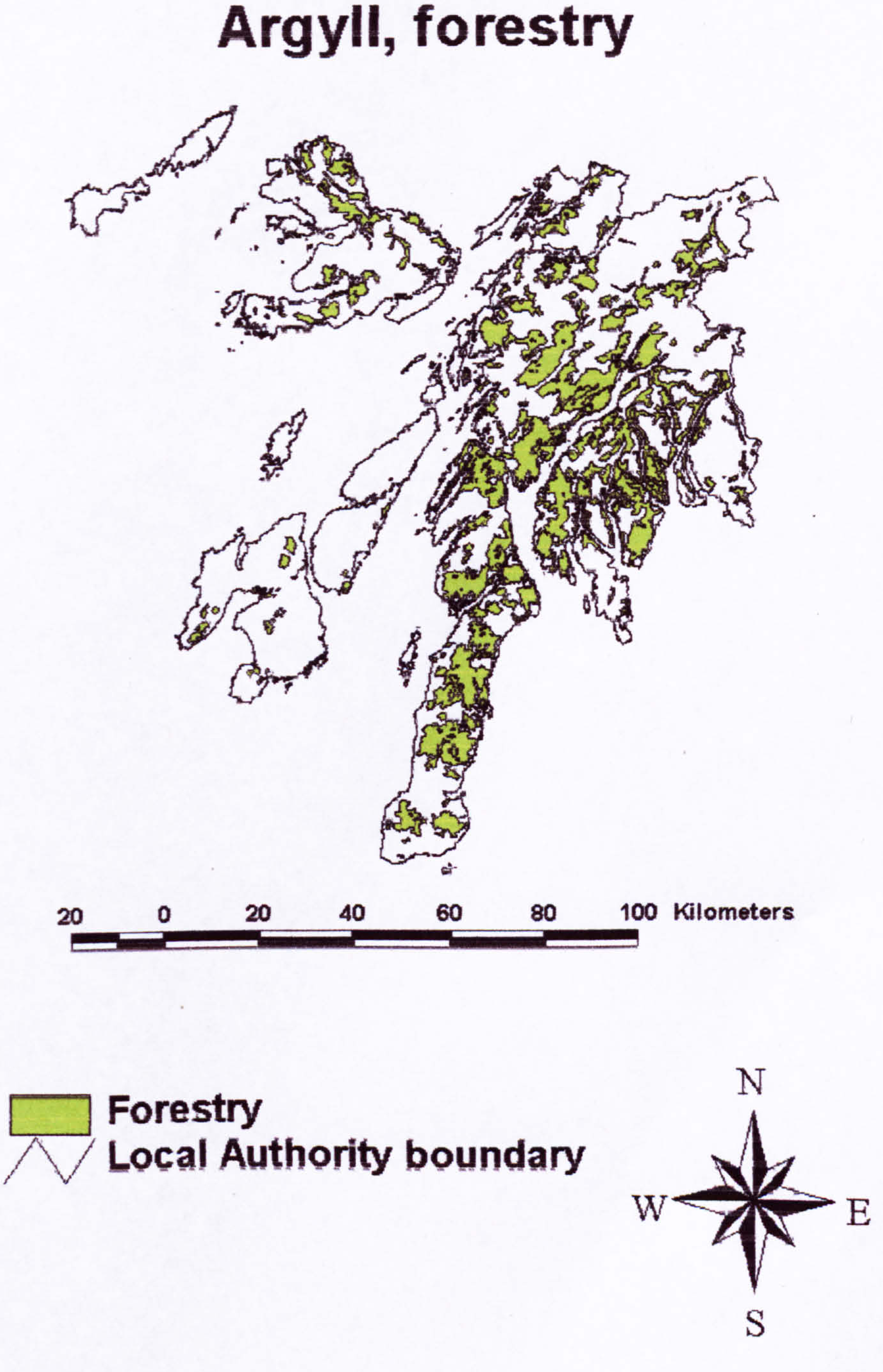


Figure 1-8 Argyll; the extent of forestry.

Stirling

Stirling has been described as "one of the most varied tracts of land in the UK" (Timms 1974). The Northern and western parts in many ways resemble Argyll with which it shares a common boundary. Stirling has a significant area of uplands, where rough grazing and forestry are important land uses. Stirling has also a substantial area of low-lying land surrounding the Rivers Forth and Teith, towards the eastern end of the Stirling region. This area was inundated by shallow sea during, and for a period after, the last Ice Age. Silts were deposited at this time, which were later covered by a layer of peat. As late as the 17th century much of this area was raised bog. This was extensively cleared during the 17th and 18th centuries and agricultural activities developed across much of the region. One large fragment of this peat bog remains at Flanders Moss, the largest lowland bog in the UK.

Underlying the eastern parts of Stirling region are sedimentary rocks, many dating from the Carboniferous era. These include several coal deposits and oil shale, both of which have been exploited in the past. Much of the industrial development associated with these deposits occurred further downstream on the river Forth around Falkirk, but until recently coal mining was an important employer in the Stirling area.

The population of Stirling has been growing steadily over the past few decades, Communications with the rest of the central belt are good, and the economy has diversified to include a large service sector. Agriculture still plays an important role in determining land use but the numbers employed are only around 3% of the total population according to the data supplied by the Scottish Executive Environment and Rural Affairs Department (SEERAD). The topography of the region is illustrated in Figure 1-9 and the distribution of population in Figure 1-10. It can be seen that the majority of the population is resident in the eastern parts of the region on the relatively low-lying land. A population in 2000 of 85,220 and an area of 224,320 hectares gives a population density of 38 persons per square kilometre.

Rough grazing is important in the western and more northern parts of the region where there are extensive areas of high ground. Towards the southern and eastern parts there is predominantly mixed agriculture combining arable and livestock production.

Figure 1-11 shows the distribution of forestry in Stirling, much of which is found on areas which were previously rough grazing. Although not as extensive as in Argyll, there is still a significant amount of forest cover.

The varied landscape and rich history of this area generates an important tourist industry. As in Argyll this amounts to around 9% of the population working in tourism related jobs. Stirling has a more mixed economy than Argyll, with a large service sector but retaining an industrial base as well.

Further general information is available at the Stirling Council website (Stirling council 2003)

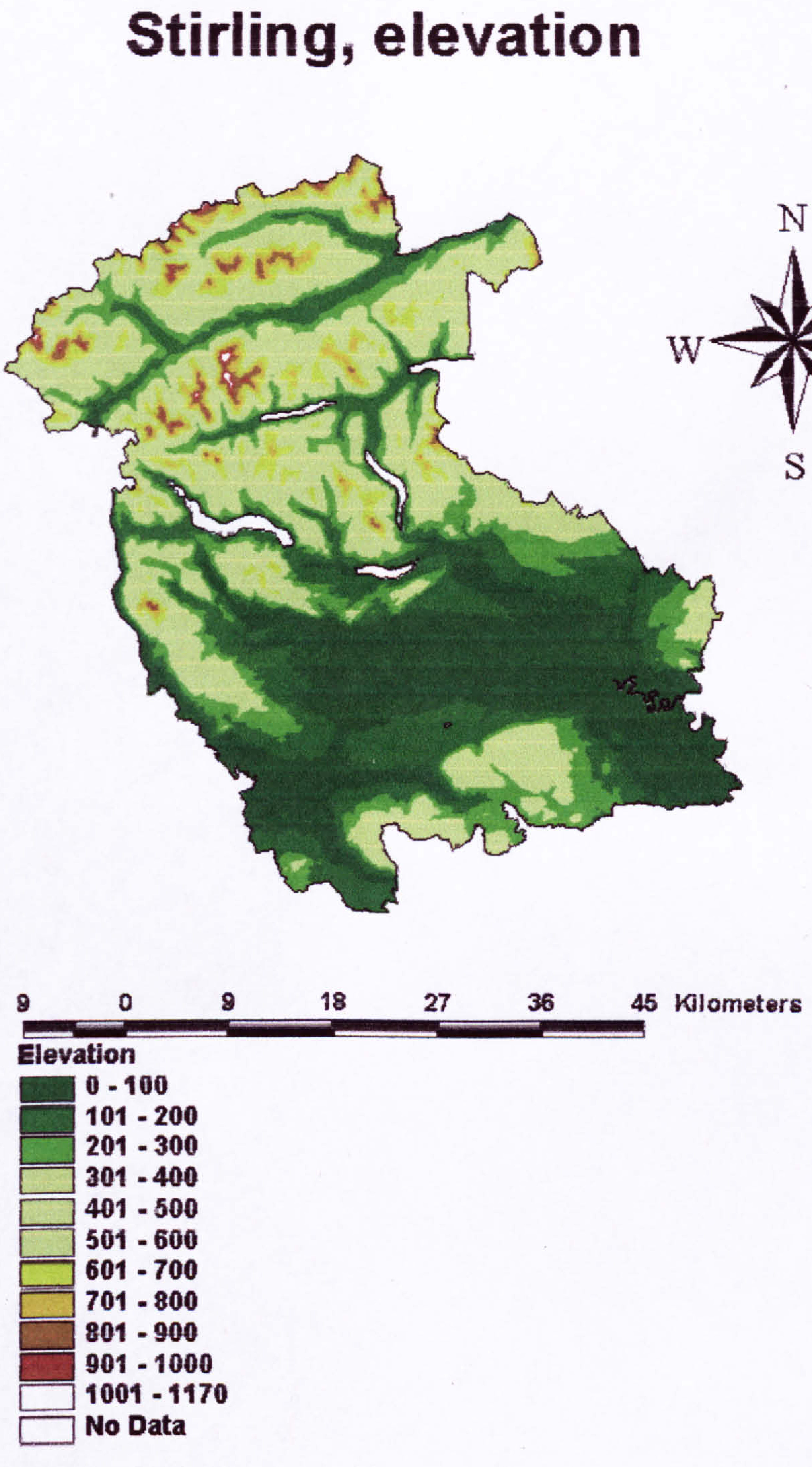


Figure 1-9 Stirling; topography with heights in metres above sea level.

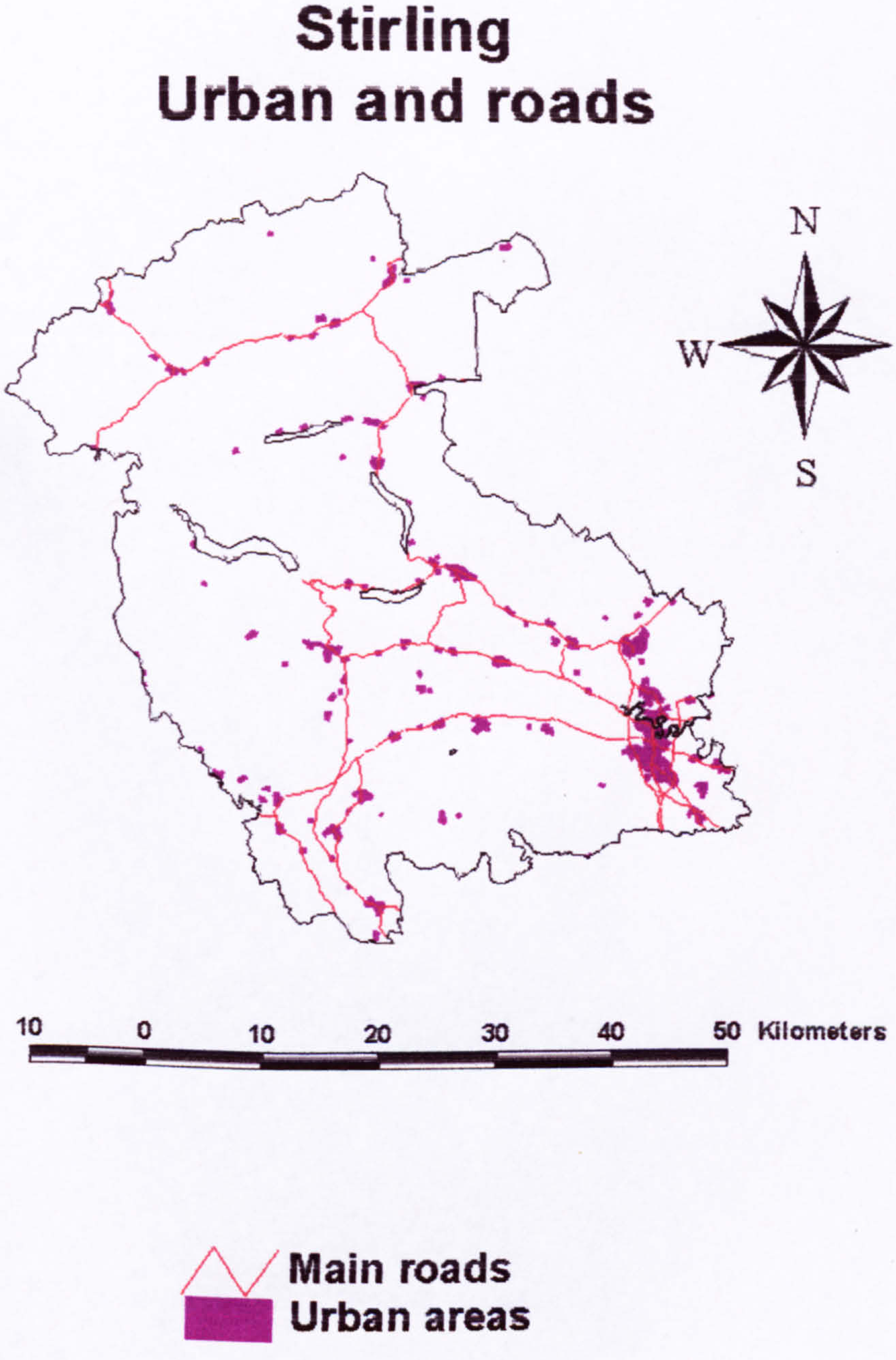


Figure 1-10 Stirling Urban areas and main road network.

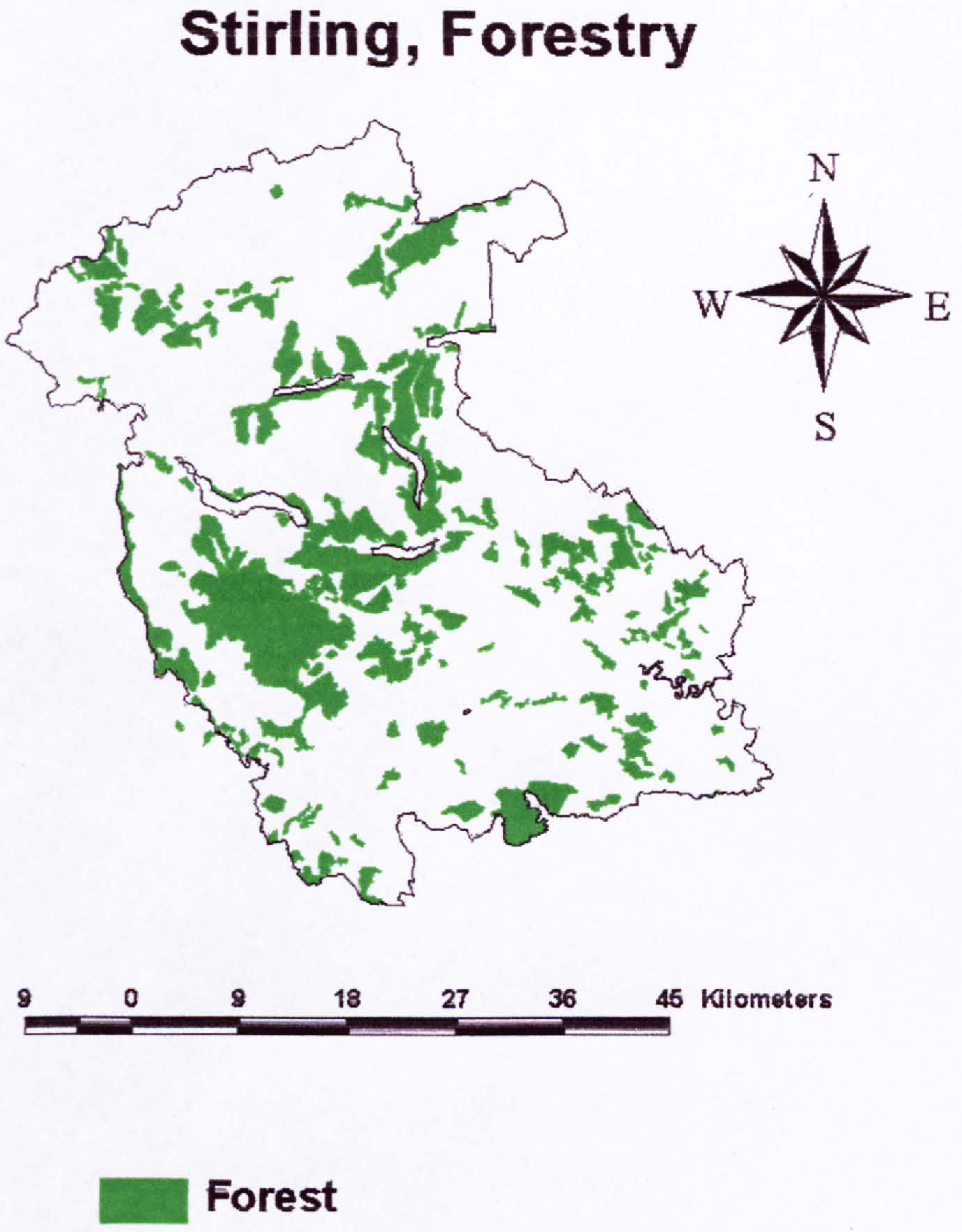


Figure 1-11 Stirling Forested areas.

Fife

With a population of around 350,000 Fife has a greater population than the other two regions combined. There are a number of large towns in the region as well as numerous small towns and villages, reflecting the importance of the agricultural settlements as well as the later industrial developments. The population has been growing over the past few decades although the employment structure has changed. The Fife coalfield was once a major employer in the region and there were engineering and shipbuilding works on the coast. The decline of these industries was partly offset by new work associated with North Sea oil, such as oilrig fabrication and a major natural gas terminal.

The landscape is relatively low lying, and the fertile soils have led to a well developed agricultural sector. The majority of Fife is farmed with cereal production being important along with other crops. Livestock is raised mainly on improved pasture, there being little land classed as rough grazing. Figure 1-12 shows the topography of Fife. This map uses the same scale as the previous maps of Argyll and Stirling and illustrates the contrast between them. Much of Fife is below 300m in altitude. There is very little above 400m- only a few hilltops along the northern boundary. The coastline of Fife has a number of fine beaches as well as a number of old fishing villages which retain much of their character.

Figure 1-13 shows the distribution of settlements, and it can be seen that in comparison to Argyll and Stirling there is a far denser pattern. An area of 134,045 hectares and a population in 2000 of 350,400 persons gives a population density of 261 persons per square kilometre. This is in stark contrast to the 13 and 38 persons per square kilometre in Argyll and Stirling respectively.

Agriculture dominates the landscape of Fife, many of the towns inland owing their origins to agricultural settlements which have expanded over time. Although still an important industry in Fife, it currently employs less than 2% of the population, a number comparable in real terms to the agricultural workforce of Stirling, but dwarfed by the size of the non-agricultural workforce. Forestry is not a big employer in Fife, most of the land being more productive as agricultural land. This is illustrated in Figure 1-14.

Tourism plays a large part in the economy of Fife. In each of the three regions the percentage of the workforce employed in tourist related activities is around 9%, which, given the size of the Fife workforce, makes the actual numbers in Fife significantly larger. The picturesque coastal villages and beaches, numerous golf courses and rich history attract many visitors.

The website for Fife Council (Fife council 2003) can provide additional information on this region.

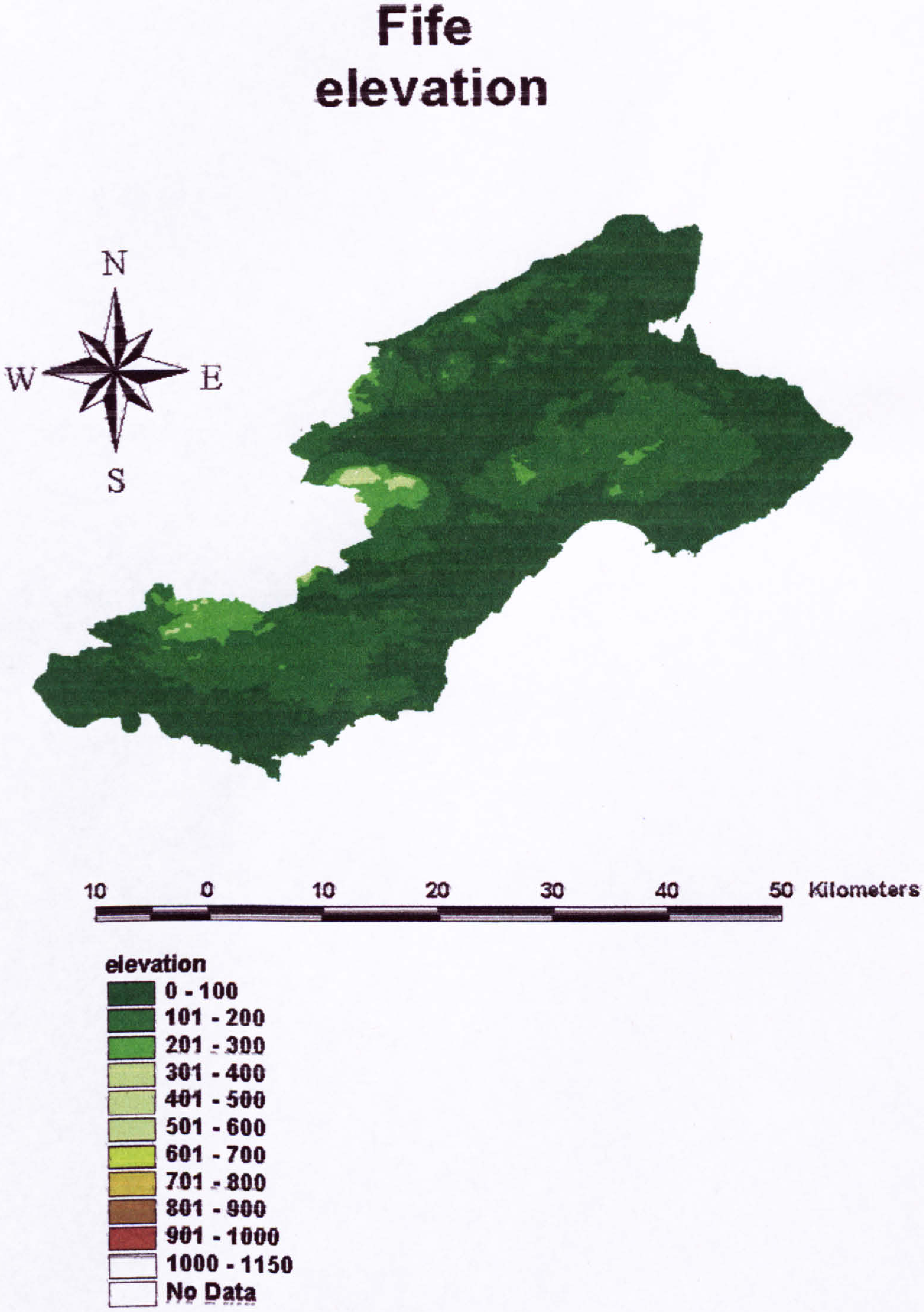


Figure 1-12 Fife heights in metres above sea level

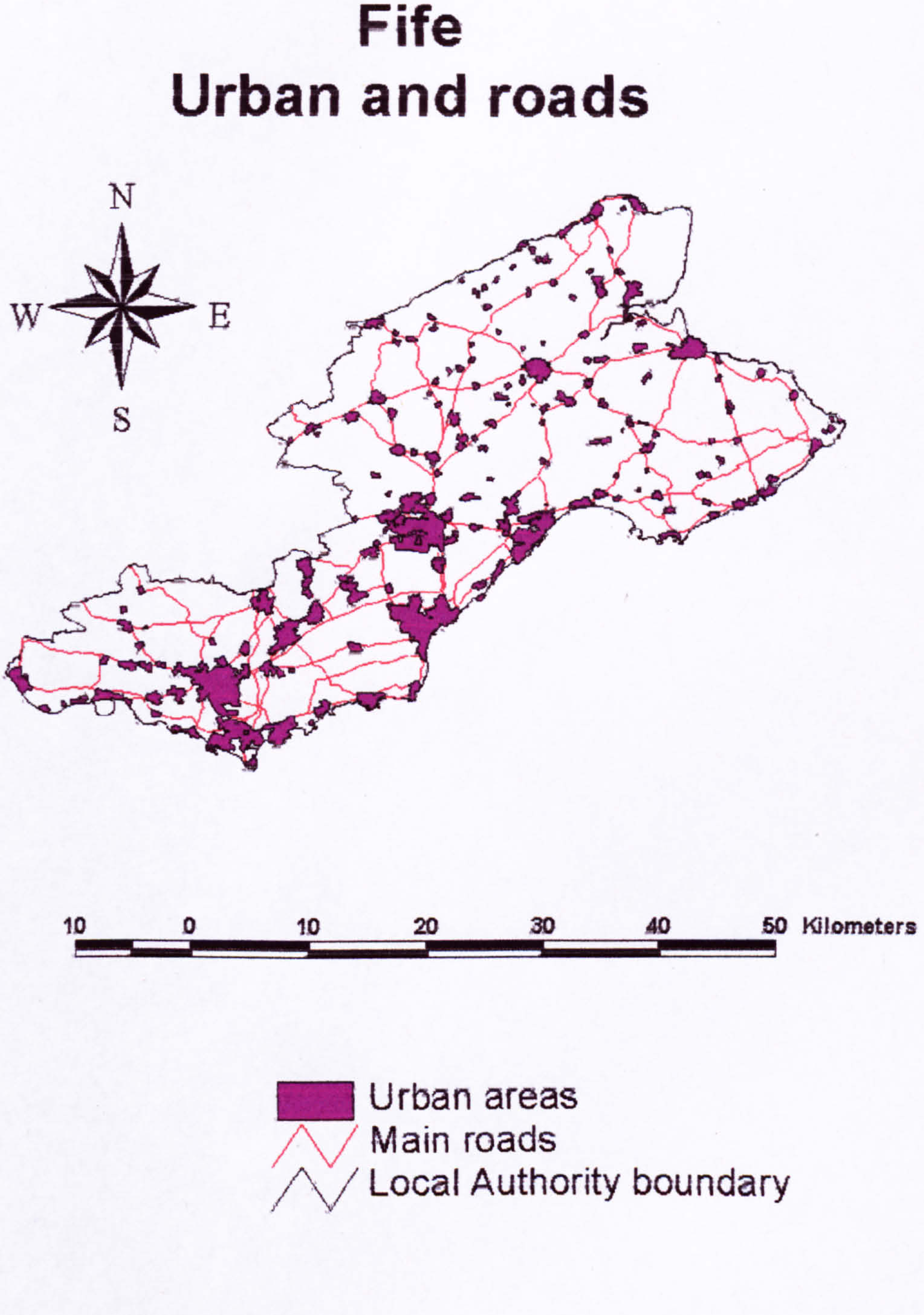


Figure 1-13 Fife: Urban areas and main roads

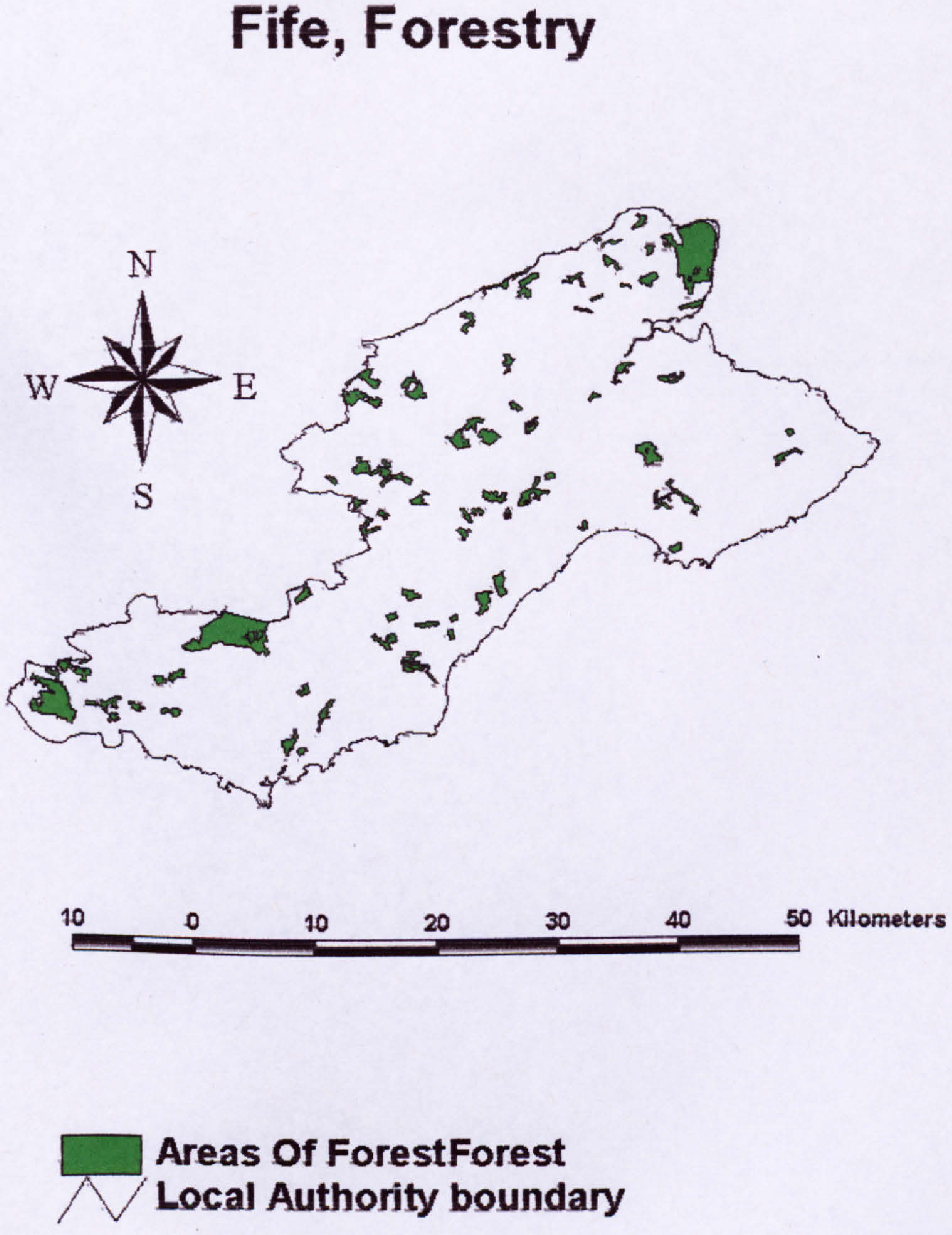


Figure 1-14 Fife: areas of forest cover.

1.7. The structure of the Thesis

Chapter 1 has introduced the aims and objectives of the study and discussed briefly the problems associated with the interdisciplinary nature of the work. This was followed by a short description of each of the three Local Authority areas which form the basis of the study.

Chapter 2 gives an overview of the global climate system, including the natural factors which have been identified as playing a part in past climate changes. Some recent evidence which supports the view that the global climate is currently changing is then presented along with a description of the human activities which are understood to be causal in this process. There follows a brief summary of some of the recent work which has been done to identify potential impacts of climate change, affecting human and natural systems.

Chapter 3 is concerned with the various data sources used in both the climate and socio-economic sections and describes the methodologies relating to each of these parts of the thesis. This includes a description of the system dynamics approach to modelling.

This is followed in Chapter 4 by the analysis of meteorological data from sites in each of the three regions of the study, focusing on temperature, precipitation and wind speed.

Chapter 5 looks at the factors which can be identified as determining the climate of the three regions of the study, by performing regression analysis on a range of data sets.

Chapter 6 describes the process of construction used to build a simple climate model for the three regions, which can be run through simulated time to the year 2100. This model is designed to simulate temperature and precipitation on a regional basis for the three regions of the study. Four different climate change scenarios are used, and the results from this model are compared to the empirical trends and the output from the UKCIP02 regional climate model in Chapter 7.

Chapter 8 deals with the construction of a multi-sector socio-economic model for each of the three regions. This comprises six interacting sectors, population, employment, land use, housing, water resources and emissions. This is linked to the climate model which forms a seventh sector.

The sensitivity of the model to changes in a range of parameters is investigated in Chapter 9.

Chapter 10 presents the results generated by runs of the model, comparing the four different climate change scenarios with a scenario based on constant climate. Results relating to each of the six sectors of the socio-economic model are presented, illustrating the main changes which the model simulations identify as resulting from climate change.

Chapter 11 provides a discussion of the results, dealing with each sector in turn then discussing the results in general.

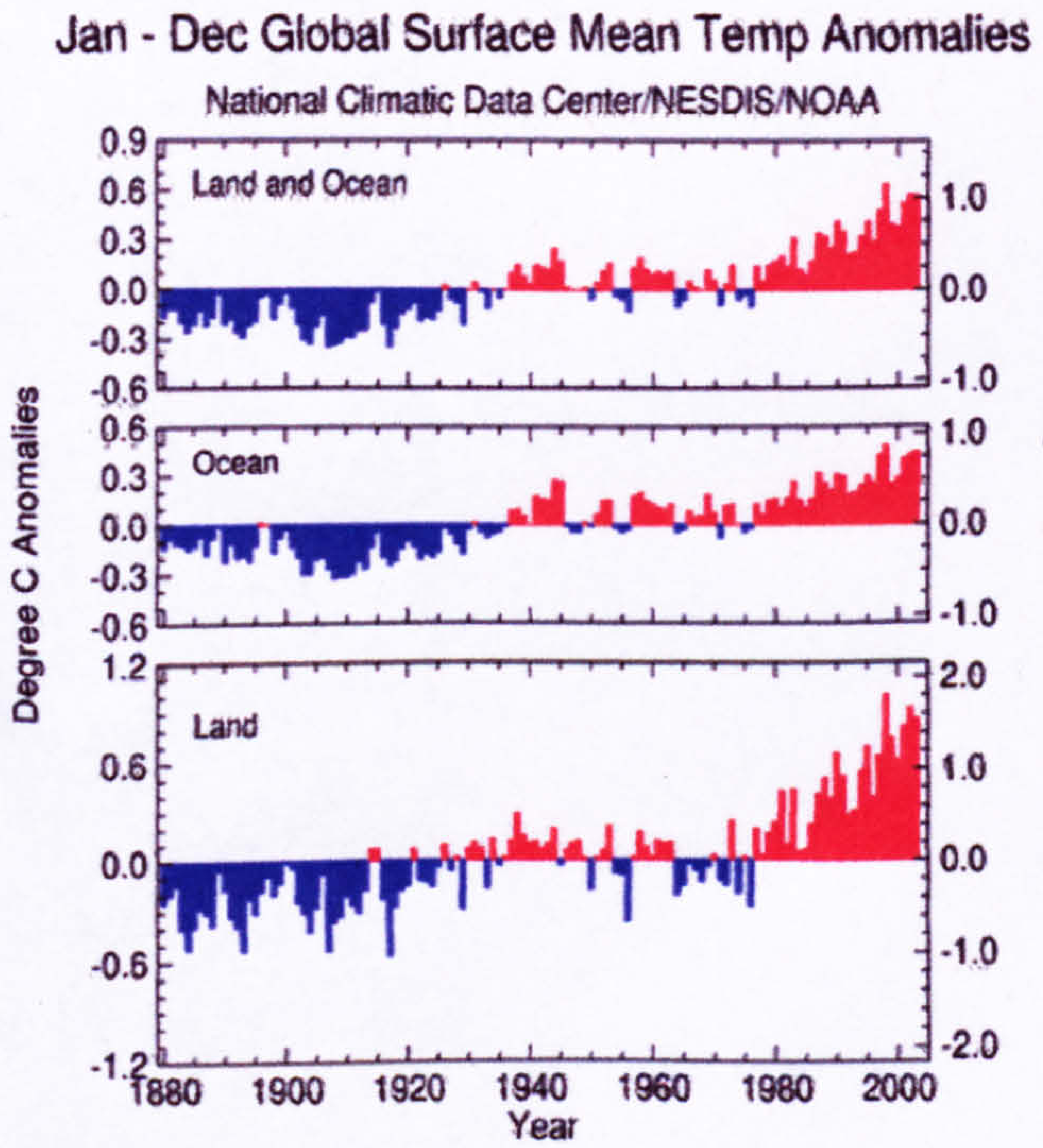
A conclusion is provided in chapter 12 and the Appendix has full listing of the model codes and details of the internal feedback loops from the model.

Chapter 2 Climate change

2.1. Recent temperature trends

Meterological obsevations carried out over the past century indicate that global temperatures have increased by around 0.6°C over the course of the 20th century (UKCIP 2002). This increase is more rapid and of greater magnitude than what would be considered to fall within the range of natural climate variability and is therefore seen as largely due to human activities (IPCC 1996).

Figure 2.1 illustrates the temperature records covering the period 1880 to 2000.



Source NOAA, 2004

Figure 2.1 Temperature anomalies from 1961-1990 average for Land , Ocean and combined.

This illustrates how mean surface temperature differs from the 1961-1990 average for land based measurements, ocean based measurements and the combined global mean surface temperature.

All three sets of results indicate an upward trend, accelerating towards the end of the 20th century. As well as the temperature records, there are a number of other observations which indicate that the global climate is changing. The warming of the oceans has caused thermal expansion of the water, with the result that sea level has increased by about 20 cm between 1900 and 2000. Glaciers in mountainous regions around the globe have decreased in extent and have lost mass and sea ice amounts have decreased, with a thinning of Arctic sea ice during the summer and early autumn (UKCIP 2002). Given this compelling evidence that the global climate is changing, attention has focused on the mechanisms which drive these changes.

This chapter will examine the basic climate system and describes the "greenhouse effect", the contribution that the particular gaseous composition of the atmosphere makes to maintain the surface temperature of the earth.

Climatic variability over timescales ranging from thousands of years down to annual variations are then examined along with a summary of the possible impacts such changes have had on past cultures.

The following section looks at the evidence which supports the current consensus of opinion (IPCC 1996) that human activities are largely responsible for current global climate change

Recent studies of climate change and a description of the attempts to provide forecasts of future climate change are then described. The future climate change scenarios provided by modellers have been used to examine a range of impacts on human and natural systems, some of the recent work is described in this section. The importance of the local climate in determining local impacts is examined in section 3.5.3

2.2. Basic concepts

The climate system of our planet can be seen as the manifestation of the energy flows which have the Sun as their source. These flows of energy represent a "closed system", this being one in which there is a transfer of energy but not of mass. The flow of incoming solar radiation is balanced by the flow of outgoing terrestrial radiation. Due to the difference in temperature of the Sun (6000 degrees K) and the Earth (288 degrees K) there exists a significant difference in the wavelengths of these two flows of radiation. Thus solar radiation tends to be short wavelengths, with a peak in the visible parts of the spectrum, whereas the outgoing terrestrial flow tends to be longer wavelength infrared radiation. The inflow and outflow balance each other. Failure to do this would result in an ever increasing or decreasing temperature for the planet Earth.

Although overall the system is balanced, the distribution of insolation across the Earth's surface is not even. The areas of the Earth's surface close to the equator receive the maximum amount of solar energy, whereas the polar regions receive considerably less. The radiative cooling of the planet is more evenly distributed, leading to an excess of energy near to the equator and a deficit towards the poles.

The process which establishes the thermal equilibrium on the planets surface involves the transfer of energy polewards in order to counteract this deficit between radiative energy loss and incoming solar radiation. This is, in effect, what gives rise to the climate systems of planet Earth. The two main processes by which energy is transferred polewards are by atmospheric circulation and by the motion of ocean currents. The former operates relatively quickly whereas the latter, due to the enormous heat capacity of the oceans, operates on a much longer timescale.

The rotation of the Earth on its axis means that a simple north/south transfer of energy is not possible, with the correolis force (a more rapid rotation at the equator than towards the poles) deflecting the prevailing winds and giving rise to distinct bands of atmospheric circulation. This circulation is further complicated by the presence of land masses, where topography, vegetation and land surface characteristics all play a part in determining the movement of the atmosphere. Ocean circulation is similarly constrained by the presence of land masses and the depth and topography of the ocean basins.

It is the interaction of the various elements of the atmosphere, hydrosphere, cryosphere, biosphere and lithosphere that generates weather patterns, and the climate of a region is simply defined as the long term (30 year) average of these short term weather phenomena.

2.2.1. The greenhouse effect

Due to the very high temperature of the sun, the incoming energy to the Earth's surface is predominantly of short, high-energy wavelengths (~0.2-4 μm). When the Earth radiates energy back to space, the lower temperature means that it involves lower energy and therefore longer wavelength radiation (~6-30μm). Without our present atmosphere the net effect of this would be to maintain the Earth's surface at an average temperature of approximately -18°C. Calculations (Drake 2000) have shown that with an atmosphere consisting of only oxygen and nitrogen the surface temperature would average around -6°C., this including the greenhouse effect of water vapour and low level clouds. The present average surface temperature which we experience is around 15°C, and these differences are due to the naturally occurring greenhouse effect which results from the particular composition of our atmosphere and the properties of the constituent gasses.

The gasses in the atmosphere are largely transparent to short wave radiation, hence we can "see through" it. Incoming solar radiation can therefore pass through the atmosphere and is absorbed or reflected by the Earth's surface. Certain gasses have the property of being able to absorb and emit infrared radiation, so a proportion of the outgoing long wavelength radiation is absorbed by gasses in the atmosphere. Since Nitrogen (78%) and Oxygen (21%) do not absorb this energy, it can be seen that the vast majority of the atmosphere plays no part in the greenhouse effect. It is the minor constituents, normally measured in parts per million by volume (ppmv), or parts per billion by volume (ppbv), which have the greatest effect. Table 2.1 lists these gases and their present atmospheric concentrations.

Concentrations of greenhouse gasses	
Gas	Atmospheric concentration
CO_2 Carbon Dioxide	~360 ppmv
CH_4 Methane	~1.8 ppmv
CFC's and related chemicals	~1ppbv
H_2O Water vapour	locally variable between around 0.2%-2%
N_2O Nitrous Oxide	~0.3 ppmv

Table 2.1 Atmospheric concentrations of greenhouse gases

Source IPCC, 2001

Each of these gasses absorbs terrestrial radiation at specific wavelengths and allows other wavelengths to pass through. The absorption warms the atmosphere and maintains the mean surface temperature at a level approximately 33°C higher than would be the case if there were no atmosphere, and 21°C warmer than if the atmosphere consisted of only Nitrogen and Oxygen.

Not included in the list, but nevertheless an important factor in the radiation budget of the Earth, is ozone, O_3, which forms mainly in the upper atmosphere at heights of around 25 000m. Ozone is capable of absorbing incoming radiation and acts as a filter to certain wavelengths of light, particularly ultra-violet. This has the effect of screening out harmful wavelengths and protecting living organisms from damage. Ozone also absorbs longwave infrared radiation in a band where few other greenhouse gases do, but the warming potential of this gas is dependent on the height and latitude where it forms. Damage to stratospheric ozone from CFC's and related chemicals reduces its contribution to the greenhouse effect, but the warming effect of the CFC's outweighs this across low latitudes. At the poles, where damage to the ozone layer is concentrated, the contribution to warming from CFC's is outweighed by the loss of absorption from the reduced ozone layer.

With the exception of the CFC's and related chemicals, these gasses are natural constituents of the planets atmosphere, without which the distribution of life on the planet would be severely restricted.

2.2.2. Past climate change

The system described above is a balanced system, and, although in equilibrium, there is evidence to suggest that this equilibrium is unstable and subject to significant changes over time. Global climate has altered considerably in the past, and evidence for these changes comes from a variety of sources.

Most recently there are meteorological observations, and although patchy and lacking consistency initially, they can provide reasonably accurate records for the past hundred years, and a less reliable, but nonetheless useful, record for the previous century and a half in some areas.

In parallel are historical records, detailing crop yields, extreme weather events, sea conditions and other factors which can be used to reconstruct past climates over hundreds and perhaps thousands of years.

Other indirect sources, which can be used for reconstruction of climate on a longer timescale, include ice cores, tree rings, records of lake levels, glacier advance and retreat, and evidence from lake sediments and peat bogs of pollen distribution. All of these techniques can be used to yield information which can be used to build up probable climatic regimes over thousands of years.

To go even further back in time ice cores from Greenland and Antarctica have been analysed using the ratio of different isotopes of oxygen trapped in air bubbles in the ice ($\delta^{18}O$). Similarly deep sea sediment cores have been taken, in which distributions of microfaunal remains and sediment constituents can yield information relating to sea temperatures and ocean circulation patterns.

The picture which builds up is not one of a steady and stable climate for the planet, but one where quite significant changes have taken place, on timescales ranging from millions of years to changes which have occurred on a timescale of decades.

2.2.3. Long term changes

Since the formation of the solar system, approximately 4.5 billion years ago, it is likely that the luminosity of the sun has increased by around 40% from its original intensity (Drake 2000). This is a significant increase but has occurred at a slow and steady pace, which is relevant on a geological timescale but not over shorter periods. The luminosity of the Sun is expected to continue to increase but the timescale over which this is likely to occur makes this of no relevance to current concerns.

From the geological record there is evidence of several distinct phases of glaciation having occurred in the past. We are at present experiencing a glacial phase, the warm temperatures of the Holocene being the exception rather than the rule for the prevailing climate over the past several hundred thousand years. Previous phases of glaciation have lasted for millions of years, and it is thought that tectonic plate movements are implicated in the establishment of glacial phases. A prerequisite for glaciation appears to be the situation of a continent over or close to one or both poles.

The rate of tectonic plate movement is such that this process operates over millions of years and is therefore from our perspective a relatively stable phenomenon. Since currently we have the continent of Antarctica situated over the South Pole and the continents of Asia and North America encircling the North Pole we are at present in the middle of a glacial period. Seven major ice advances have been identified over the past 600 000 years with relatively short (~10,000-20 000 years) interglacial periods separating the spells of major ice advance.

The present warm spell is just one of many and indicates the variability of the global climate during a period of glaciation. Measurement of the ratio of different isotopes of oxygen trapped in the remains of microfauna from deep sea sediment cores have been used to reconstruct the volume of water which has been frozen in polar ice caps over the past several hundred thousand years. The results indicate a certain regularity to the advance and retreat of the ice caps and shows that the maximum extent of ice sheets occurs with a frequency of around 100,000 years.

The most likely and widely accepted theory behind this apparent periodicity of glacial advance and retreat has been attributed to Milankovitch, a Yugoslav mathematician who demonstrated that the total amount, and importantly, the distribution of solar radiation reaching the planets surface varies due to periodic variations in the Earth's orbit.

Three main factors are of significance to these cycles: the eccentricity of the Earth's orbit, variations in the angle of tilt of the axis of rotation and the procession of the equinoxes.

The first of these, the eccentricity of the orbit affects the total amount of solar radiation reaching the Earth's surface over the course of a year. Because the orbit is not perfectly circular but varies, becoming more and less elliptical over time, the total amount of solar radiation reaching earth on a seasonal basis varies by a small amount. This cycle has a period of approximately 100 000 years, very similar to that of the timing of maximum glaciation.

The orientation of the axis of the Earth's rotation also varies over time, ranging from 21.6 degrees to 24.5 degrees from vertical. This does not alter the total amount of energy reaching the planet's surface, but does alter the distribution, creating a variation in the difference between the seasons. When at the maximum angle of tilt the seasonal range of temperatures is at its greatest. This effect has a period of approximately 41 000 years.

The third factor, which again alters the distribution of solar radiation rather than its total amount is the precession of the equinoxes. This affects which season of the annual cycle occurs when the earth is at its closest to (or farthest from) the sun. If winter in the Northern Hemisphere occurs at aphelion, then less sunlight is available during this season. However the following summer will occur at perihelion, and as a result slightly more energy will be available to melt any lying snow. The period of this cycle is approximately 23 000 years, during which time one complete reversal takes place, with weaker summer sunshine and marginally warmer winters. Figure 2.2 illustrates these orbital variations.

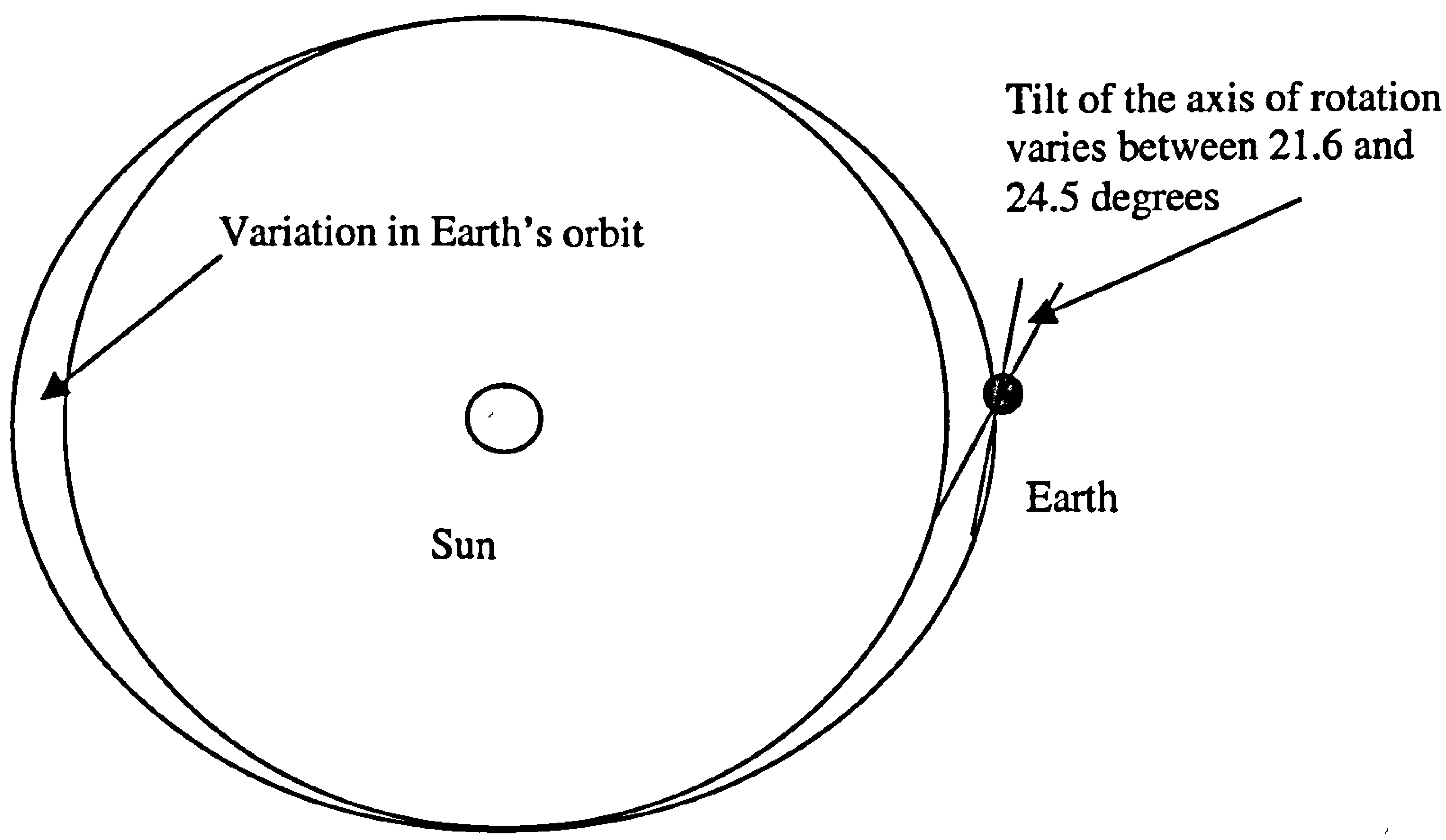


Figure 2.2 Orbital variability of the Earth

Each of these effect has a small impact on the total radiation budget of the planet, but combined they do collectively have a considerable influence on the distribution of energy. Of significance is the fact that the total amount of summer sunshine in the Northern Hemisphere, where land masses are situated at high latitudes, can vary due to the combination of periodic factors by as much as 10% (Houghton 1997).

Periods which are characterised by weak summer sunshine at the poles are associated with a gradual build up of ice, which accumulates for tens of thousands of years.

A following rapid rise in sunshine at the poles, with summertime at perihelion in the Northern Hemisphere, the tilt of the axis of rotation at or near maximum, and the eccentricity of the orbit at a maximum, leads to a rapid melting of the ice sheets. This is accompanied by rapid increases in the concentration of CO_2 and Methane in the atmosphere.

The importance of ocean circulation and mixing appears crucial in this process, as the rising levels of CO_2 and Methane provide a positive feedback to the warming associated with the orbital cycles. The rapid rise in the concentrations of these greenhouse gases requires a process which allows a carbon store to release large quantities of these gasses in a relatively short time.

A study by Muller and MacDonald (Muller and MacDonald 1995) suggests that of the three factors affecting distribution of solar radiation it is the tilt that has the most pronounced effect, although the changes in sunshine distribution, although significant, are not by themselves enough to explain the major changes in climate. The amount of summer sunshine is not by itself enough to explain global temperature changes in the region of 10°C, and it is the existence of feedback mechanisms in the climate system which amplifies the changes brought about by orbital cycles. These feedback mechanisms are discussed later in this chapter.

The Milankovitch cycles seem to be implicated in the major climatic changes which occur over thousands of years, but it is apparent from sources such as tree rings and other proxy data that variations in climate occur at a shorter timescale. The "Medieval warm epoch" of the 10^{th} to 13th, followed by the "little ice age" of the 15^{th} to 19^{th} centuries cannot be explained by Milanovitch cycles. Yet evidence exists for climate change operating on a timecsale of centuries which have local and global significance.

On this timescale no significant effect from orbital variations can be used to explain the evidence of changes in global climate, as no significant changes have taken place in the distribution of solar radiation. Nevertheless significant changes in mean global surface temperature have been established.

One theory which attempts to explain this involves the variability of solar output associated with sunspot cycles. It is known from astronomical records that the 17^{th} century was peculiar in having records showing virtually no sunspot activity. Absence of sunspots is related to lowered solar activity and it has been estimated that the reduction in solar output at this time amounted to approximately 0.4%, representing a reduction of around 1 wattm^{-2} across the globe (Drake 2000). The fact that at this time glaciers were advancing and frost fairs were a common occurrence on the Thames suggests a correlation. Similarly, evidence has been uncovered which suggests a maximum of solar activity during the 12^{th} century, corresponding to the medieval warm epoch (Barry and Phillips 2003). Since 1850, making use of reliable measurements of sunspot activity, it has been estimated that the maximum variations in solar output have been in the region of 0.2%, representing around 0.5 wattm^{-2}.

Whether such small variations in solar output are significant, perhaps subject to amplification by feedback mechanisms, has still to be established. Although a correlation has been identified, no causal mechanism has been verified.

If such a link could be established, it may explain in part the apparent oscillation in temperatures which have seen the climate of Europe deteriorate from the warmth of Roman times to the cooler wetter period of the dark ages. This was, in turn, followed by a warming towards the medieval warm epoch, then a cooling again as the little ice age took hold. The link with cycles of solar activity may be of relevance for these fluctuations which occur over periods of several centuries, but within these broadly defined climatic episodes considerable short term variability has been present.

2.2.4. Short term variability

During the period commonly referred to as the little ice age, mean temperatures across Europe were approximately 1-1.5°C cooler than those of the latter half of the 20th century. This was not a uniform cooling, and cold spells were interspersed with decades which had relatively warm temperatures. For example, the period from 1690 to 1730 was one of the coldest spells during the little ice age, but was followed by a relatively warm decade, the 1730's, during which temperatures were similar to those of the late 20th century. This was followed by a return to colder temperatures during the 1740's (Burroughs 1997).

All areas of the globe did not experience the little ice age simultaneously, and although recognised as a global phenomenon, there is evidence of considerable variability both geographically and temporally (Drake 2000). In looking for an explanation of these climate changes on a shorter timescale, it is clear that the factors discussed above operate on cycles which have a period far in excess of the timescale of these decadal fluctuations.

The fact that cold spells were not experienced at the same time around the globe, but peaked at different times in different regions, suggests that fluctuations in the pattern of global circulation may be responsible for this climate variability. There is strong evidence of major impacts on global climate associated with changes in ocean circulation, with both the El Nino Southern Oscillation (ENSO) and the strength of the North Atlantic Drift (NAD), being of considerable importance.

El Nino

The event known as El Nino represents a reversal of sea surface temperature patterns across the Pacific Ocean close to the equator. In normal years, the Western coast of South America is bounded by cold seas, fed by the Humbolt current with water originating in the Antarctic region.

The up-welling of cold water along the coast of Chile brings nutrients to the surface which helps support a major fishing industry, as well as a considerable diversity of marine species. Atmospheric pressure gradients across the pacific tend to keep warm surface waters near to Australia and Indonesia. During El Nino events the pressure gradient alters and the warm surface waters spread rapidly eastwards, raising the sea surface temperature along the Chilean coast by around 7°C.. The warm waters devastate the fish populations, and can have a serious effect on wildlife and human populations along the length of the coast. The effects, however, are felt much more widely than this as the warmer waters allow for a much greater evaporation rate and hence lead to increased rainfall across all of the west coast of the Americas. Heavy rain falls in normally arid regions close to the warm waters, but the impact of El Nino is felt much farther afield.

Much of the land surface of the southern hemisphere experiences an altered regime of rainfall, with El Nino events being associated with drought in southern Africa, Australia and much of South East Asia. Impacts have been described North of the equator as well. Kripalani and Kulkarni proposed a link between El Nino events and the strength of the Indian monsoon (Kripalani and Kulkarni 1997) and an increase in winter rainfall over the United Kingdom following such events having been detected (Willby, O'Hare, and Barnsley 1997).

These effects illustrate the importance of ocean circulation on not just the local climate, but as a result of the teleconnections which exist in the global climate system as a whole.

Gulf Stream/ North Atlantic Drift

Further evidence of the important contribution made to the global climate by ocean circulation comes from studies of the North Atlantic Drift, in particular relating to the period around the end of the last period of glaciation, approximately 12,000 years before present.

The warm current of the Gulf Stream, originating in the tropical waters of the Caribbean, transports large amounts of heat northwards. This water drifts towards North Western Europe, raising the sea temperature and hence the surface temperature of the atmosphere considerably. The total amount of heat energy reaching the area of ocean between the British Isles and Iceland in this manner is equivalent to the heat energy arriving from insolation (Houghton 1997). As a result, North West Europe and Scandinavia enjoy temperatures well in excess of those experienced by other regions at a similar latitude around the globe.

As the warm surface waters move to the north east, considerable evaporation takes place, leading to cloud formation and to the increased salinity of the water. The evaporation has the effect of reducing the temperature of the surface waters, and this cooled water drifts northwards until it encounters sea ice. Beneath the sea ice it cools further and due to its relatively high salinity, and hence density, it begins to sink. This cold dense water sinks to the sea floor and begins to drift southwards through the Atlantic basin. The formation of this North Atlantic Deep Water (NADW) is crucial to the continuance of the cycle, and drives what is known as the conveyor belt circulation.

Evidence from deep ocean sediment cores (Zahn 1992), (Lehman and Keigwin 1992) suggests that this pattern of circulation is not constant but exists with two, and possibly three, distinct modes. Ocean sediment cores have been used to map the distribution of the abundance of different species of microfauna over considerable periods of time. Since these species of microfauna inhabit waters within a discrete temperature range, their distribution can be used as a proxy measure of the temperature of the upper layers of the ocean. The analysis of the cores showed that during the end of the last period of glaciation, as ice sheets across Scandinavia and North America melted, a sudden reversal in the warming trend took place. A rapid cooling, accompanied by re-advancing ice sheets, took place and persisted for approximately 1 500 years between 12,000 and 10,700 BP. This cold phase, the Younger Dryas, ended very rapidly, and the warming to conditions similar to the present followed. The warming trend which had been established for around 6,000 years prior to this event was interrupted, and around the seaboard of North West Europe sea surface temperatures dropped by as much as 7°C, a change similar in magnitude to that experienced off the coast of Chile during an El Nino event. This event was not a global phenomenon, as the melting of glaciers elsewhere on the planet continued unabated. The explanation for this reversal in the warming trend is generally thought to involve the discharge of huge amounts of fresh water into the North Atlantic as the Laurentian and Finno-scandinavian ice sheets disintegrated (Broeker and Denton 1990), (Lehman and Keigwin 1992), (Zahn 1992). This influx of fresh water decreased the salinity of the warm water, preventing the formation of cold deep water and effectively cutting off the conveyor belt circulation. Whether there was a complete absence of deep-water formation, and hence no warming effect from the NAD, is topic of debate. Zahn (1992) argues that there is evidence of vigorous circulation in the North Atlantic basin but that it was of a different type, with the return current of cold water still evident, but at a much shallower depth.

The addition of large quantities of fresh water to the North Atlantic certainly had a dramatic effect on the ocean circulation. Whether it was stopped or significantly altered may be debatable, but the impact was marked on the climate of the surrounding continents. Once the cold conditions were established they persisted for more than 1000 years. During this time the ice sheets grew again and the discharge of fresh water would have almost ceased. This would suggest that the North Atlantic can exhibit at least two relatively stable circulation patterns which, once established, can persist for a considerable time, with the flip from one to the other requiring some major perturbation such as a massive discharge of fresh water. The present pattern of circulation became established prior to the final warming phase and hence the final melting of the ice sheets (Zahn 1992). This change, which altered sea surface temperatures by more than 5°C across the North Atlantic, happened in a very short space of time, a figure of 40 years being suggested from the deep ocean sediment core data (Lehman and Keigwin 1992).

This cold snap appears to have been peculiar to the region bounding the North Atlantic, as evidence from glaciers in other regions of the Earth show the warming trend continuing unabated (Broeker and Denton 1990). Thus the North Atlantic seems more vulnerable to ocean circulation induced climatic variability than other regions of the Earth.

Both the El Nino/ La Nina oscillation, and the strength of the North Atlantic deep-water formation with consequent North Atlantic Drift, illustrate the important link between ocean and atmosphere in determining the climate on a local and global level. They also demonstrate the relatively short periods over which major changes in climate can take place.

The North Atlantic Oscillation

In the same way that changes in the ocean currents of the Pacific generate the perturbations of atmospheric circulation patterns over considerable distances, so changes in the flow of the NAD can influence the climate of the area surrounding the North Atlantic. Sea surface temperature influences atmospheric sea level pressure as well as the rate of evaporation and wind strength. The pressure gradient between the Azores, off the African coast, and Iceland has been used as an indicator of the prevailing atmospheric circulation patterns. This is known as the North Atlantic Oscillation Index (NAOI).

Strong ocean currents reduce the ocean temperature gradient from north to south, while weaker advection lowers the sea surface temperature around Iceland and creates a strong temperature gradient. This affects the energy budget across the whole region and has an effect on the sea level pressure of the atmosphere. It is the averaging of the pressure gradient from north to south which is used to create the index (Hurrell 1995). A positive value indicates a strong gradient between the high pressure over the Azores and low pressure over Iceland. A negative value indicates a weak pressure gradient between these two sites. High values of the index are associated with a stronger flow of westerly winds, increased rainfall over the western seaboard of Europe and Scandinavia, and an increased temperature over much of Western Europe. Low values of the index are associated with colder winters in Europe and a decrease in precipitation. Cold seas off Iceland therefore create warm conditions over Western Europe, and warm seas off

Iceland produce colder conditions. Measurements taken over the previous centuries show that, once established, a particular pattern can be self-sustaining, for periods measured in decades, though reversals can happen quite suddenly. The sinking of the Titanic happened during a strong positive phase of the NAOI, when colder waters off Iceland and Greenland allowed icebergs to float farther south than usual.

During the positive phase of the NAO, when less warmth is carried northwards by the ocean currents, a strong pressure gradient is established. This in turn increases the strength of the westerly airflow, bringing mild and wet weather to the western seaboard of Europe and Scandinavia. This produces increased precipitation, which either directly, or via runoff, helps to reduce the salinity of the water in the North Atlantic. This in turn prevents the sinking of the water, reducing the formation of cold deep water and reducing the northward flow of warm water. Recent studies suggest that the formation of deep water has declined by as much as 20% over the past 5 decades and this is linked to a run of positive values for the NAOI (Hurrell 1995).

Volcanic Activity

Short term variations in global climate have been linked to the major eruptions of volcanoes. Only volcanoes which eject large quantities of dust, ash and aerosols high into the atmosphere produce any impact on the climate. The eruption of Mount Pinatubo in the Philippines in 1992 ejected large quantities of ash and sulphur high into the atmosphere where it circled the globe in the upper troposphere and lower stratosphere. Photochemical reactions converted the sulphur dioxide into fine droplets of suphuric acid and sulphate particles. This had the effect of partially blocking solar energy by scattering it back into space. Such events produce a veil of fine dust which can influence the global climate, usually for one or perhaps two years. After this time the dust and sulphur compounds have settled back down to Earth, washed out by cloud and rain formation. However major eruptions can have a significant impact on global climate, albeit short lived. Estimates of a global temperature drop of around 0.25 °C for Mt Pinatubo's eruption, along with anomalous weather conditions reported from around the globe, suggest that such events could have a significant impact on the climate, particularly if a series of eruptions were to happen within a short timespan. The Early 19th century was one such period which saw considerable volcanic activity, and the demise of past cultures, dependent on agricultural produce, has been linked to the short lived though sudden catastrophic changes in climate which have followed major eruptions (Lamb 1995).

The composition of the atmosphere

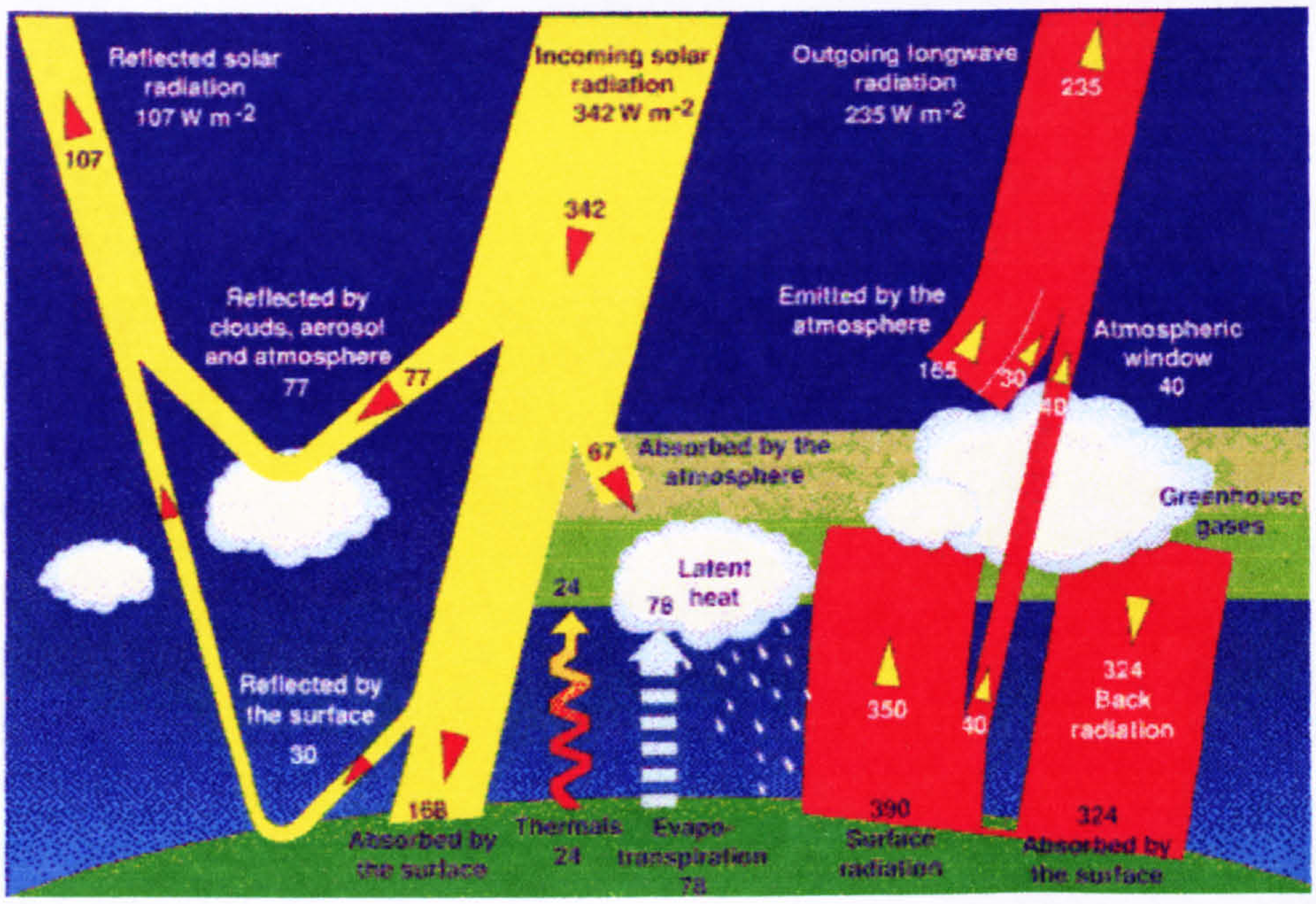
Analysis of gas bubbles trapped in ice, which formed as a result of the compaction of snow falling over Greenland and Antarctica over the past several hundred thousand years, reveals considerable changes in the levels of certain gasses. Although minor constituents of the atmosphere, these are the greenhouse gasses responsible for providing the "blanket" effect, which maintains the Earth's surface temperature at a level approximately 33°C higher than would otherwise be the case. Both CO_2 and Methane show a strong positive correlation with past global temperatures. During periods of maximum glaciation, when temperatures reached a minimum, evidence suggests that levels of CO_2 and Methane were also at a minimum level of concentration.

Methane is a powerful greenhouse gas and is produced mainly through the anaerobic decomposition of plant matter. During periods of glaciation the levels of methane dropped considerably, indicating a drier climate and fewer swampy areas where this decomposition could take place. Similarly levels of CO_2 were at a minimum during periods of major glacial advance, implying that the carbon cycle was operating in a different mode. The role of the oceans in absorbing and storing carbon is of importance, with different ocean circulation and mixing patterns possibly explaining the lower atmospheric concentrations. A colder climate would also imply reduced moisture in the atmosphere, with less evaporation occurring over the oceans. Since water vapour acts as a greenhouse gas, this would again lower the absorption of outgoing infrared radiation. The warming phases which mark the end of glaciation, and the establishment of warmer interglacial periods, are associated with a rapid rise in the levels of both CO_2 and Methane.

Melting ice caps would release trapped methane from the ground below, and the inundation of coastal zones at all latitudes across the globe, as a result of rising sea levels, would also create large areas where decomposition of plant matter would occur. The rise in methane levels would therefore act as a positive feedback to the warming process. Similarly, the release of carbon dioxide from the oceans would accelerate the warming trend, as would increased levels of water vapour associated with warmer temperatures.

The changes in the distribution of insolation associated with the Milankovitch cycles are not sufficient to explain the dramatic and rapid temperature rises associated with the melting of the ice sheets. Other positive feedback mechanisms are required to explain this, the rise in greenhouse gases being a major part of this explanation.

Figure 2.3 below illustrates the overall energy balance of the atmosphere and planet surface in percentage terms. Note that the Earth's surface absorbs around twice as much energy in the form of longwave radiation from the greenhouse gasses as it does from direct incoming solar radiation. At each stage of the energy transfer, changes brought about by alterations to the constituents of the atmosphere can have an impact on the overall energy flows. Many of these can act as feedback, either as positive feedback, reinforcing the change, or as negative feedback, acting to return the system to equilibrium.



NASA/Langley, 2002

Figure 2.3 The Earth's energy balance

2.2.5. Feedback mechanisms.

Cloud cover

Taking the incoming solar radiation, it can be seen that an increase in cloud cover, resulting from greater evaporation due to a warmer climate, would result in more short wave energy being absorbed by clouds and water vapour. This would serve to heat the atmosphere. At the same time the increased cloud cover would reflect more short wave energy back into space, serving to cool the atmosphere. Whether clouds act as a positive or negative feedback on temperature depends on the type of clouds which are formed, with high level clouds acting as a positive feedback, while low level clouds tend to act as negative feedback. Overall, it is thought that cloud cover has a slight negative feedback effect (Houghton 1997).

Albedo

The amount of solar radiation absorbed by the planets surface depends on its reflectivity. This reflectivity is known as surface albedo, which is measured on a scale from zero to one. Total absorption, as with a matt black surface represents an albedo of zero, and total reflection, as from a mirror, has albedo of one. Different areas of the Earth's surface, owing to their different surface characteristics, have different levels of albedo. Water tends to absorb sunlight, though the rate of absorption depends on the state of the surface. Rough waters tend to absorb more than smooth calm waters, though, overall, the albedo of water is around 0.10. Given that 70% of the earth's surface is covered by oceans, their importance as a store of solar energy and a source of outgoing energy is apparent.

The extent of ice cover at the poles is an important factor when considering the albedo of the planet as a whole. The white surfaces of the ice caps reflect a large proportion of incoming radiation back into space. During glaciation this acts as a positive feedback, colder temperatures giving rise to more ice cover, which by reflecting sunlight back serves to further cool the planet. As warming occurs the feedback loop is also positive, warmer conditions reduce the ice cover, less sunlight is reflected back into space and so warming is accelerated.

Dense vegetation has a very low albedo of around 0.18, desert regions have a higher albedo of around 0.50 or more, with grassland having a figure of around 0.24 (Rayner and Malone 1998). The loss of forest in the tropics and the increased extent of desert and grassland regions would act as a negative feed back on temperature, effectively increasing the average albedo of the planet.

Backscatter from atmospheric dust and aerosols high in the atmosphere can be increased by volcanic eruptions as discussed earlier, having a cooling effect on the atmosphere for the relatively short time they remain suspended.

The biosphere.

Feedback mechanisms also exist in the biosphere, associated with changes in the concentration of greenhouse gasses. Increased levels of CO_2 in the atmosphere have been shown to increase growth rates of certain plant species (Jarvis 1999). Faster growth rates will have the effect of locking atmospheric carbon in woody tissues of plants, effectively acting as a negative feedback. Not all plants respond in this way so the total effect due to land plants may be minimal. Plankton in the oceans could also be fertilised in this way, leading to changes in the rate at which the ocean's biological pump operates.

Increased global temperatures can increase the rate of respiration of plant species, the important by-product of this increased respiration being an increase in the output of CO_2 . Increased temperature has the added effect of speeding the decomposition of organic materials, be it in wetlands, oceans or the soils. This has a positive feedback effect, releasing methane and CO_2 in greater quantities.

Warming, particularly in the polar regions, may also release large quantities of trapped methane which has been held in peat bogs or beneath permafrost. Very large quantities of carbon are stored in this way and their release would be a strong positive feedback to temperature increase.

A further source of methane is the large reservoir trapped on the sea floor as a result of decomposition of plankton. Under the great pressure and at low temperatures this forms methyl hydrate. Changes in the temperature of the surrounding sea water could allow the release of large quantities, again acting as a positive feedback to global warming. On balance, there are more potential positive feedback loops than negative ones.

This description of the many factors affecting climate is followed by an examination of some of the archaeological and historical evidence for impacts of past climate change on human societies.

2.3. Past Climate Change and Human Impacts

2.3.1. Introduction

The importance of the relationship between humankind and the environment is reflected in the extent to which this theme has emerged in the belief systems and literature of cultures throughout history. The natural environment is the resource base which maintains human life, and as such has had a central position in the cultural values which societies develop.

Considerable debate has centred on the importance of climate as a factor in the development of societies through both historical and pre-historical times, with attitudes ranging from those who see climate as being of central importance (Wedland and Bryson 1974) to those who would assign to it a relatively minor role. The major difficulties in this area are the degree of accuracy with which past climates can be reconstructed, and the degree of confidence with which evidence of a historical or archaeological nature can be used to describe past cultures (McGhee 1981).

The dating of events in the archaeological record, which relies mainly on radiocarbon dating techniques, can be done to an accuracy of perhaps decades (Roberts 1989). The responses of cultures to climatic factors may however have taken place in a time-span of months or perhaps years, so a precise knowledge of the timing of events is rarely possible.

Similar problems exist in the dating of palaeo-environmental events, where although dendrochronology allows for patterns of climate to be established year by year for certain locations, other dating techniques, including ice and peat cores, have an accuracy similar to the archaeological techniques.

A chronological correlation between climatic factors and events in human societies has been identified (McGhee 1981), (Burroughs 1997), (Lamb 1995) but it is important to note that, given the uncertainties in both archaeological and palaeo-environmental records, there is some difficulty in assigning a causal relationship. As well as problems with dating there is the problem of the complexity of the human response to environmental changes.

Even hunter-fisher-gatherer societies or early Neolithic farming communities possessed a level of technology and detailed knowledge of their environment, which would suggest that a gradual shift in climate of any other environmental factor could be coped with in a variety of ways, depending on the level of sophistication and flexibility of that particular group. To assign an environmental cause to a societal effect is to deny the possibility of the latter occurring as a result of social, economic or political factors of which there may be no surviving evidence. The view that human responses are not solely determined by climatic or other environmental factors, but are strongly influenced by the ideas, values and knowledge particular to a society or culture is proposed by Kirk (Kirk 1963).

This view rejects the notion of mankind and environment as separate entities, where an environmental cause produces a human effect in a deterministic manner, but rather looks for the relationship between what is described as a phenomenal environment and the behavioural environment.

The phenomenal environment includes all natural phenomena, including climate, plants and animals, all of which exist in the natural environment. Included in this are the products of human action, whether in the form of tools or the artefacts which have been manufactured.

The behavioural environment includes the ideas and values of a culture, the level of knowledge and awareness, and manifests itself in the socio-economic and political organisation of that culture. It is the combination of these two environments and their interrelationship which is seen as the legitimate object of study (Kirk 1963). This is described as occurring in two main ways.

Firstly there is direct contact, where humans individually or collectively interact with their environment and in the process change it, and are themselves changed by this action. This could manifest itself as a hunter-fisher-gatherer obtaining food and other basic necessities of life, and, by satisfying his/her needs, changes both the natural environment (in a limited way) and changes their circumstances and possibly those of their group in a positive way. Direct contact could also include the strip mining of minerals, which again satisfies certain social and economic needs, but has a significant impact on the natural environment.

Secondly there is the interaction between behavioural and phenomenal environments in which the latter enters the former in the form of facts. Aspects of the natural environment are perceived by humans, not in an objective manner, but through a filter imposed by the motives, preferences and modes of thinking which are established in the social and cultural context of a particular society. Thus the same feature of the natural environment may be perceived quite differently by different cultures, or by the same culture at different times. Neolithic farmers who found coal near the surface of the land would have seen it as a useless material, unfit for the production of tools or weapons. Their culture valued flint for this purpose and their cultural filters would have led them to reject or simply ignore this material.

Thus the behavioural environment serves to organise phenomenal facts into patterns and structures which have value in the context of that particular culture. It is within the behavioural environment that decisions are taken, based on the knowledge and values pertaining to that culture, and these decision may then be translated into the physical world or phenomenal environment. Figure 2.4 illustrates the position of the decision maker with respect to the phenomenal environment.

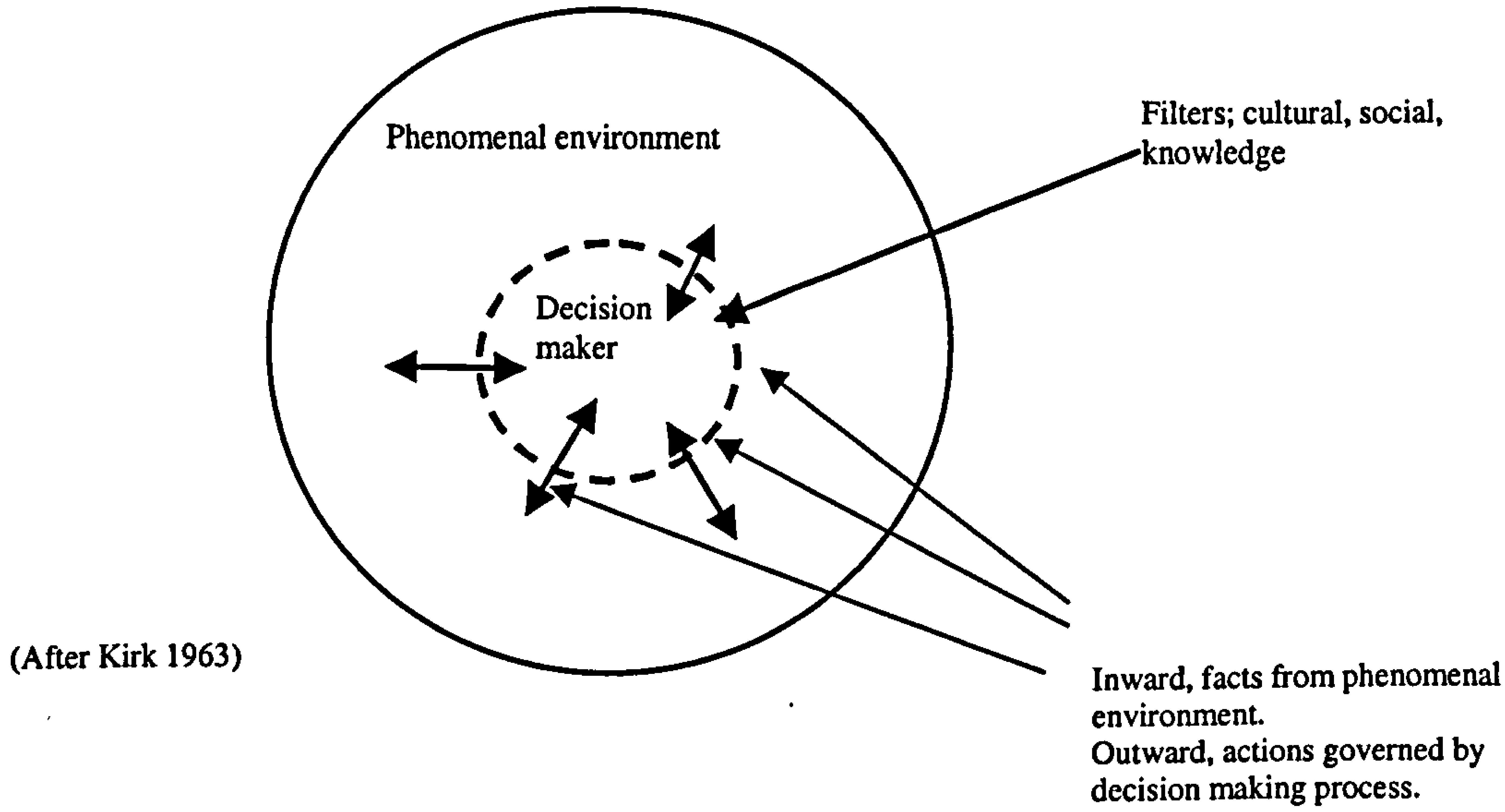


Figure 2.4 Cultural filters influence decision making

The following sections examine the evidence to support the view that climate (and climate change) has been an important part of what Kirk would term the phenomenal environment. The pattern of life for past cultures may not have been determined by climatic factors, but evidence exists to support the view that changes in past climates of certain areas has indeed had a significant impact on the lives of the inhabitants.

2.3.2. The post glacial world

Evidence exists from archaeological and paleontological sources of the existence of hominid species dating back over 2 million years. Modern humans however are believed to have evolved in Africa between one and two hundred thousand years ago. The population spread out of Africa to many parts of the globe but remained at relatively low population densities until the end of the last glacial period around 10,000 years ago. Nine interglacial epochs have been identified during the past 0.8 million years. However, ancestral human populations were either too sparsely distributed or simply unable to take advantage of the opportunities which were presented by the improving climate of these times (Roberts 1989).

It is only during the present inter-glacial period, the Holocene, that human populations have flourished and expanded. Their mere survival during the previous 1 million years of intense environmental variability, when rates of extinction of other species were unusually high around the globe, suggests an adaptability and resilience of early humans and their ancestors (Roberts 1989).

The ending of the last period of glaciation took perhaps 8,000 years, starting around 16,000 years BP. Sea levels were up to 100m lower than today, creating numerous land bridges between islands and continents, allowing the spread of species into the areas which became free of ice and harsh conditions as the climate warmed.

Large areas previously beneath ice and snow became colonised, at first mainly by grasses and sedges, which provided ample grazing for herds of reindeer, horses and other herbivores.

Human populations which existed with a hunting-fishing-gathering economy, or mesolithic cultures, were able to follow these herds. The requirements for game, water and other resources would limit the human population density. Estimates of an area of 75

km^2 for group of perhaps 25 individuals has been suggested (Roberts 1989), putting the entire world population of humans at around 10 million individuals at the beginning of the Holocene (Roberts 1989).

There is evidence that the first half of the Holocene saw global climatic conditions somewhat warmer and than those of the present day(Roberts 1989). Circulation patterns appear to have been different, with areas of North Africa, the Middle East, the Indian sub continent and Australia being considerably wetter than at present. As hunting-fishing-gathering populations expanded into new territories, there is evidence (Roberts 1989) that in the Near East, in an area stretching through what is now southern Anatolia, and south through present day Syria, Israel and Palestine, there emerged a distinctly sedentary pattern of settlement. The consequent growth of population led to attempts to provide sufficient food supplies by adopting agricultural techniques.

The practice of agriculture spread gradually outwards from the original sites into areas where forests had become established in response to the changed climate. Such areas were less favourable to mesolithic cultures, whose lifestyle was more suited to the open grasslands which supported large herds of herbivores. The archaeological record suggests that this was primarily a movement of people, rather than a spread of ideas to the hunter-gatherer societies, that allowed agriculture to spread widely (Tringham 1971).

Much of this expansion and the subsequent growth of the human population occurred during a period of relative warmth, with the prevailing temperatures in the region of 2°c warmer than at present. However by about 5000 years ago there occurred a gradual cooling and much more arid conditions developed over much of the Middle East and North Africa (Burroughs 1997).

Abandonment of large areas which were previously inhabited, including much of the present Sahara, can be dated to this time, around 3,500 – 2,800 BC (Lamb 1995). A similar sharp cooling occurred in other regions around the globe, with evidence from California and Australia, where desertification took place.

This represents a significant change in global climate and there is evidence of the development at this time of the first major civilisations. The Nile, the Tigris and Euphrates, The Indus Valley and the major rivers of China all saw the emergence of highly organised societies with previously unheard of concentrations of population.

The evidence of widespread desiccation of land has been seen as a likely explanation for this concentration of population in areas which, due to the presence of large river systems, would be assured supplies of the water necessary for the continuance of agriculture (Lamb 1995)

The growth of these civilisations led to many other developments, including metal working and the start of written records. Many of these ancient cultures make reference to a "Golden Age" similar to the biblical Garden of Eden (Glacken 1967). These have been interpreted as referring to the period prior to the middle of the fourth millennium BC, when certainly climate was more stable and humid in North Africa and the Middle East, and agriculture was practised on soils which had not been degraded by continuous agriculture.

The relatively stable climatic conditions which had prevailed between 6,000 and 3,000 BC appear to have come to an end around the middle of the 3rd Millennium BC. This period saw changes around the globe including the desertification of Australia, the spread of glaciers in Europe, and at the same time the spread of peoples into the high Arctic of Alaska and Siberia, suggesting a less extreme climate there at this time (McGhee 1981).

There is evidence from areas as diverse as North and Central Europe, Yellowstone Park, Japan, New Guinea New Zealand and the Andes of South America that there was a marked lowering of the upper tree line in mountainous areas at this time (Lamb 1995).

This shift in climate produced a period of instability and archaeological evidence suggests that there were also major social upheavals in a number of locations.

Egypt suffered drought and famine around 2,300 BC, then again in 2,150 and 2,000 BC. This effectively ended the Old and Middle Kingdoms of Egypt. At the same time there was widespread destruction throughout the Mediterranean and Middle East, ending the Helladic 2 period in the Aegean and the early Bronze Age culture in Anatolia. Around this time the Saragonid Empire in Metsopotamia was all but destroyed by invasion and internal revolt, a fate suffered by the Harrapan civilisation in the Indus Valley where the subsequent decline and abandonment of settlements lasted for centuries (McGhee 1981).

This climatic instability continued through the 2nd millenium BC and around 1500 BC there is evidence of the re-growth of glaciers in the USA, Scandinavia, New Zealand and in Central and South America (Lamb 1995).

From around 1300 BC there is evidence of the construction of fortifications throughout the Eastern Mediterranean, around settlements which were later abandoned. This "dark age" of Greece lasted for several centuries, and is linked to large scale movements of people throughout the Mediterranean region. Temple carvings in Egypt show Ramases' victory over an invading army, composed not only of soldiers but depicted as an entire population on the move. This time saw a marked re-growth in peat in Ireland (Lamb 1995) suggesting colder and wetter climate in the north west of Europe as the drier conditions prevailed in the Eastern Mediterranean. Bronze Age society in Greece reverted to subsistence and only began to flourish 2-3 centuries later. The Dorians who moved south into Greece found it sparsely populated and major movements of population took place as the Hittites abandoned the Anatolian Plain and peoples moved in large numbers from the Hungarian plain to surrounding areas.

Glaciers continued to advance, western Wales saw unprecedented wetness, as did the Alps where lakeside villages were abandoned. It was not until around 400 BC that climatic conditions changed to a warmer more stable regime.

This period in history, dating from around the fourth century BC to the fourth century AD, saw the rise of Greek and Roman influence eventually extending throughout a major part of the Mediterranean basin, Northern Europe and through the Middle East as far as India. These developments occurred during a period of relatively stable and warm climate in this region, which lasted until the 4th century AD (Lamb 1995).

The fall of the Roman Empire followed a period of internal conflict and growing incursions from Slavic peoples from the East of Europe. Evidence from the Caspian Sea shows marked decline in rainfall in this region from around 300AD. The shoreline dropped considerably at this time (Lamb 1981) and it has been suggested that this could explain the movements of the Slavic peoples westward, which stressed the Roman defences and eventually led to their collapse.

Evidence of marked climatic shift in the late 4th and early 5th centuries AD comes from peat bogs in Sweden and Ireland where marked growth is evident. Glaciers in Norway expanded between 450 and 850 AD and there are records of major storms in the North Sea during the first few decades of the 5th century. This caused coastline changes in England and led to numerous deaths along the Dutch coasts (Lamb 1995).

The Mediterranean region experienced drought at this time and this was at its worst in the 7th century AD. The north of Europe was cool and very wet, suggesting an alteration of climate patterns. Evidence from other regions of the world tends to confirm this, with China and Japan experiencing a warm phase, as did the High Arctic, which was resettled by Inuit peoples after a period of abandonment.

The climate of the Northern Hemisphere shows an asymmetrical pattern during the period from the 6th to 9th centuries. When Europe was cold, China, Japan and the North pacific region appear to have experienced a notable warm spell. This situation reversed itself and the following centuries produced the medieval warm period, when temperatures in Europe were as warm as at any time in the post glacial epoch. Japan and China experienced a cold spell during these centuries (Lamb 1995).

It was during this warm spell that the Vikings began their expansion from their homelands in Scandinavia. Although advanced in seafaring techniques, there was nevertheless a decline in the storminess of the North Sea (McGovern 1981), which aided this travel.

The 10th to 13th centuries saw the peak of warmth in medieval Europe, a period of expansion which included the crusades to the Holy Land and a programme of construction of cathedrals across Europe. The population also expanded and there is evidence of settlement on land which is now unsuited to cultivation, but which at the time allowed for the production of cereals (Parry 1981).

This warm spell did not endure beyond the middle of the 13th century when a more variable climatic regime resumed over Europe. After the very warm spell sea levels were higher than previously and the storminess led to further loss of land along coastal regions, particularly along the North Sea coasts. Land which had been under cultivation was abandoned, as were many villages, mainly the ones with poorer soils or located at altitude (Beresford 1981), (Dury 1981).

The climatic deterioration of the 14th century is illustrated by the fate of the Norse colony on Greenland. This had been established during the period of Norse expansion, which had seen Viking settlements on Iceland and across much of North West Europe.

Trade with Norway had been an important part of the economy of the Greenland settlement, but by 1342 the traditional route was not possible, as a result of increasing storminess and advancing sea ice. By the early 16th century there were no surviving Norse colonists left on Greenland. The decline and subsequent extinction of these colonists has been in part attributed to the shift in climate associated with this period. It has been pointed out however that the Inuit peoples survived by adapting their lifestyles and developing their technology to cope with the changed circumstances. The Norse settlers appear to have clung rigidly to their traditional farming methods and settlements, failing to adopt any Inuit technology and failing to adapt in the face of serious changes to their environment. Their system of animal husbandry, supplemented by fishing and hunting, was compromised by the cooling of the climate experienced during the late 13th and 14th centuries. Little change appears in the archaeological record which would suggest that a shift in dress, hunting practices or the in the agricultural techniques employed, took place. This, coupled with the absence of trade with the European mainland, seems to have been a major factor in the decline of the society (McGovern 1981).

The 15th and 16th centuries were markedly cooler in Europe than those experienced during the High Medieval period only a few centuries earlier. There was also greater variability in the climate. By the middle of the 16th century Europe, as a whole, was experiencing predominantly cool conditions. With the exception of a few warm decades the cold spell in Europe lasted well into the 19th century. This pattern of cold weather seems to have been experienced throughout the Northern Hemisphere, though the climax, in terms of the coldest spells, was felt at different times in different places.

The impact of the climate change was felt particularly in areas which were marginal for farming. The more northerly areas of Europe, along with settlements at altitude, were most notably affected, with the abandonment of such areas being evident. In some cases this was inevitable as advancing glaciers overran previously productive land, as in Norway (Lamb 1995).

The pressure of a deteriorating climate across Norway led to a drift south of population, as well as to a concentration around coastal areas. One response to declining agricultural output was in the development of forest resources. Timber was not only felled for export, but provided the raw material for the construction of ships, leading to the growth of one of the region's most important merchant navies.

During this period the Icelandic farming and fishing communities were also experiencing hardships. The persistent cold conditions altered the distribution of cod around Iceland, the most important resource both as food for the population and as an export commodity. The main shoals of cod moved farther south, but a strict adherence to the traditional methods of fishing in small open boats powered by oars, meant that the catches diminished. Other European fishing fleets began using larger craft, more suited to the rough conditions far offshore. The Icelanders did not adopt similar practices and as a result their problems multiplied. This was particularly evident during periods of poor weather, with poverty and hunger giving rise to crime and other social problems (Ogilvie 1981).

2.3.3. Summary

It would appear that there has been at least a correlation between climatic events and the fate of societies over a considerable period. It is possibly unjustified to suggest that climate alone was responsible for the demise or the growth of major civilisations but there does appear to be evidence that climate change has a significant role to play. Table 2.2 lists the main events described above. This is not intended as an exhaustive listing of all episodes of dramatic changes in the fortunes of past cultures. It is intended to illustrate the fact that there is evidence that climate change has affected societies to some extent in the past. It is in areas which are marginal for agriculture, where the crop species or animal forage species are close to the limits of their "climatic envelope", that the main impacts are concentrated. Cold and drought appear as the main factors in this list, and areas where a small shift in temperature or precipitation leads to conditions which are no longer within this band of acceptable climate are those which suffer most.

Societies which are predominantly agrarian, and where the ability to store food for long periods of time is lacking, show a sensitivity to climatic change. Established patterns of agricultural production, distribution and storage may be inadequate when significant climatic changes occur. Over time, new strategies could be developed, but a society which is largely dependent on subsistence farming, as most were until industrialisation, would not necessarily have sufficient resources to deal with a prolonged reduction in agricultural output. One year with crop failure might mean hardship, but two in a row, or a longer spell of altered climate, may prove disastrous. If climate change progressed faster than new methods of production could be developed, for example the construction of aqueducts, then large areas could experience considerable stress. An already stressed population would be hard pressed to embark on major works but might find it easier to contemplate a move to more suitable surroundings instead. The mass movements of populations which have been recorded, and for which there is archaeological evidence, often brought instability and competition for resources to previously stable and ordered societies.

The evidence listed in Table 2.2 cannot be taken as proof of climate change determining the fate of past societies, but it does suggest that strong a correlation exists. Other factors may well have played a part. Political rivalries and instabilities could account for the demise of political dynasties and cause major upheavals to the upper echelons of society but would not explain the abandonment of large areas and the movements of entire populations.

Location	Dates	Societal change	Climate change
Near East	~10000 BC	Neolithic revolution, domestication of livestock and plants	Rapid post glacial global warming
Sahara	3500 BC-2800 BC	Abandonment of Sahara region	Desertification, global cooling.
Major river valleys, Nile, Tigris, Euphrates Yangtse etc.	~3500 BC	Concentration of populations, development of major civilisations.	Cooling and reduction in rainfall over large areas.
Egypt, Agean, Anatolia, Mesopotamia	End of 3rd Millenium BC	Drought/ famine, decline of civilisations	Cooling over N Europe, drier conditions in Mediteranean and Middle east.
Greek/Roman civilisation	400 BC – 400 AD	Growth of Hellenic civilisation/Roman empire	Stable warm period in Europe
Europe, North and South Americas	~400 AD – 900 AD	Decline of Roman influence, Much drier conditions; West coast of S. America and Great plains of N. America.	Cooler, wetter Europe, drier conditions ovr much of Americas
Europe	10th –14th centuries AD	Medieval society flourishes	Medieval warm period in Europe.
Greenland	14th century AD	Decline and eventual colapse of Norse colony	Cooling in Atlantic Basin
N. Hemisphere	16th-19th centuries	Poulation decline in Iceland, population movements in marginal areas of N Europe.	The Little Ice Age.

Table 2.2 Some examples of climate and societal changes.

Increasing frequency of harvest failure, gradual decline in agricultural productivity and sudden catastrophic events are all likely candidates which help explain the instability amongst populations over large regions of the globe in the past. Episodes of climate change are the most likely cause of such changes in the natural systems upon which agricultural societies depend.

The impact of extreme climatic events is still evident today and it is likely that climate change will have an impact on societies in the future. The impacts of climate on developed societies are likely to be less than in the past (Ausubel 1991), (Roberts 1989). It can be seen from palaeo-climatic reconstruction that the past 10,000 years have seen variable climatic conditions. Periods of relative warmth have been interrupted by cooler periods, and stable climatic conditions have given way to periods of variability. The global pattern of weather has altered with some areas experiencing benign conditions, while the climate has deteriorated in others. Throughout this period human cultures have suffered setbacks but the overall population has increased, very rapidly in the last 300 years.

There is a close correlation between the timing of climate change and significant alterations in the distribution of populations and the stability of cultures. Periods which show a deteriorating climate appear to coincide with the disruption in social structures and the decline of complex societies, and where changes bring an improvement in climate there is evidence of the flourishing of cultures. This is particularly notable in areas which are marginal for agriculture, either being close to the limit of productivity because of low temperatures, as in the more northerly areas of Europe, or due to the susceptibility to drought, as in the Eastern Mediterranean and Middle East.

Hunter-fisher-gatherer societies, as well as those practising subsistence agriculture, have shown a greater susceptibility to the impact of adverse climatic conditions. Many of the developments in societies from different parts of the globe have been designed to reduce the negative impact of climate variability. Agriculture itself can be seen as one such adaptation. It allows for the production of surpluses which can be stored for use in an emergency, and has led to social developments associated with the organisation of such activities.

The impacts of climate change are not predictable simply from the nature of the event itself. The responses of different cultures can vary considerably and, as a consequence, the impact of the same conditions can be felt differently. Those societies which show a rigidity of structure, bound with tradition and custom show less ability to adapt to changing conditions and suffer as a consequence. Flexibility and adaptability have been features of cultures which have survived and flourished. The climatic deterioration of the post-Roman era in Europe saw widespread disruption, as did the deteriorating climate at the end of the High Medieval period. The adverse conditions of the "little ice age" in Europe saw the expansion of European influence and the development of science and technology which enabled the economy to function with far less influence from the prevailing climatic conditions.

It would appear therefore that episodes of climate change have had significant impacts on societies in the past. Modern technology and communications can be seen as safeguards against the most detrimental consequences. Flexibility and the ability to respond to opportunities, by the development of new practices, technologies or through trade have allowed societies to survive or indeed expand their activities when faced with climate change.

Although the impacts may not be as significant to society in general as in the past, it is still probable that impacts will be felt, perhaps only by certain sectors of the economy which are, by nature, sensitive to changing climatic variables.

Past climate change has been the result of natural variability due to the complex workings of the climate system. The current climate changes are due to the effects that man's activities are having on the system, primarily changes to the gaseous composition of the atmosphere. The following section gives an overview of anthropogenic climate change.

2.4. Anthropogenic climate change.

Section 2.2 looked at the factors which can offer some explanation of variation in the climate on different timescales due to natural effects, along with the feedback mechanisms which serve to amplify changes. When looking at climate change on the scale of decades we can disregard those factors operating over considerable periods of time. Thus Milankovitch cycles and the growing luminosity of the sun are not relevant. However sunspot numbers, representing the short term variability of solar output, ocean and atmospheric circulation patterns and levels of greenhouse gasses, are all factors which have been shown to operate over relatively short timescales and which are therefore relevant to the study of climate change over a period of decades.

2.4.1. The enhanced greenhouse effect

An understanding of the role of greenhouse gasses in the warming of the atmosphere was first presented by Fourier in 1827 and by Pouillet in 1838. Their experiments demonstrated the heating effect of long wave radiation on CO_2 and represent the birth of the theory of greenhouse gasses (Mudge 1997). In 1896 the Swedish scientist Arrhenuis predicted that the release of CO_2 into the atmosphere from the burning of fossil fuels would lead to an enhanced greenhouse effect and, should the concentration of CO_2 double, to a rise in the surface temperature of the planet of around 4°C.

This was echoed by T.C. Chamberlain, the American geologist, only a couple of years later in 1899, and was picked up again by Callander in the late 1930's.

All recognised that the concentration of carbon dioxide in the atmosphere was an important factor in maintaining the Earth's surface temperature at a level which prevents all water on the surface from freezing. Adding to the existing concentration of CO_2 would, it was argued, trap more heat in the form of outgoing long wavelength radiation from the Earth's surface while allowing in the relatively short wave energy from the sun. The major sources of increased levels of CO_2 were identified as the burning of coal and oil, releasing carbon which had been effectively removed from the cycle for millions of years.

The rate at which fossil fuels are burnt has increased dramatically over the past 40 years, leading to the steady increase in the atmospheric concentration of CO_2, as illustrated in Figure 2.5.

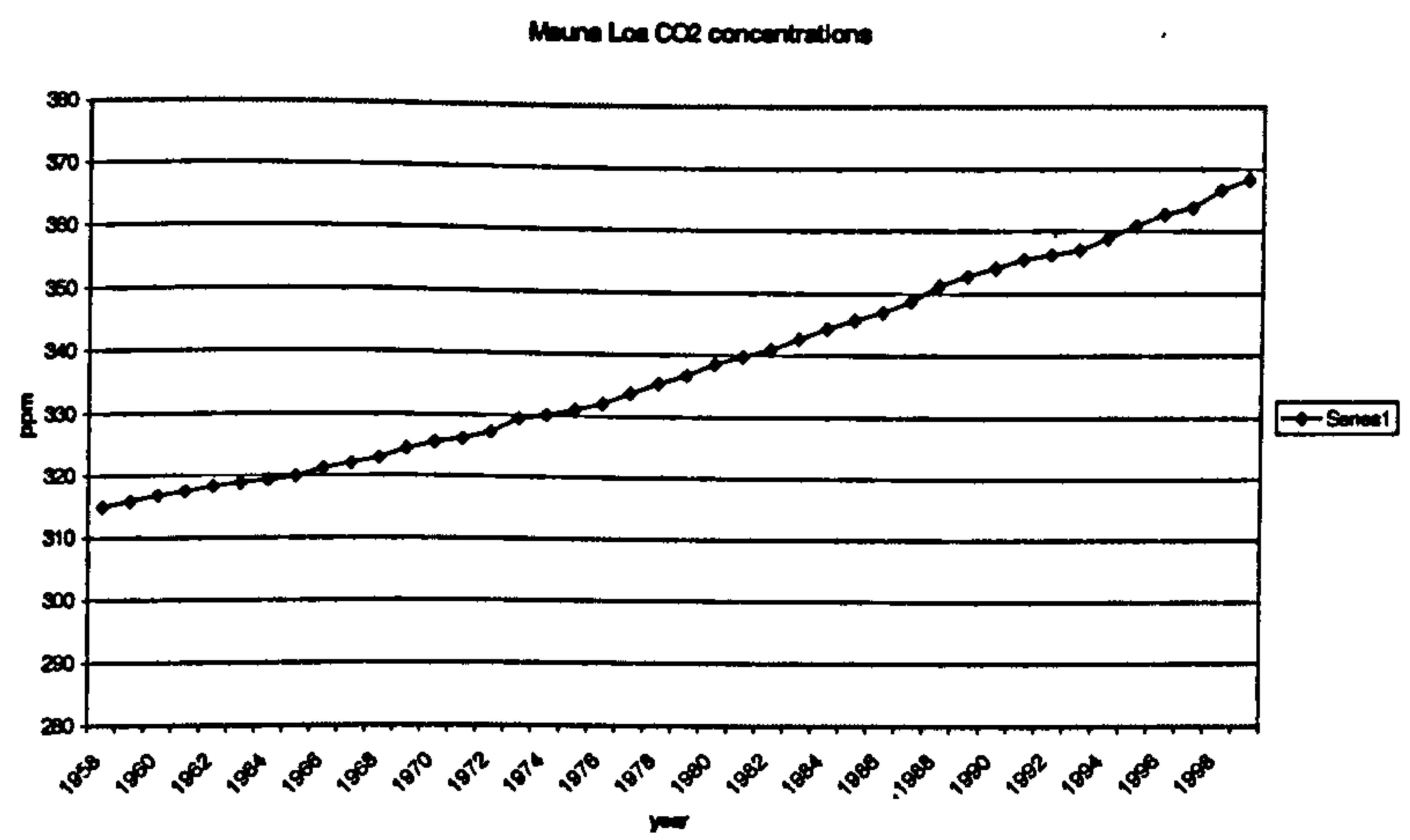


Figure uses data from carbon Dioxide Information Analysis Centre, 2001

Figure 2.5 Annual mean atmospheric CO_2 as measured at Mauna Loa in Hawaii.

Estimates of pre-industrial levels of CO_2 are in the region of 270ppm to280ppm and, given the current rate of increase of approximately 1.5ppm per annum, a doubling of CO_2 concentration is possible by the end of the 21st century. Presently the concentration is around 360ppmv, representing an increase of approximately 30% over pre-industrial levels. Current emissions are largely the result of fossil fuel burning in the industrialised countries of the West, and as more nations pursue the goal of industrialism and the increased consumption of resources which accompanies this, the rate at which concentrations increase is likely to grow. Estimates of a doubling of atmospheric CO_2 by the middle of the 21st century are therefore not unrealistic (IPCC 1996).

A doubling of CO_2 in the atmosphere would alter the radiation balance of the planet, trapping more energy in the troposphere. This would by itself trap an estimated 4 Wm^{-2} over and above the incident 240 Wm^{-2} which the planet receives. To restore the balance between incoming and outgoing radiation the temperature of the earth and lower atmosphere would rise by approximately 1.2°C (Drake 2000). This rise is calculated without reference to the changes that such a rise in temperature would bring to the atmosphere and surface characteristics of the planet, and does not take into account the feedback mechanisms which would influence the climatic changes.

Current estimates, derived from Atmospheric General Circulation Models (AGCM), suggest that a doubling of CO_2 in the atmosphere is likely to increase the mean surface temperature by between 1 and 3.5 degrees centigrade (IPCC 2000). Recent revisions to this figure, in the light of new model outputs, set the upper limit higher at around 5°C (IPCC 2000).

It is this rise in temperature which is the main cause for concern, and although some uncertainty exists as to how global climate change driven by human emissions of greenhouse gases will manifest itself, there is a consensus of opinion that changes will occur. Relatively small changes to the energy budget, brought about by the variation in orbital cycles, appear to have been amplified by feedback mechanisms to produce considerable climatic changes. Small changes in the composition of the atmosphere could have similarly large impacts and produce climate surprises which models fail to quantify.

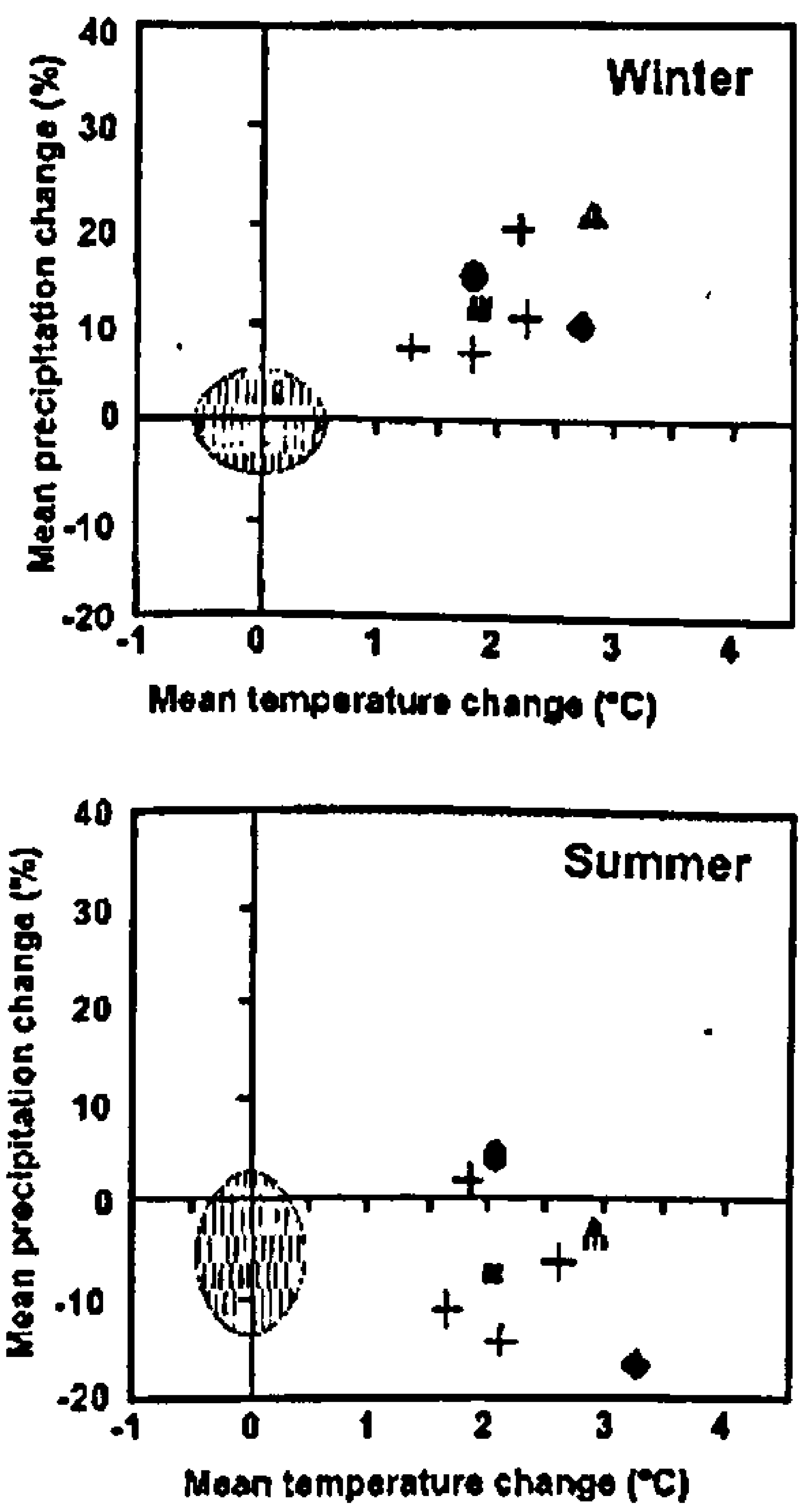
Extreme weather events around the globe, and the fact that four out of five of the warmest years on record have been in the last decade, have served to focus attention on the reality of climate change. This has helped lead to a scientific consensus that anthropogenic sources of greenhouse gasses have indeed begun to influence the global climate.

2.4.2. Climate Models

Having established that trends are discernible amongst the noise of natural climatic variation and that these trends can be attributed to human activities, the question remains as to how these changes are likely to manifest themselves in the coming decades. In order to answer this, various groups have developed complex climatic models, which rely on large data sets drawn from measurements of a wide range of factors. These include measurements of cloud cover, land surface temperatures, sea surface temperature and ocean currents, and the motion of the atmosphere at a range of levels. The more detailed models also include the effects of the carbon cycle, aerosols, the growth and decay of ice sheets and changes in solar output to produce forecasts of the direction in which increased greenhouse gas concentrations will force the global climate.

Several research establishments around the globe have developed such models which are known as Atmospheric General Circulation Models (AGCM). In the UK the Hadley Centre has developed the UK Meteorological Office's (UKMO) HADCM3 model. Among others from around the world are those from the Max Plank Institute for Meteorology in Germany, which has developed a series of models (ECHAM), and the Canadian Centre for Climate Modelling and Analysis with a series of Canadian Global Coupled Models (CGCM).

Figure 2.6 gives a comparison of the outputs from 5 such models and compares changes to precipitation and temperature in the United Kingdom by the year 2050. The vertical axis represents the percentage change to precipitation totals and the horizontal axis represents the change to mean surface temperature in degrees Celsius, both compared to the 1960-1990 averages. The grey oblong at the origin represents the range of current natural variability in both rainfall and temperature. The symbols represent the output from different models, the four crosses being the output from the Hadley centre model under different climate change scenarios.



(After UKCIP, 2002)

Figure 2.6 Projected changes to precipitation and temperature according to different AGCMs

It can be seen that all models agree that temperatures will rise beyond the range currently experienced for both summer and winter. Precipitation in winter is predicted to rise by all the models though by varying degrees, whilst summer rainfall is predicted to decline, though most models see it within the range currently experienced.

One of the main differences between the models rests with the predictions of future CO_2 levels which are used. Future concentrations of CO_2 represent the major driving force behind climate change. The levels can only be guessed at, as present trends may continue, or dramatic changes could ensue in either direction, depending on the willingness of Governments to deal effectively with the issue. Actions by the international community through legislation may significantly alter the emissions into the atmosphere. This could represent a reduction in the *rate of increase* of greenhouse gas concentrations rather than a reduction in the concentrations themselves. Zero emissions of CO_2 and the other greenhouse gasses is not a realistic prospect in the near future, so as their levels rise the scenarios developed by the climate modellers become more probable. The only control that can be exercised is over the time-span of the process, with reductions in emissions effectively slowing the rate of climate change.

The model produced by the Hadley Centre for the U.K. Met Office is run with different future rates of increase in CO_2 built in. These are a medium low, which assumes a 0.5% increase per annum, and a medium high, which assumes a 1% increase per annum. On either side of this there is a Low and a High scenario, which are included to take account of the sensitivity of the model to increased CO_2. These scenarios, in effect, define the boundaries of the output produced by the model.

One feature common to these Global Climate Models is that they tend to partition the surface of the Earth into a number of interacting grid boxes, each with inputs and outputs to and from neighbouring grid boxes, in the horizontal and vertical planes. The computational requirements of such models means that these grid boxes have to remain at a size that is manageable, for example the Hadley Centre's GCM HAD2 has a resolution based on grid boxes which measure approximately 350km by 250 km.

As a consequence a country the size of Scotland fits into two grid boxes, one covering the North and the other covering most of the South of Scotland and large parts of the North of England. The Scenarios generated by such a model inevitably apply to the entire grid box, and do not take into account the significant effect that local factors, most notably the topography and prevailing wind direction, have on the local climate.

In order to study climate impacts on a regional scale it was considered necessary to have detailed simulation of future climate, which could take into account features such as the precipitation gradient which exists across Scotland. At this stage of the work on this thesis no such regional climate model existed. Rather than downscale the projected climate change from the UKCIP98 global model it was decided to construct a simple climate model which was tuned to match the particular climate of each of the regions. The subsequent publication of the results of the UKCIP02 model, with a resolution based on grid squares measuring 50km X 50km (UKCIP 2002), allowed a comparison of the two sets of output for the two models. Chapter 7 shows this comparison.

2.5. Climate Change and Climate Impacts

Evidence indicating that the climate is changing comes from many sources. Accurate temperature measurements are available from many parts of the globe covering the past hundred years or so, prior to this the records are less widespread but in many regions are continuous for around 150 years (BADC 1 2001). Methods have been developed to generate temperature records by proxy, using tree ring data (Martinelli 2004), analysis of ice core data relating to oxygen isotope ratios (Grootes et al. 2001) measures of the extent of glaciers and borehole temperature measures (Majorowicz and Safanda 2001). This has allowed reconstruction of past temperatures, allowing long term trends to be established. Measures of oxygen isotope ratios, from ice cores drilled from the Greenland Ice sheet and from locations in Antarctica, can give evidence of global climate changes, on the scale of tens of thousands of years. Tree ring evidence, relating growth of trees to prevailing climate variables can give very accurate evidence of annual conditions at a very local scale assuming a continuous record can be established from preserved samples of trees. These methods have allowed past time series to be created which can be used to assess the natural variability of the climate system and assess the rate at which change has occurred in the past.

One such record is the Central England Temperature Series (Parker, Legg, and Folland 1992). This has used actual measurements, and proxy methods to recreate a temperature series for England from 1772 to 1991. Used along with climate models these allow the nature of current and projected future changes to be assessed in comparison to past changes.

The scale of temperature rises projected by the models and the rate at which these changes are likely to occur fall out-with the natural variability of the climate system (Hurrell 2000). This has led to a great deal of scientific activity devoted to attempts to assess the potential impacts that such rapid and dramatic climatic changes may have.

2.5.1. Assessing the Impacts.

A broad ranging report into the potential impacts of climate change has been published by the European Environment Agency (European Environment Agency 2004). This summarises recent trends and gives projections of potential future impacts of the changing climate on a European scale.

This report details the trends and projections of a wide range of indicators. Among these indicators is the extent and duration of snow cover.This has declined and is expected to decline further in the coming decades. There has been a decline of around 7% in the area of sea ice since 1978 and the average thickness has decreased by around 40%.

The marine environment has experienced a warming trend, with changes to the distribution of plankton species and sea levels have risen by between 0.8mm and 3mm in different regions over the past three decades.

Terrestrial environments have experienced changes with both southern and northern Europe experiencing a loss of plant species in the past three decades. There has been a northward movement of many species leading to an increase in bio-diversity in many north-western areas where the effects on cold tolerant species has not yet had an effect. As well as a northwards movement of species there has been an upward movement of species in mountainous areas.

Agriculture, especially in Mid and Northern Europe is expected to benefit from rising temperatures and the increasing CO_2 concentrations in the atmosphere. There is also expected to be a northwards expansion of cultivated areas. Problems with agriculture are expected to increase in areas which already experience water stress during the summer months. Bad harvests are expected to increase in frequency due to greater variability in the climate. This report is a broad view of how Europe as a whole is being affected by the changing climate and draws on many studies which deal with local and National impacts within Europe.

At a more local level there is the report published by the Scottish Executive Central Research Unit (Kerr et al. 1999) which seeks to identify the organisations and groups affected by climate change and assess the scope of predicted impacts within Scotland. This report looks at the natural environment and at various sectors of the economy with a view to identifying where potential problems and benefits might lie. The emphasis is on the kind of changes which may be necessary to firstly adapt to climate change and secondly to mitigate greenhouse gas emissions. A sector by sector approach is taken and for each area the main drivers for change are considered and the potential impacts of climate change assessed. Few sectors of the economy identify climate change as being a major driver for change, disruption caused by the increased incidence of flooding or storms being the extent to which climate change is seen as affecting most business enterprises. Tourism generally is seen as being sensitive to weather conditions, with warmer temperatures improving the attractiveness of Scotland as a tourist destination. However other socio-economic factors are seen as having a greater impact, with home grown tourists continuing to increase in numbers though mainly on short break holidays.

Agriculture is seen as being vulnerable to increased variability in the weather, though an increased growing season and warmer temperatures will lead to increasing diversity of crops and probable benefits for livestock production.

This report is, as with the European Environment Agency report, very general in approach and cannot give regional scale impacts due to a lack of spatial resolution in the scenarios for future climate change. Variations between regions within Scotland, in terms of temperature, precipitation and land use are therefore not considered. In order to asses the more detailed picture it is necessary to examine some of the more detailed studies of climate impacts which relate more precisely to the regions of Scotland. In many cases similar studies for other regions of the British Isles give results which can be of interest to the Scottish situation.

The impact of climate change on snow cover in Scotland was the subject of a study (Harrison, Winterbotom, and Johnson 2001) which looked at past trends and modelled possible future conditions based on the four scenarios of the UKCIP98 climate model. This found that there was a trend towards fewer days with snow lying at low altitude and little change at high altitude in the mountainous areas of Scotland. It was at intermediate levels, most significantly around the 400m level that the most noticeable changes were likely to occur. At this level, the difference between present and future numbers of days with snow lying was found to be the most sensitive to changes in temperature. The implications for the skiing industry were discussed, as was the impact on the natural environment.

The sensitivity of agriculture to climate change has been a major area of investigation. Although on a national scale agriculture is a relatively small employer relative to other industries, at the regional scale, particularly in rural areas, it is of great importance to the local economy. Both the European Environment Agency report (2004) and the Scottish Executive Scoping Study (1999) suggest that the single most important factor affecting the agricultural sector is the Common Agricultural Policy. However climate, and the weather patterns associated with local climates, is of central importance in determining the activities which can be undertaken within a region. Climate change is therefore likely to be a major factor in determining future patterns of agricultural land use across Europe. Agricultural policy will have to respond and adapt to the problems and opportunities that this brings (Olesen and Bindi 2002).

Studies of climate impacts on agricultural production involve an assessment of the conditions which are favourable to particular crops. Climate model scenarios can then be used to determine the future range of these favourable conditions. One such study of cereal production in England and Wales (Richer and Semenov 2004) suggests that yields are likely to increase in all areas, though local climate plays an important role in determining both yields and variability of yields. Neighbouring areas, with different patterns of precipitation, are shown to have considerably different yields resulting from local weather patterns, notably the distribution of precipitation between coastal and inland districts. An increased frequency of drought in the south-east of England is likely to create greater variability in cereal yields under climate change scenarios.

Similar results are obtained for Ireland in a study of changes to the climate and its impact on two crops, barley and potatoes (Holden et al. 2003). Here the cereal crop is predicted to increase yields under climate change scenarios, with potatoes being adversely affected by water shortages in the drier east of the country. This study only examines yields on land that is currently used for these crops and does not investigate potential changes to the distribution of these two crops. Changes to the range of plant species has been the focus of a number of studies into the impacts of climate change on the natural environment, with particular attention being given to conservation issues surrounding the distribution of rare plants and those at the edges of their geographical distribution.

The impacts of such changes are hard to quantify in economic terms and are therefore difficult to include in any cost benefit analysis of the impacts of climate change. However the scale of the effects and the implications for biodiversity at the local and global scale is profound (Leemans and Eikhout 2004). This study uses the IMAGE model (Alcamo, Leemans, and Krielman 1998) which assesses the impact on ecosystems around the globe of different scenarios of global mean temperature increase. One of the main findings is that the *rate* of temperature increase is important in determining the ability of ecosystems to adapt. Rapid temperature increases are likely to have serious negative impacts on a number of sensitive areas. In particular tundra, wooded tundra and cool conifer forests are identified as the areas most likely to be adversely affected by rapid changes to global mean surface temperature. When the rate of changer is slower then the plant and animal species have time to migrate and move to more suitable areas.

Although the scope of this study (Leemans and Eikhout 2004) is global, it is worth noting that within the mountainous areas of Scotland areas at the highest altitudes are comparable with the tundra, and lower down the slopes the climate and vegetation resembles these sensitive regions defined by the model.

More detailed studies of the impacts of climate change on the natural environment within the British Isles have been carried out, including the MONARCH project (Harrison, Berry, and Dawson 2001). This study examined the effect of climate change scenarios on bio-climatic zones, examining the areas of sensitivity. The summary of this study lists the species which will lose space and those which will benefit from the climatic changes. Again it is the mountain environments which show the greatest changes, with montane vegetation predicted to lose climate space. All of the habitats of conservation concern show changes, some will experience an increase in biodiversity while others will suffer losses.

The impact specifically on nature reserves in Great Britain was the focus of a recent study (Dockerty, Lovett, and Watkinson 2003). This study again used the concept of climate space to identify the conditions which are favourable to particular species. The impact of climate change is to alter the distribution of the available climate space. The location of nature reserves, often established to protect specific plant communities and the associated fauna, can then be compared to the likely future distribution of suitable climatic conditions. This study identifies species which will lose out, notably montane vegetation such as Dwarf Birch (*Betula nana*). However species will also be lost as a result of the hotter, drier summers experienced in the south-east of England. In particular species which are at present at the southern or western edges of their geographical distributions are those which will experience the greatest changes. A similar study (Pearson et al. 2002) using the SPECIES model identified the reduction of climate space for different species, citing the example of Dwarf Willow (*Salix herbacea*). The distribution of this species is mapped under different climate scenarios to illustrate the reduction of its climate space. This species is lost from the southern parts of its current distribution progressively through time as the climate warms. It also disappears from areas at lower altitude.

2.5.2. Summary

Climate change will impact on the distribution of plant species as a result of changes to the distribution of the "climatic envelopes" which they require. This will have implications for conservation and the natural environment. Agriculture is also dependent on the climatic envelopes of the species grown for food or as forage for farm animals. The studies suggest that adaptive strategies will be required to utilise the potential benefits and avoid the problems which may arise. In some areas the variety of crops could be increased as temperatures warm. Areas which are free from recurring droughts should experience a net gain both in the composition of natural ecosystems and in the variety of crop species which farmers can plant.

The main loses in bio-diversity are expected to occur in areas where temperature increases and summer drought frequency put the local climate outwith the climatic envelope of a number of locally occurring species. Those species which can adapt by altering their distribution by northwards migration or changing the altitude at which they grow may be relatively unaffected, but the montane vegetation will effectively have nowhere to go.

In terms of agriculture the distribution of crop species can be altered to suit changing conditions, and crop breeding can be used to produce varieties more suited to the altered climate of a region (Olesen and Bindi 2002). In this sense the impacts of climate change on agriculture are likely to involve adaptation to reduce the problems and utilise any potential benefits of an altered climate.

The effects on tourism discussed earlier in this chapter will also require adaptation. Skiing is likely to suffer from less certain snow cover but diversification of the tourist market could provide alternative activities during the predicted milder winters (Harrison, Winterbotom, and Johnson 2001). Summer tourism is likely to benefit from warmer and slightly drier weather, and an extension to the length of the still relatively dry spring conditions should allow an extension of the tourist season.

These various climate impacts are considered when the integrated climate-socio-economic model is constructed in Chapters 6 and 8.

2.5.3. Local Climate

Given that greenhouse gas concentrations have been increasing for a considerable period, and this increase has accelerated in the post-war era, it is reasonable to assume that the effects of climate change should be visible in the empirical record. If trends are discernible, then it would be of value to examine how regional trends compare, with each other, and with the scenarios generated by the climate models.

In order to do this, initially three site were chosen, one from the west coast, one in the centre and one on the east coast of Scotland, the details of which are given in Chapter 3. The effect on climate of Latitude was excluded by choosing sites on what could be described as a West–East transect, and all three sites chosen were close to sea level in order to avoid the effects of altitude. Chapter 3 describes the data sources and methodology which were used for the climate analysis, and in the modelling of both the climate and the socio-economic sectors of the final model. Chapter 4 gives the results of the analysis of data from the Met office weather stations identifies a climate profile for each of the three regions of the study. The data is also analysed in order to identify trends in the data which could be evidence of a changing climate. The three regions are compared to identify any differences at the local level.

Chapter 3 Data and Methods

3.1. Data and Methods; the climate of the three regions

3.1.1. Meteorological sites

All of the data relating to meteorological observations was accessed at the British Atmospheric Data Centre (BADC) (BADC 1 2001) which is a large database held at the Rutherford Laboratories, http://www.badc.nerc.ac.uk. From the U.K. Surface Observations data set, a number of sites belonging to the regions selected for the study were chosen according to the following criteria:

Length of continuous data (3 decades, 70's to 90's being preferred)

Range of variables recorded; rainfall, temperature and wind speed if possible.

Geographical distribution, a reasonable spread across the regions.

Quality of data; sites with a large percentage of missing data were rejected.

Numerous sites were available with precipitation records covering the period of the study. However, those with temperature records were less common, as were those with wind measurements. The distribution of sites was largely restricted to populated areas, which means that most were at relatively low altitude. This was not considered problematic, since it is the assessment of the impacts of climate on economic activity of the regions which is the main purpose of this thesis. Examining the climate of populated areas fits well with this aim.

The details of the observation stations are summarised in Table 3.1,Table 3.2 and Table 3.3, including the District County Number (DCNN) and rainfall identification number.

Taking into account the above criteria, ample sites were available for Argyll. Stirling was a problem in terms of continuous data sets which contained records of temperature. The site at Stirling University provided one set. However, it was considered necessary to take a site just outside the Stirling Authority area, at Grangemouth, to provide another good quality record. The West of the Region had no single site with continuous data sets, so one was generated from 3 sites which are reasonably close to each other at Aberfoyle, Callander and Loch Venechar.

Fife had good sites. However, some were very close to each other. To achieve a reasonable geographical spread it was decided to include one site from outside the Local Authority boundaries at Kinross, an inland site with characteristics similar to much of the surrounding countryside in Fife.

All data was downloaded as text files, taken into Microsoft Excel (where analysis of rainfall intensity was performed), then transferred to SPSS for Windows V 10.0 for statistical analysis.

Argyll

SITE	DCNN	RAIN	Grid Reference	Latitude	Longitude	Elevation
Dunstaffnage	6068	683628	NN881340	56.450	-5.438	3m
Aros	6025	715177	NM553453	56.533	-5.983	37m
Benmore (Botanic Gardens)	6085	666484	NS141857	56.028	-4.983	12m
Orsay	6013	677985	NR165515	55.674	-6.509	23m
Machrihanish	6040	675178	NR663226	55.441	-5.695	10m

Table 3.1 Sites in Argyll

Stirling

SITE	DCNN	RAIN	Grid Reference	Latitude	Longitude	Elevation
Parkhead (Stirling University)	6289	894223	NS815969	56.150	-3.907	35m
Grangemouth refinery	6297	896894	NS943813	56.013	-3.695	2m
Aberfoyle	1411	889872	NN526007	56.176	-4.374	27m
Loch Venechar	1422	892604	NN598063	56.228	-4.261	50m
Callander	1434	892634	NN627077	56.242	-4.215	70m

Table 3.2 Sites in Stirling

Fife

SITE	DCNN	RAIN	Grid Reference	Latitude	Longitude	Elevation
Leuchars	1577	885313	NO468209	56.239	-2.806	10m
Kinross	1516	886981	NO125033	56.214	-3.410	116m
Elmwood (Agricultural college)	1556	884630	NO362145	56.318	-3.301	42m
Belliston	1582	886152	NO500055	56.239	-2.806	82m

Table 3.3 Sites in Fife

Files accessed at BADC

Most sites included in the study used the same format for meteorological data. For temperature files were of the type DLY3208 which records daily minimum and maximum temperatures to an accuracy of 0.01 degrees Celsius. The exceptions were Tiree and Leuchars, where the DLY 3259 or NCM format was used. This reports minimum and maximum temperatures separately for day and night. These files were aggregated to produce a single maximum and minimum figure for each 24-hour period.

Rainfall was recorded giving a daily total using the Wadrain or DLY 3208 files, with the exception of Machrihanish, Tiree and Leuchars, where readings for day and night were recorded. These were aggregated to produce all data sets with the same daily measurements. Rainfall measurements are assumed to have a maximum error of 5% for the most exposed sites (BADC 2 2001).

Other files accessed

Data relating to sunspot monthly numbers were accessed from the NASA website (NASA 2001) http://science.msfc.nasa.gov/ssl/pad/solar/greenwch/spot_num.txt

Data relating to monthly CO_2 concentrations in the atmosphere as measured at Mauna Loa were accessed at the Scripps Institute of Oceanography website (Carbon Dioxide Information Analysis Centre 2001)

http://cdiac.esd.ornl.gov/ftp/maunaloa-co2/maunaloaco2

Data relating to the North Atlantic Oscillation Index was accessed at the NOAA website (NOAA 1 2001)

ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/tele_index.nh

Data relating to the Southern oscillation index was accessed at the NOAA website (NOAA 2 2001)

ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/soi

3.1.2. Missing Data: Temperature

The quality of the files held at the BADC was generally very good. However, certain sites recorded gaps in the observations for temperature. The method of dealing with such errors was to use the standard method involving comparisons with nearby sites. The extent of missing temperature data is shown in Table 3.4.

SITE	% OF DATA MISSING
Tiree	0
Machrihanish	1.8
Dunstaffnage	0
Benmore	0 (3 days missing)
Aros	3.1
Stirling	4.6
Grangemouth	0.8
Aberfoyle*	0.6
Belliston	0 (4 days missing)
Elmwood	0.7
Leuchars	0
Kinross	5.1

Table 3.4 Percentage of data missing for each site.

The method for replacing missing data points involved taking a nearby site for which an overlap of data existed (Linacre 1992). For the overlapping period a linear regression was performed, the resulting equation being used to fill the missing data from the file. Where a number of sites were available, the choice of which site to use for the regression was decided by calculating the correlation coefficient for each pair of sites. The site with the strongest correlation was then used.

The equations used are listed below, with all temperature measurements being in 0.1 of 1°C.

Argyll

Dunstaffnage and Aros were found to have the highest correlation (0.96) and so this pair was dealt with first. The regression equation used was;

Dunstaffnage = 5.322 + 0.976 x Aros. (sig = 0.000, R2 = 0.958, n = 9684)

(Where "Dunstaffnage" refers to the mean daily temperature at Dunstaffnage measured in 0.1 degrees celsius.)

Similarly missing data in the record at Aros was filled using the equation;

Aros = -1.552 + 0.982 x Dunstaffnage. (This being derived from a regression using Aros as the dependent vaiable and Dunstaffnage as the independent)

The next highest correlation (0.94) was between Dunstaffnage and Benmore. The regressions produced the equations below;

Dunstaffnage = 12.580 + 0.897 x Benmore. ($R^2 = 0.947$, sig < 0.001, n = 9684)

Benmore = -8.283 + 1.051 x Dunstaffnage.

Benmore and Aros showed a correlation of 0.92 and the regression equations were;

Benmore = -3.391 +1.035 x Aros. ($R^2 = 0.921$, sig < 0.001, n = 9684)

Aros = 9.988 + 0.889 x Benmore.

Machrihanish and Dunstaffnage showed a correlation of 0.89 and the following equations were generated;

Machrihanish = 11.065 + 0.882 x Dunstaffnage ($R^2 = 0.891$, sig < 0.001, n = 9256).

Dunstaffnage = -1.267 + 1.01 x Machrihanish.

No further equations were necessary as all missing data points could be filled using these sets of equations.

Stirling

While a similar procedure was used for the Stirling sites, the treatment of Aberfoyle required considerable generation of data. Without a site in the west of Stirling which had a continuous time series of data, it was necessary to construct one using overlapping data sets from a total of 3 sites. The details of this are shown below.

Available data

Aberfoyle	1970-1975	1978	1994-1999
Callander	1970-1981		
Loch Venechar	1982-1999		

Aberfoyle had six years of data in parallel with Callander. A regression equation was produced using these years and was then used to fill the years 1976, 1977, 1979, 1980 and 1981. The equation produced was;

Aberfoyle = 0.802 + 1.008 x Callander. ($R^2 = 0.843$, sig < 0.001, n =1821)

Aberfoyle had six years of data in parallel with the Loch Venechar site from 1994 up to 1999. A similar procedure to that described above produced the following equation which was then used to generate data for the missing period from 1982 to 1993.

Aberfoyle = 10.981 + 0.894 x Venechar. ($R^2 = 0.877$, sig < 0.001, n = 1821)

This allowed a continuous data set to be produced for the western part of the Stirling area.

Any missing data in the Stirling and Grangemouth records were filled using the pair of equations listed below which were generated using linear regression.

Grangemouth = 11.078 + 0.963 x Stirling. ($R^2 = 0.966$, sig < 0.001, n = 9860)

Stirling = -8.095 + 1.003 x Grangemouth.

Fife

For the sites in fife the strongest correlation was between Belliston and Elmwood (0.984) followed by Leuchars and Elmwood (0.952), Leuchars and Belliston (0.952) and Kinross and Elmwood (0.784).

Linear regression produced the following equations, which were used to fill missing data points.

Belliston = 9.212 + 0.9 x Elmwood. ($R^2 = 0.969$, sig < 0.001, n = 9637)

Elmwood = -7.244 + 1.076 x Belliston.

Elmwood = 0.820 +0.989 x Leuchars. ($R^2 = 0.906$, sig < 0.001, n = 9668)

Leuchars = 7.302 + 0.915 x Elmwood.

Kinross = -7.921 + 9.79 x Elmwood. ($R^2 = 0.615$, sig < 0.001, n = 9121)

Although the generation of data points necessarily introduces some error, it was considered preferable to omitting all sections of data where one or more sites had missing data.

3.1.3. Missing data: Precipitation

Where rainfall data was missing one of two methods was used depending on the availability of a nearby site.

If no suitable site was present, then a missing monthly total was produced by taking the mean monthly total for that particular month, using all existing records (Linacre 1992). The variability of rainfall totals suggested that for isolated cases this method was both simpler and just as effective as any comparison between sites.

Where a nearby record was available and there was a considerable percentage of missing data, for example in Aberfoyle, then nearby records were used, with linear regression producing an equation linking the monthly totals for the two sites. This was done for Dunstaffnage using the following equation;

Dunstaffnage =18.94 +0.727 x Aros. ($R^2 = 0.703$, sig < 0.001, n = 388)

Similarly the results for Aberfoyle were generated using the equation;

Aberfoyle = 1012.22 + 0.239 x Flanders ($R^2 = 0.41$, sig = 0.001, n = 269)

Where "Aberfoyle" is the monthly total for Aberfoyle and "Flanders" the monthly total for the nearby site of Flanders Moss.

In total, Aberfoyle had 16.5% missing data and the method described took care of all but 7 months where neither site had any records. These were filled in the Aberfoyle data set using the mean value of the missing months calculated from the existing data.

Where none of the sites in a region had data for a particular period, notably the entire year of 1973, no attempt was made to fill the gap.

3.1.4. Missing data: Windspeed

The files from Tiree were missing every month of July, except 1997 and 1998. No method of correcting this was available so monthly figures for windspeed were not available for Tiree for this month. Seasonal means were calculated, using only the data for June and August.

3.1.5. Merging of data

The time series for each individual year were combined to produce a single file for the length of the available data. In most cases this covered the period from 1970 to 1999, although certain records did not cover the full period. Each file contained data organised by year, month and day.

Seasons were defined as follows:

1. Spring: March, April, May.
2. Summer: June, July, August.
3. Autumn: September, October, November.
4. Winter: December, January, February.

Winter of a particular year was defined as the period starting in December of that year and carrying through to February of the following year. The remaining three seasons belong to one calendar year.

For temperature, the files contained a daily maximum and minimum temperature reading. These were converted to a daily mean temperature by taking the arithmetic mean of the two values.

Precipitation was recorded as daily amount, where readings were not taken for a period of time this was recorded as a total relating to a given number of days.

Records of windspeed were taken on an hourly basis at the sites. These were aggregated to produce a mean daily windspeed by taking the arithmetic mean, and the maximum value of daily readings was recorded as the daily maximum.

For certain aspects of the analysis these files were aggregated to produce time series which contained, for temperature, a monthly mean temperature and for rainfall a monthly total. Mean windspeed was calculated for monthly periods and the maximum recorded windspeed for the month was taken as the monthly maximum.

Seasonal means were calculated for temperature and windspeed, seasonal totals for precipitation and a seasonal maximum for windspeed.

3.2. Methods; climate analysis

3.2.1. Analysis of Temperature data

The data from individual temperature sites was analysed in order to produce:

1. Details of, and comparisons between, individual sites.
2. Evidence of any long term trends, seasonal or annual.
3. A regional mean value which could be used for descriptive and comparative purposes.

1.

For each of the twelve sites across Scotland the mean daily temperature records were used to produce monthly, seasonal and annual mean temperatures for the length of the available data. These were used for comparisons within and between regions.

2.

The length and intensity of the growing season can be measured using the number of degree-days for each year (Linacre 1992). This involves the calculation of the sum of the number of degrees above 6°C for each day of the year. Warmer spring and autumn temperatures, as well as more intense warmth in summer, will increase the number of degree-days. The number of degree-days for each year were plotted against time and a linear regression performed in order to establish whether or not significant trends were discernible. SPSS allows curve estimation to be carried out, in order to test the functional form of the relationship between variables.

In many cases throughout this analysis the plotting of variables on an XY scatter plot indicated that the relationship was linear. However in order to verify this, curve estimation was carried out and the significance of the model and R^2 values compared. This would be of value if the relationship could possibly be exponential or logarithmic as any extrapolation of the trends would be significantly different. Testing the distribution of the residuals is used to ensure that the assumptions of the model are valid. The residuals should show no pattern when standardised residuals are plotted against standardised predicted values. This will generate a random scatter of points if the assumptions of regression are met. In all cases where regression has been used these plots were obtained and examined for any sign of patterns which could indicate that the use of linear regression was invalid. In addition normal P-P plots of the regression standardised residuals were obtained to ensure that the distribution of the residuals conformed to the assumptions of the model. In all cases where linear regression has been performed it was found that this was indeed the case.

The mean daily temperatures were tested for long term trends using linear regression. A similar procedure was performed using the seasonal subsets of the data in order to establish seasonal trends in temperature.

The results were used to make comparisons between sites and between regions across Scotland.

3.

The mean daily temperature figures were used to create a regional mean temperature for each of the three regions, this being produced on an annual, seasonal and monthly basis. This allowed broad comparisons of the regions and formed part of the regional profile.

All temperature records showed temperature measured in tenths of one degree Celsius, with an accuracy of 0.01 degrees.

3.2.2. Analysis of Precipitation data.

Analysis of daily amounts was complicated by the inclusion of measurements spanning more than one day. Where daily amounts were analysed this required the omission of such readings. The data relating to daily amounts contained a large number of zeros, and it was decided that no regression equations could be generated using these figures. Aggregation to form monthly, seasonal and annual totals was carried out, and this did allow for this type of analysis.

When the full data set was split to form seasonal and monthly subsets, it was found to conform to a normal distribution allowing regression analysis to be undertaken.

Where the rainfall recording site was moved, resulting in a change in the identification number, this was accompanied by an overlap in the records (eg Tiree). Monthly records were calculated for both sites and the relationship between them quantified using linear regression. The latter site was then adjusted using the regression equation to conform to the amounts recorded at the first site. This produced only a very small change in the monthly totals as new sites were never at distance or significantly more exposed than their predecessors.

The data from individual sites was used for comparative purposes, including their amalgamation to produce regional rainfall figures.

Rainfall intensity was investigated using the quantile method (Osborne et al. 2000). The daily amounts for each site, excluding multiple records, were sorted in descending order for each year of the study. A cumulative sum was calculated and a record made of the daily amount which, when added, produced a figure which was greater than or equal to 10% of the total rainfall for that year. These figures for the 10% threshold for each year were then plotted against time, and linear regression used to establish whether long term trends were evident.

All precipitation records showed daily, or twice daily, amounts measured to an accuracy of 0.1mm.

3.2.3. Analysis of Windspeed data.

Fewer sites were available with records of windspeed. As a result the comparisons are between one West and one East coast site.

Hourly measurements from files of the type HWINDAUTO were aggregated to produce mean daily windspeed and maximum daily windspeed. To achieve a normal distribution, mean monthly windspeed was then calculated and subsequent analysis performed on this data set. Regression analysis was used to establish the existence of any long-term trends, examining the complete data set as well as looking at monthly subsets of the data. The data was also used for comparative purposes between the regions. The data from Leuchars was intact, though the data from Tiree did not contain records for the month of July, until 1997. Any results from this month were discarded.

All windspeed measurements were recorded in Knots.

3.3. Data and Methods; determinants of Scottish climate.

3.3.1. Carbon Dioxide

Monthly CO_2 concentrations, as measured by the Scripps Institute of Oceanography at Mauna Loa in Hawaii (Carbon Dioxide Information Analysis Centre 2001), were used and the natural logarithm taken. The warming effect of increased CO_2 levels is proportional to the logarithm of the actual level (Drake 2000). To allow for any time lag in the effects on climatic variables of increased levels of CO_2, the figures were then lagged by 1,2,and 3 months. These figures were then correlated with rainfall and temperature data, the one with the highest correlation eventually being included in the multiple regression. For CO_2 this was found to be the 3 month lagged variable.

3.3.2. Solar Output

Short term fluctuations in solar output have been linked to the cycle of sunspot activity, a period of approximately 11 years, with variations from minimum to maximum output of around 2% being described (Schneider and Mass 1975). The relationship between solar output and sunspot numbers is not linear. The maximum output is associated with approximately 80 sunspots, with a declining solar output experienced as the number of sunspots increases or decreases from this number. This has been quantified (Schneider and Mass 1975) by use of the formula derived empirically by Kondralyev and Nikolsky, working in 1970, which gives solar output as:

$$S(n) = 1.903 + 0.011n^{1/2} - 0.0006n$$

Where n is the number of sunspots, and S(n) represents solar output measured in cal $cm^{-2} m^{-1}$.

Sunspot numbers were found at the NASA website (NASA 2001) and converted to an approximate solar output as above. The monthly figures were then lagged by 1,2 and 3 months to allow for any delay in the effect of increased or decreased insolation. When these time lagged variables were correlated with the temperature and rainfall data, it was found that the strongest correlation existed with the 1 month lagged data. This was then included in the multiple regression.

3.3.3. Circulation patterns.

Data relating to indices for circulation patterns was found at the NOAA website (NOAA 1 2001). Analysis was restricted to those circulation patterns which were centred on the North Atlantic and Western Europe. The one exception was the Southern Oscillation (ENSO), which, because of the magnitude of the energy transfer associated with the El Nino/La Nina, was also included. Evidence for impacts of the ENSO have been detected across large areas and include distant parts of the globe (Glantz, Katz, and Nichols 1991), including the British Isles (Willby, O'Hare, and Barnsley 1997).

The indices associated with the circulation patterns which were included in the study are listed below, with an explanation of their main features.

3.3.4. The North Atlantic Oscillation (NAO)

The North Atlantic Oscillation consists of a North /South dipole of anomalies in pressure, with one centre located over Greenland /Iceland and the other centre of opposite sign spanning the central latitudes of the central North Atlantic between 35° N and 40° N, the latitude of the Azores.

The different phases of the NAO are associated with changes to the intensity and location of the jet stream and storm track in the North Atlantic basin, bringing changes to the patterns of heat and moisture transport.

Strong positive phases are associated with above normal temperatures across much of the eastern United States and Northern Europe, with below normal temperatures across much of the Mediterranean and Middle East as well as Greenland. Precipitation across Northern Europe and Scandinavia tends to increase with positive phases of the NAO, while the Southern and Central parts of Europe experience lower than average precipitation. Opposite effects are experienced during negative phases.

The NOA shows considerable variability both on seasonal and annual timescales, and, in particular, the wintertime NAO shows considerable variability measured on timescales of years and decades. From the mid 50's to the late 70's the negative phase dominated, with long runs of negative values and very few episodes where the positive phase was apparent. The situation was reversed during the winter of 1978/9 and has remained in a predominantly positive mode ever since (Hurrell 1995). Figure 3-1 illustrates the values of the NAO index for the period 1950-1997, and shows the predominantly negative values before the late 70's where a change to more positive values is detectable. The range of values on the vertical axis represents the standardised values of the pressure anomaly. This changes actual pressure differences to a scale with mean zero and standard deviation of 1. All of the variability in the different circulation patterns is represented in this way.

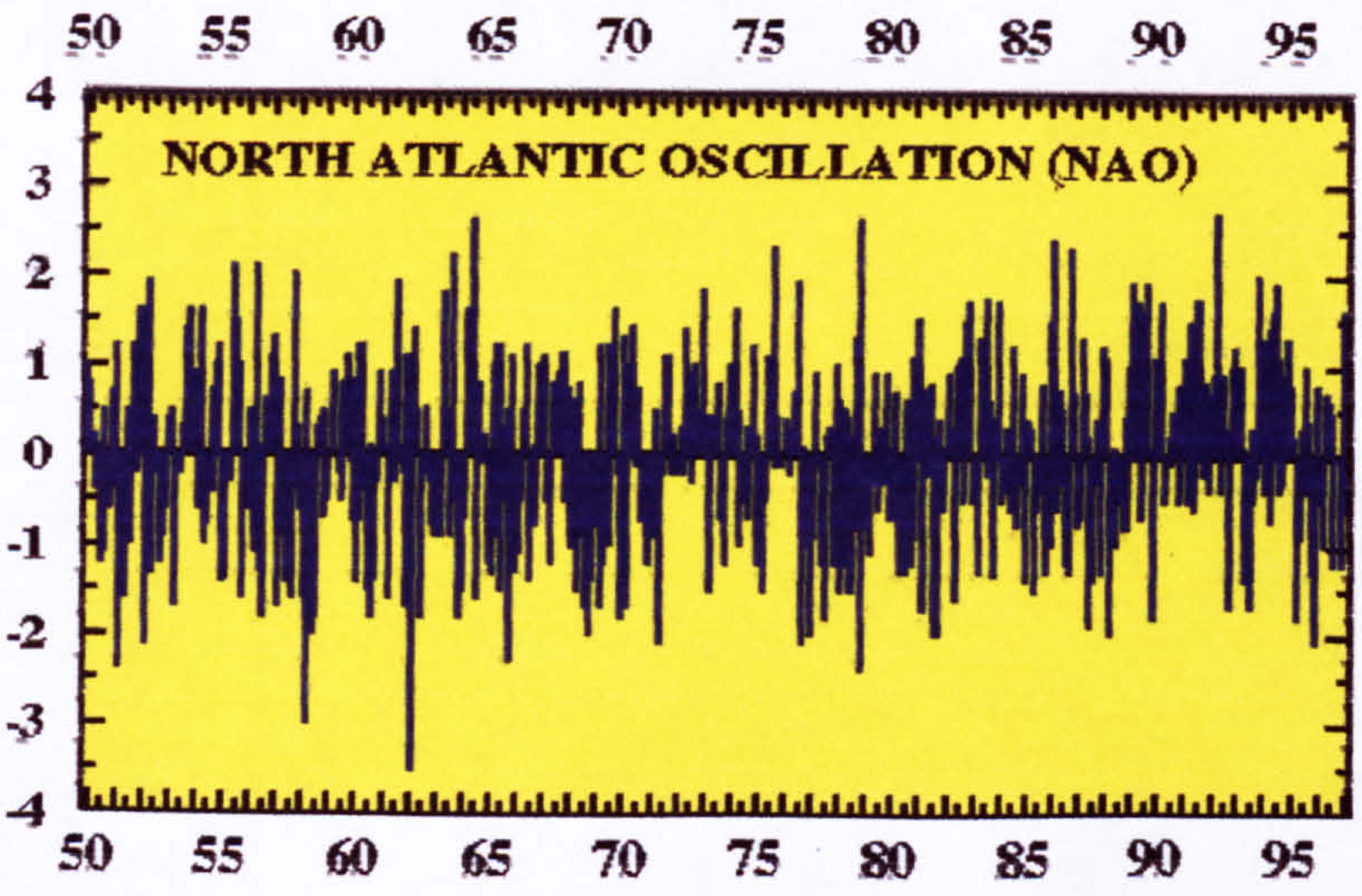


Figure 3-1 Time series for the North Atlantic Oscillation

3.3.5. The East Atlantic Pattern (EAP)

The East Atlantic Pattern is structurally similar to the NAO but spans the entire Atlantic Ocean from West to East. The anomaly centres, where pressure is measured, are displaced to the Southeast, relative to the NAO. This means that the index is influenced by the subtropical ridge, which makes it distinct from the NAO. The measurements of the EAP are made in all months, with the exception of the period from May to August. It is evident from Figure 3-2 that a predominantly negative phase existed through the 60's and much of the 70's but that the 80's and early 90's have shown a prolonged positive phase.

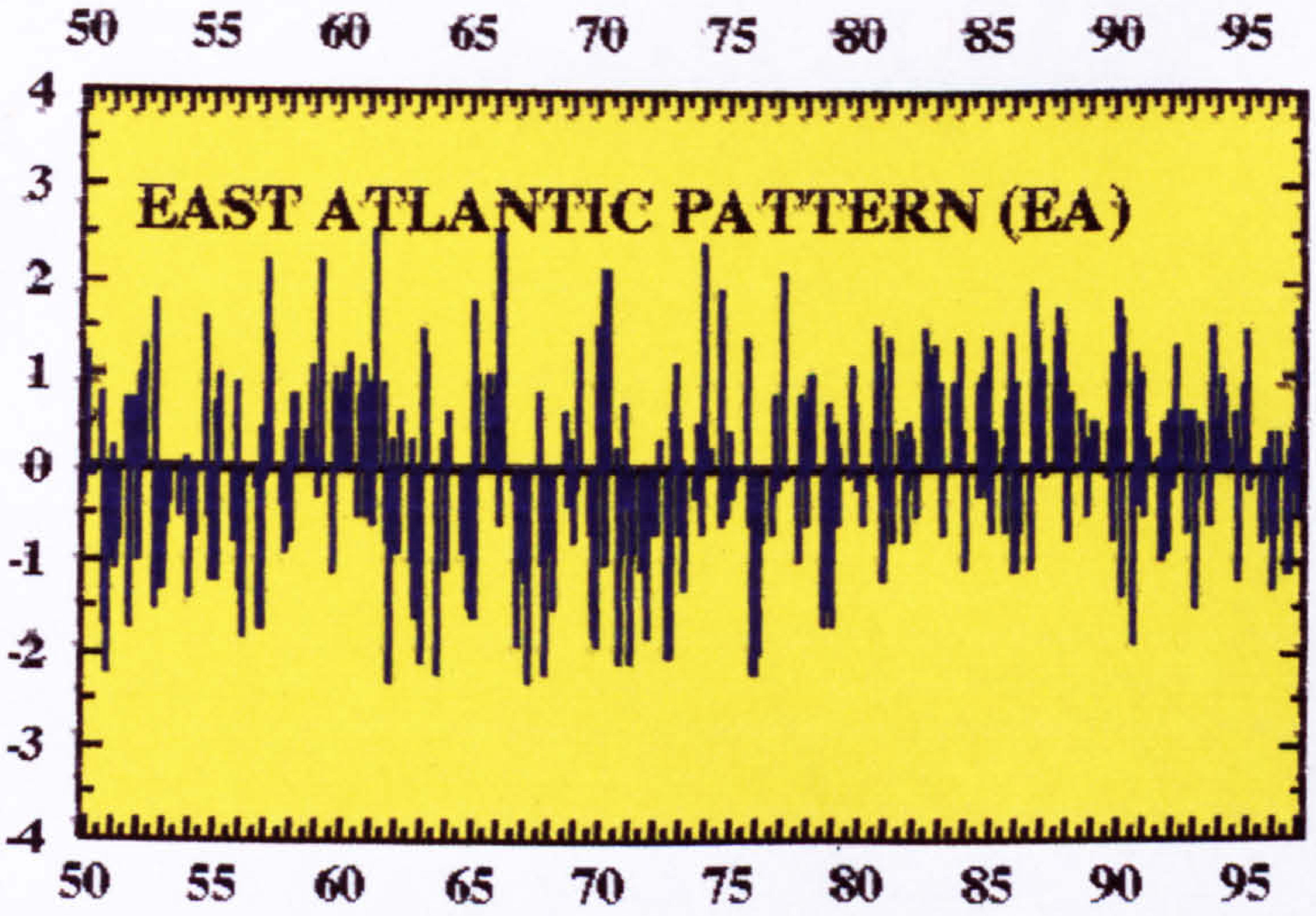


Figure 3-2 Time series for the East Atlantic Pattern

3.3.6. The East Atlantic Jet (EAJET)

The East Atlantic jet appears between the months of April and August, and is again similar to the NAO in that it consists of a North/South dipole of anomaly centres. One centre is located over the far Northeast of the Atlantic and Scandinavia, while the other is located over Northern Africa and the Mediterranean Sea.

A strong positive phase is associated with strong westerlies across much of the Eastern Atlantic and much of Europe, while a negative phase is often associated with a split flow across these regions, often accompanied by a blocking anticyclone in the northern Atlantic.

Figure 3-3 shows the time series of the EAJET and shows that again the positive phase has dominated for much of the 80's and 90's. The effect of strong westerlies in the summer months is to increase precipitation across much of the western seaboard of Europe during this season, whereas negative phases are associated with particularly warm dry summers across much of Europe.

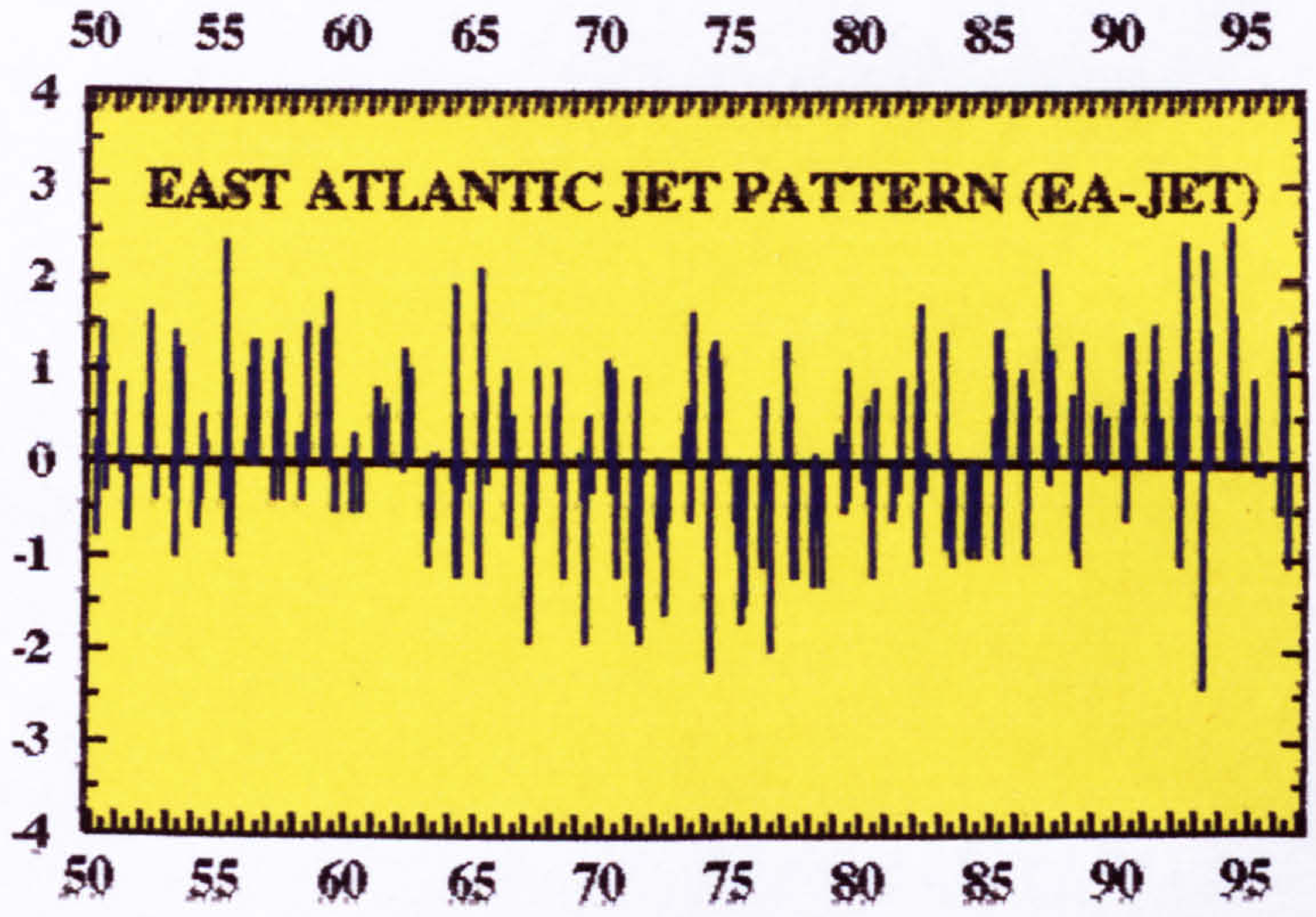


Figure 3-3 Time series for the East Atlantic Jet Pattern

3.3.7. The East Atlantic/Western Russia pattern (EAWR)

The East Atlantic/West Russia pattern affects much of Eurasia for most of the year, with the exception of the summer months. In contrast to the previous patterns this involves a more East/ West contrast in pressure. During the winter the centres of the anomalies are centred over the Caspian Sea and over Western Europe. In the spring and autumn there exists a third centre located to the west of Portugal, though in Autumn this tends to drift westward towards Newfoundland.

Positive phases of the pattern are characterised by lower pressure over the west and southwest of Russia, and higher pressure over Western Europe. The weather associated with this involves warmer and wetter than normal conditions over Scandinavia and western Russia, with cold dry conditions over the Eastern Mediterranean Sea and the Middle East. The positive phase is also associated with drier conditions over much of mainland Europe.

Figure 3-4 shows the time series for the EA/WR pattern from 1950 to 1997. Negative phases seem more common, with periods in the mid eighties and early nineties showing a tendency towards positive phases.

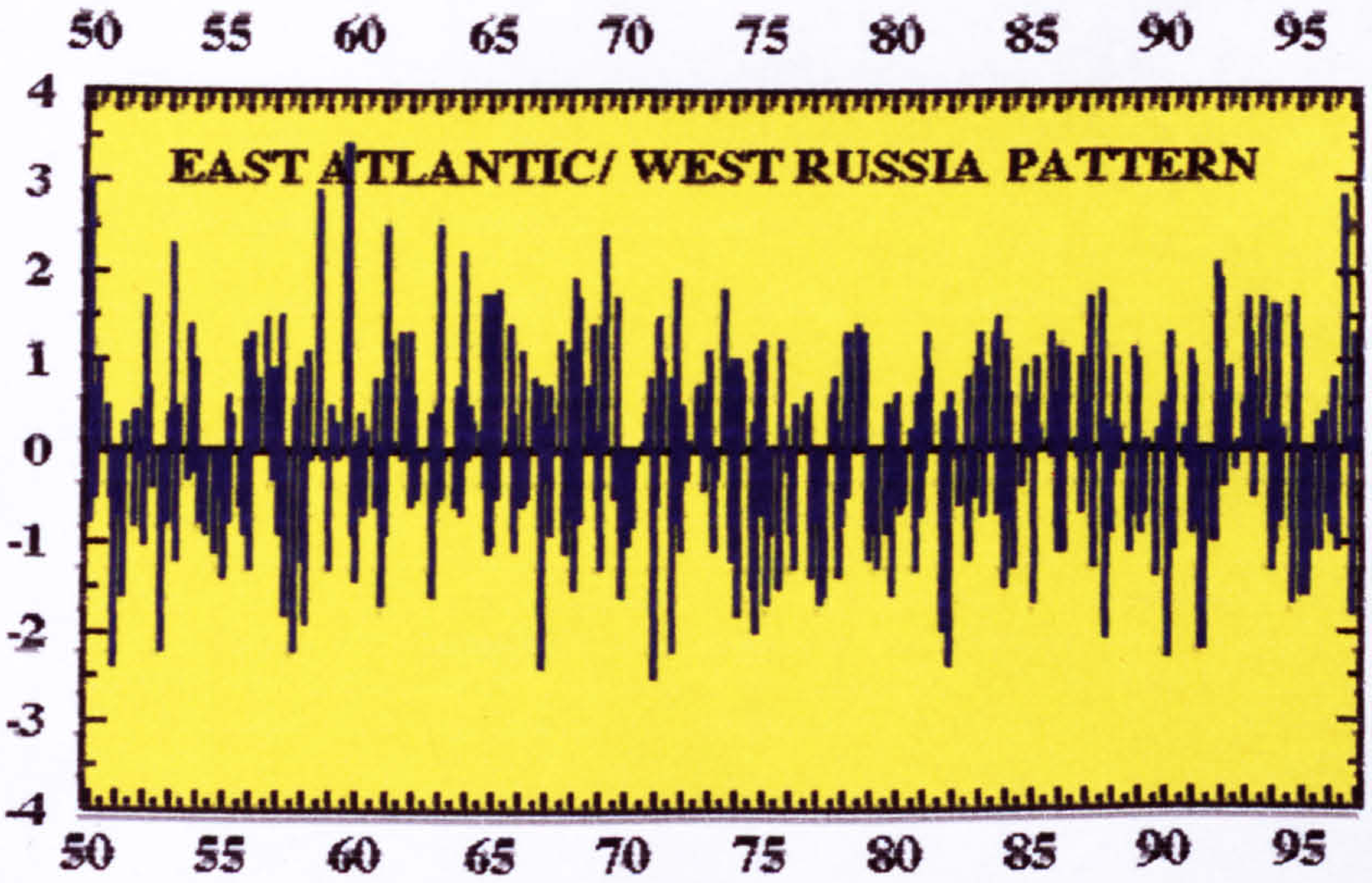


Figure 3-4 Time series for the East Atlantic/West Russia Pattern

3.3.8. The Scandinavian Pattern

The Scandinavian Pattern (SCAND) is described as a circulation centre which is centred on Scandinavia and parts of the Arctic Ocean north of Siberia. Two centres with the opposite sign are located over Western Europe and central Asia, around Mongolia and Western China. This pattern is measured in all months except June and July, with its positive phase being characterised by high pressure over Scandinavia, often in the form of blocking anticyclones over this region. The negative phase indicates the reverse, with relatively high pressure across the other two sites and low pressure over Scandinavia.

Figure 3-5 shows that the Scandinavian pattern exhibits considerable variability on seasonal, annual and decadal timescales. Positive phases during summer, as in 1976, are associated with warm and dry conditions while Scandinavian high pressure in the winter is associated with cold and often snowy conditions, particularly along the East coast.

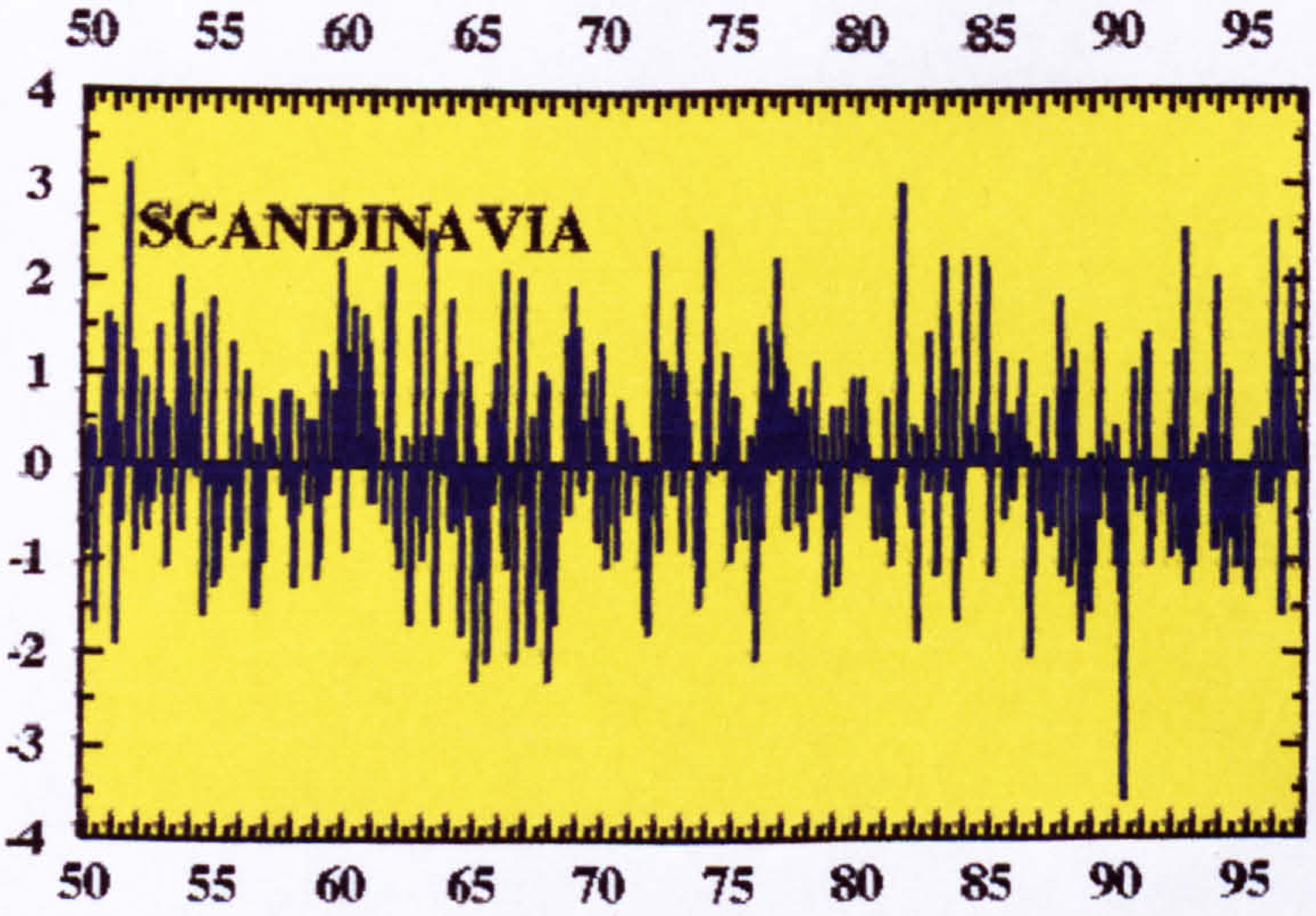


Figure 3-5 Time series for the Scandinavian Pattern

3.3.9. The Polar/Eurasian pattern (POLEUR)

The polar/Eurasian pattern occurs only in the winter months, and consists of one major anomoly over the polar region, with smaller centres, of opposite sign, over Europe and Northeast China. This pattern reflects major changes in the strength of circumpolar circulation and the accompanying changes in circulation at lower latitudes.

Positive phases are indicative of an enhanced polar vortex, negative phases being associated with a reduced polar vortex with low pressure over much of Europe and east Asia. Positive phases are associated with milder winters and negative phases with colder conditions. Figure 3-6 shows the time series for the period 1950 to 1997.

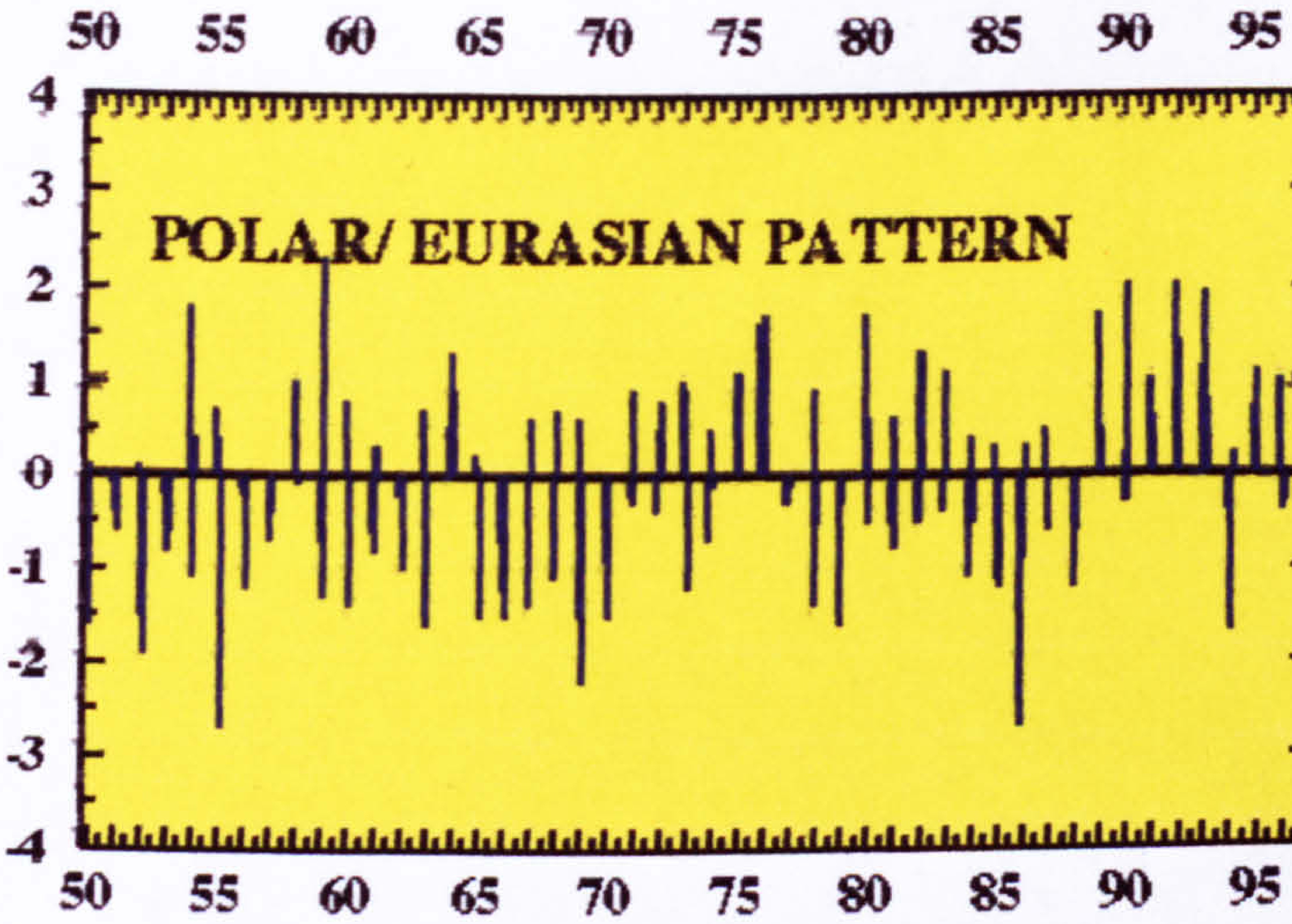


Figure 3-6 Time series for the Polar/Eurasian Pattern.

3.3.10. The Southern Oscillation Index (SOI)

The southern oscillation index is derived from pressure anomalies centred on Tahiti in the central Pacific and Darwin in Northern Australia. Although superseded by alternative methods of calculating the circulation patterns in the tropical pacific the long historical record associated with these two sites still make this a valuable index.

Positive phases of the index are associated with cooler sea surface temperatures (La Nina), whereas negative phases are associated with El Nino events where sea surface temperatures across the eastern parts of the pacific rise dramatically. This, in turn, allows for greatly increased convection of heat and moisture into the atmosphere, and the impacts of El Nino events can be detected around the globe. Figure 3-7 illustrates the major changes in this index from 1950 to the present.

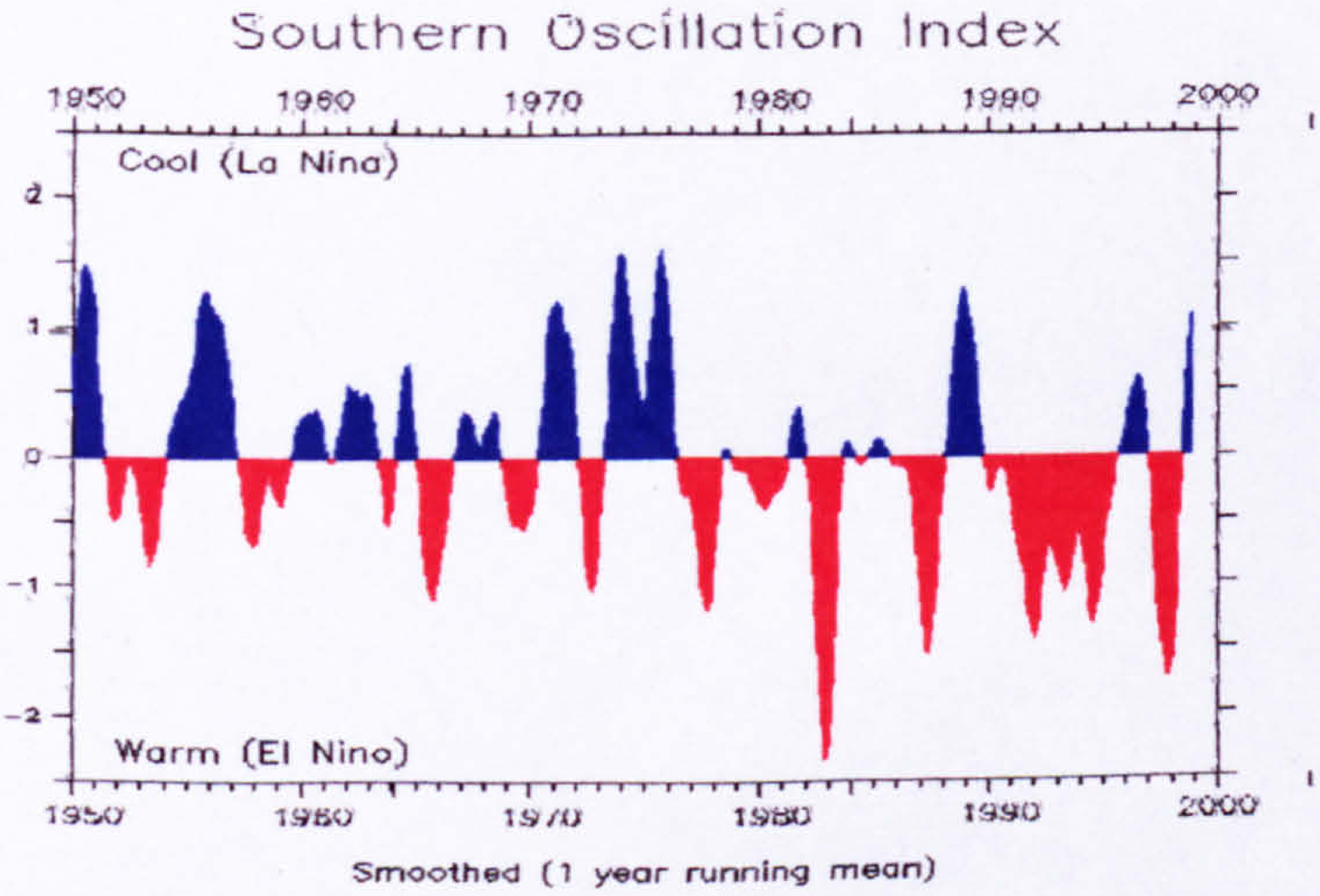


Figure 3-7 Time series for the Southern Oscillation Index.

3.4. Methods; Determinants of the Scottish climate.

The data sets relating to the above indices and measurements were all of a similar format, being monthly mean figures. A single data sheet was created in SPSS, which included monthly mean temperature and rainfall figures for each of the three regions of Scotland for the period from 1970 to, in most cases, 1999. Also included were the mean windspeed figures for Tiree and Leuchars, the former being restricted to the period from 1983 while the latter ran from 1970.

All of the indices relating to circulation patterns were included along with the time lagged CO_2 and solar output measures. For the SOI the correlation with time lagged variables was not so high but still exceeded 0.5 in all cases. It was decided that just two figures would be included, the 3-month and 1-month lagged variables. The 1-month lagged figure was included to account for almost immediate effects (correlation with SOI 0.703), and the 3 month lag to pick up any effects from season to season. Running the regression with the SOI and all the time lagged variables confirmed this choice, as these were the only two that were ever included in the final regression equation.

The strength of correlation was used in order to identify the lag structure. The correlation was calculated between meteorological data and the variables of interest lagged for 1-18 months. This was done in order to identify potential delays in the effects of, for example, changes to circulation patterns on the meteorological records. For the SOI it was found that the highest values of the correlation coefficient occurred with a lag of one month and three months. Both were included in order to allow effects to be included within a season and between one season and the next.

Not all of the data sets relating to circulation patterns covered all seasons, so for each season only variables with a complete data set were entered. These are summarised below in Table 3.5. The NAOI and SOI covered all seasons.

SEASON/PATTERN	POLEUR	SCAND	EAP	EAJET	EA/WR
SPRING		X			X
SUMMER				X	
AUTUMN		X	X		X
WINTER	X	X	X		X

Table 3.5 Season where circulation patterns are in dominant mode and are included in the analysis

3.5. Method; Systems Dynamic Modelling

3.5.1. Introduction

The creation of a model of some real world phenomenon necessarily involves the selection or abstraction of certain properties which are considered to be of interest. The type of model which is developed depends on the nature of the properties which are relevant to the problem being addressed. For example, when considering the visual impact of a proposed building on the surrounding area, a scale model could be constructed. This would extract only the external dimensions of the building, scaled appropriately, and would ignore properties such as the internal structure and material strength of components.

Such a physical model would be inappropriate when considering projectile motion, where the relevant properties to be included in the model would be measured variables such as mass, velocity, acceleration, angles and forces. Thus the model would consist of a series of mathematical equations which could accurately describe the motion of a projectile. Unlike the first example, colour, shape and location would not necessarily be included. In contrast to the first example, a physical model, this type of model uses a symbolic code to describe the elements which are of relevance.

Such mathematical or symbolic modelling has been developed over centuries, and has been applied to a range of problems, with notable success in the physical sciences. One reason for this success has been the ability to study aspects of reality in a laboratory or experimental situation. This allows for the control of many variables, leaving for examination those of particular interest to the experimenter. Much of our understanding of the world around us has been developed using this reductionist methodology where aspects of the real world are isolated and the relationships between variables studied. This does, however, have serious limitations in situations where certain variables cannot be controlled or where the elements combine in a larger network of interactions which cannot be studied independently. Such situations can be described as *systems,* which can be defined as a "collection of interrelated elements forming a meaningful whole." Examples include ecosystems, social systems, economic systems and a whole range of areas where certain aspects of the real world can be seen as combining to form a set of interrelated and mutually dependent elements. As the number of interacting elements increases so does the complexity of the model developed to explain the behaviour of the system. Rather than a simple causal relationship represented in the form A causes B, B could be a function of A, C, D and E, each of which is itself a function of a number of other variables.

The complexity of the model increases again when the structure of the system is such that feedback loops emerge. Feedback structures emerge when the relationship between elements is such that a change in A causes a change in B, which in turn "feeds back" and induces a change in A. Systems which exhibit such behaviour, require a particular method to represent these loops, and, as a result of the time delays inherent in the structure, require the passage of time, or simulated time, to fully assess the effect of the feedback structures. The method which has emerged to address these problems is that of System Dynamics, which, due to the complexity of the structures to which it has been applied, has emerged relatively recently in tandem with developments in computing. Analysis of the behaviour of systems, particularly those containing feedback structures, is often beyond the capacity of the unaided human brain. Computing power has done for modelling what the telescope and microscope did for scientific observation.

The system dynamics method has both advantages, as discussed above, and drawbacks. One weakness which is inherent in the method is, in essence, that the model relies on a set of mathematical equations which cover the system under investigation and which determine the relationships between the variables within the system. The model is therefore accurate only if the equations accurately define these relationships (Jeffers 1982). Where relationships are unclear, or are subject to changes which cannot be predicted accurately, there arises the problem of including relationships which are effectively best estimates, or guesses, but which might have a profound effect on the overall behaviour of the model. Alternatively these features can be left out of the model, reducing its accuracy and potentially missing important effects on behaviour.

In the context of this thesis, it is in the socio-economic sectors of the model where problems arise with building in the equations which will define relationships between variables through 100 years of simulated time.

The Scottish Executive Scoping Study (Kerr et al. 1999) identified the Common Agricultural Policy (CAP) as being the most important factor in determining activities within the agricultural sector, and indeed determining the financial viability of many of these activities. Future changes to the CAP cannot however be known, certainly not on a time-scale of decades stretching towards the end of the 21st century. Attempting to build in the effects of subsidies and grant schemes may be of value to the understanding of how agriculture will respond to climate change, but the lack of knowledge of how the CAP may develop prevents the inclusion of this into the model. The model will therefore look at the effects of climate change assuming that other factors which cannot be included remain unchanged.

One feature of any model is that it cannot include all relationships without becoming as complex as the real world situation under consideration. Simplification is necessary in order to reduce the complexity of the system to a level where an analytical solution is possible. On the other hand the model must preserve all of the elements which make the system sufficiently interesting for practical research (Jeffers 1982).

Economics as a discipline has developed a number of tools designed to examine the finer details of how change occurs within economic systems.

Econometrics uses statistical methods to quantify relationships in a system, which can be used for precise forecasting in the short term. The use of historical data to check hypotheses and to estimate parameters is seen as a strength in this method, however it can also be interpreted as a weakness (Moffatt I, Hanley N, and Wilson M.D. 2001). If a hypothesis is proposed then the absence of relevant data for whatever reason prevents this being included in the model. Some variables of interest to economists, such as quality of life or environmental quality, cannot be rigorously defined, and as such cannot be included in this type of model. The short term nature of the forecasts produced by econometric approach means that in the context of long term studies they are of limited value.

Input-output models are built using a transaction matrix which links each sector of an economic system to the others, by means of data which describes the flows of goods and services between them. Inputs and outputs from any one sector must be balanced, with the monetary value of the goods and services purchased being the same as the monetary value of the goods and services sold.

This allows the investigator to capture the complex interrelationships between the producing sectors of an economy by means of a set of simultaneous linear equations. Changes in one sector can affect other sectors, and input-output models allow both the direct and indirect effects of changes to be assessed (Pearson 1989). One of their strengths lies in their ability to investigate policy problems and the impacts at both the micro and macro levels. Effects on a particular sector of the economy can be assessed, as can the effects on the functioning of the whole system.

Input-output analysis has been criticised for certain aspects of its structure (Moffatt I, Hanley N, and Wilson M.D. 2001). The relationships established in the matrix are fixed, and are by necessity linear. Changes brought about in one sector of the economy by changes in another are always in a fixed ratio. Small short term changes are therefore modelled well by this system, however the longer term changes or changes of greater magnitude are not as well represented (Pearson 1989).

The data requirements of an input-output matrix are also quite demanding if disaggregated representation of the system is required. In terms of regional input output models, it is very often difficult to obtain such data, and estimates are necessary based on national figures. The time required to gather all the data necessary for a full input-output analysis of the three regions of the study was considered too great (pers comm, Dipak Ghosh). Despite the appeal of this type of model, with its sector by sector analysis of the local economies, it was considered too demanding a task to attempt in the available time.

A related modelling technique is that of Computable General Equilibrium (CGE) models. These share similar data requirements with Input-Output models and as such are considered inappropriate for this study.

System dynamics offers the ability to deal with the overall structure of the system under consideration and provides a means of establishing the linkages between climate and society. Where these relationships have been established in the form of equations, the method used has been along the lines of econometric modelling. Historical data has been used to establish the effects of climate on aspects of the economy. Aspects which cannot be included in a long term model, such as the CAP or disposable income of households, both of which would be considered important factors in a short term analysis of agriculture or tourism, have been left out. The system dynamic model, described in Chapter 6 and 8, examines the impact of climate on the economy assuming all other things are equal. The results of such a model have then to be treated with caution, they are not precise forecasts, but rather seek to identify the nature and direction of potential changes.

This method has been successfully applied to a range of situations dealing with systems which are diverse in subject matter (Barlas 2001). The problems discussed in section 1.3 relate to the differences between the natural and social sciences in terms of the establishment of "laws". This thesis deals with both natural and human systems, and, importantly, their interaction, and therefore requires a methodology which can be applied to both. Since both aspects of the study involve complex systems, and it is their interaction over time which is of interest, the choice of a system dynamics approach seems justified. The following section describes this approach and gives a brief description of the main methods used.

3.5.2. System Dynamics

The origin of system dynamics lies with a growing body of work through the 1950's and 1960's. First published in 1948, Norbert Wiener's book, Cybernetics (Wiener

Norbert 1961), discusses the problems of complex systems, primarily with reference to both the human mind and aspects of engineering. Within the chapter entitled Feedback and Oscillation, he cites the work of James Clerk Maxwell who discussed the properties of governors for steam engines. These mechanisms act to control the flow of steam into the pistons of the engines. As it speeds up the mechanism, it slows down the flow of steam thus slowing the engine. As it slows down the mechanism allows more steam in to speed up the engine. This is an early example (1868) of a feedback mechanism which acts to stabilise the behaviour of the engine.

A similar pattern is seen in systems as diverse as the control of temperature and blood pressure in living organisms and devices to stabilise output from electrical circuits. The developments in electrical engineering, and in particular computers, seems to have been a stimulus in the development of interest in the more general application of systems theory. An important step in the development of this field was the publication of Industrial Dynamics (Forrester 1961) which applied systems thinking to the organisation of factory production. The 1960's saw a growth in the application of systems theory to a wider range of questions including the growth of cities (Forrester 1969) and wider global problems in The Limits to Growth (Meadows et al. 1974) and World Dynamics (Forrester 1973).

Advances in the power of computers, and the parallel growth in software applications, have led to a situation where the computational difficulties of dealing with complex systems have been greatly reduced. There are now a number of readily available packages which allow modellers to address problems in a wide range of fields, the common theme being that they involve systems of interrelated elements, often including feedback structures and requiring the simulated passage of time to fully assess their long term behaviour. Such systems appear in a wide range of contexts and deal with ecology, engineering, the physical sciences, as well as a whole range of social science applications (Bruce Hannon 1994).

Models built using this method are not designed to provide a single solution to a complex problem. Rather they allow the modeller the opportunity to examine a range of possible futures, dependent on the control of certain variables. This, in particular in the social sciences, allows for the consequences of certain management decisions to be assessed. The following section gives a brief introduction to the basics of model construction using Stella V5.1.1, an icon driven modelling package which has been developed by High Performance Systems.

3.5.3. Model construction in Stella

3.5.4. Layers

Stella is designed with three main layers to its user interface. The upper layer gives an overview of the model by showing different sectors of the model which have been created. Included in this layer are "bundled flow" connectors, lines which illustrate any connections between the various sectors. For complex models which have been constructed with a number of different sectors, for example an ecological model with predators, prey, food supplies and human activities, this level allows a simple overview of the model by eliminating the details of the lower levels.

Below this is the diagram layer, where the overall structure of the model is created, and where values for the variables and equations which define the relationships between variables can be entered. Examples of the building blocks are illustrated in the following section. This layer allows a "conceptual model" to be constructed with the ability to edit and develop this model as the structure is fine-tuned.

Below this, Stella generates a set of equations corresponding to the variable definitions and relationships entered in the diagram layer. All variables are listed, with initial values and rates of change in the form of difference equations. This layer resembles the code for a model written in a programming language, but the great strength of Stella is that the modeller can spend time dealing with the structure and behaviour of the model rather than with the details of writing this code.

3.5.5. Building blocks used in Stella

The essential building blocks used in the construction of a model in Stella represent Stocks, or state variables, Flows which represent rates of change of the state variables, Converters or translation variables and Connectors represented by information arrows. Figure 3.8 shows these how Stella represents these building blocks.

The basic building blocks in Stella

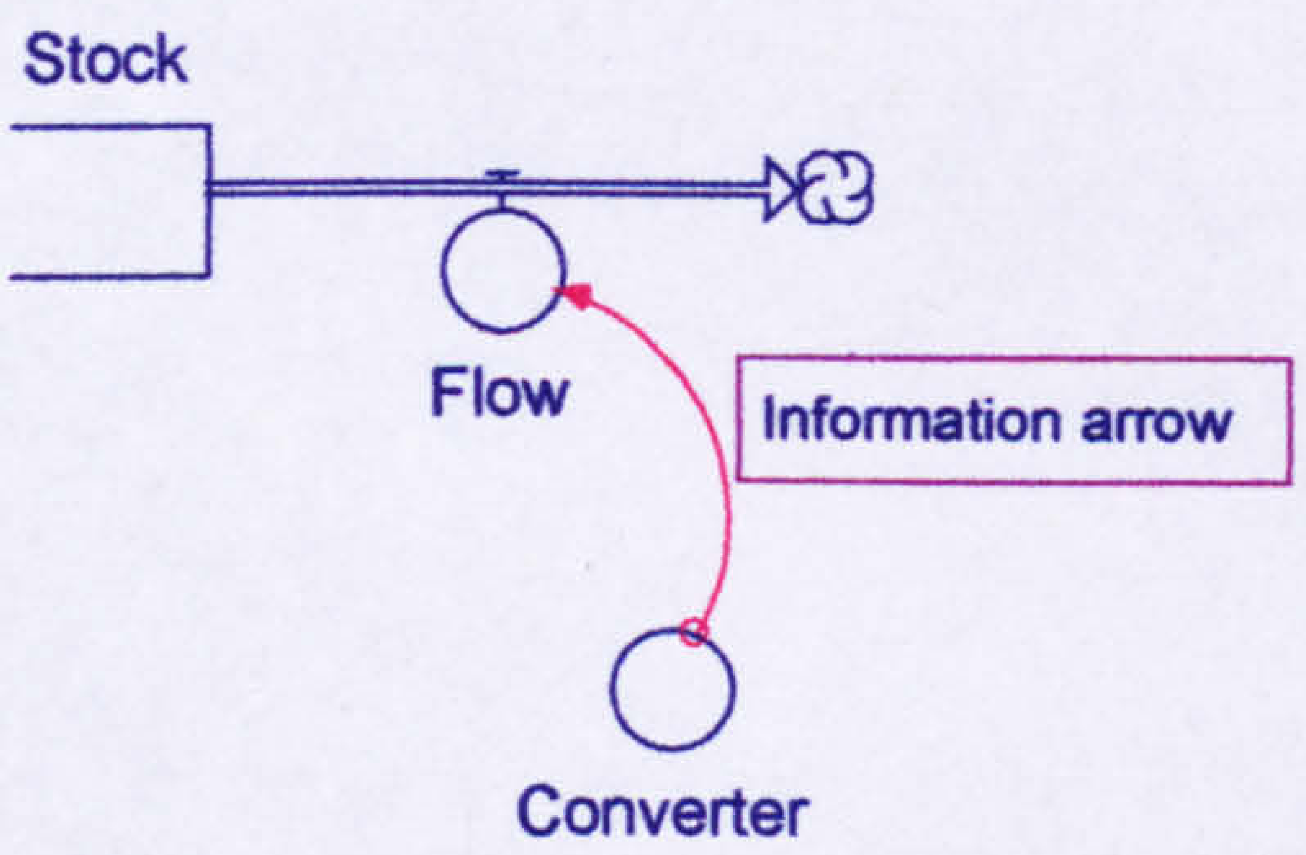


Figure 3.8 The building blocks used in Stella

Using these basic building blocks, a wide range of structures can be created, and complex relationships can be managed.

The stock represents a "state variable", a quantity which accumulates or declines through time, such as water in a reservoir, population, area of land or energy in a system. Such variables define the condition of the system at a particular time.

Flows can be directed into or out of stocks, and can be constrained to flow in one direction or can be bi-flows, where some control variable determines the direction of flow. The values entered for a flow represent the rate of change of the state variable and at every calculation interval change the condition of the state variable by the amount determined by the equations entered.

Converters or calculators allow mathematical calculations to be carried out and can also represent control variables, the values of which can be altered in order to perform experiments designed to test the effects of variations in certain parameters within models.

Information arrows allow the values held in the different building blocks to be transferred. If the current value of a stock is required in order to calculate a flow out of that stock, then an information arrow can allow this. An information arrow can only be introduced if the flow of information is necessary. Stella requires all values introduced by means of an information arrow to be used.

3.5.6. Feedback loops

A simple string of building blocks represents a series of calculations, something which could be achieved with the aid of a calculator. It is when information feeds back through the system and a change in one variable has an effect on one or more other variables, which then ultimately affect the original variable, that simple numerical solutions become more problematic. Such loops can be readily constructed using the building blocks mentioned above. One of the strengths of the system dynamics method is its ability to manage complex structures which contain feedback loops. This makes it appropriate in the context of this study.

A full description of System Dynamics Modelling with Stella can be obtained from a number of sources, including Hannon and Ruth (Bruce Hannon 1994) and Deaton (Deaton and Winebrake 2000).

3.6. Data and methods; the socio-economic model

3.6.1. Population sector

Population statistics were obtained from the Report of the General Registrar of Scotland (General Registrar of Scotland 1975-2000), which provided a breakdown of the population into 5 year age cohorts. This allowed the construction of a data set which combined the first four groups (0-19) as one group, representing "young" individuals, those of working age (20-64) representing the "middle" age group, and all retired individuals (65+) as the "older" age group.

The choice of 0-19 for young people included the group aged 14-19, and while approximately half this group would be beyond compulsory education and therefore suitable for inclusion in the "middle" age group, a large proportion would be attending School, College or University. It was therefore considered more appropriate to exclude them from the working population than to include them.

Within each region the proportion of those considered to be of working age who were economically active was noted, thus providing an estimate of the labour supply for each region.

3.6.2. Employment sector

Data for this sector was obtained from various sources. Tourist numbers were obtained from the Visitor Attractions Survey (Scottish Tourist Board 1989-2000). Employment in the forestry industry was obtained from the Forestry Commission website (Forestry Commission Forestry Statistics 2001). Data relating to employment in Agriculture was obtained directly from the Scottish Executive Environment and Rural

Affairs Department (SEERAD). Employment Multipliers for Agriculture and Tourism were obtained from "An analysis of some aspects of the Scottish economy using input output techniques" (Al-Ali and Burdekin 1978).

Employment multipliers for forestry activities were obtained from "Scottish forestry; an input output analysis" (Roberts et al. 1999).

3.6.3. Land use sector

Data concerning the proportion of land currently classed as Urban was calculated using figures relating to regional areas with figures for population density obtained from the Edinburgh University Geography Department website (Edinburgh University Geography Department 1998). This was combined with figures for the area of urban land in Stirling (Stirling District Council 1996).

Areas of agricultural land, classified as either crops and grass or as rough grazing, the breakdown used in the SEERAD data, were obtained directly from the Scottish Executive Environment and Rural Affairs Department (SEERAD) in the form of a time series covering the period 1985 to 2001.

Statistics relating to the extent and nature of forestry in the three regions was supplied by Ewan Purser of Highland Birchwoods, (Purser, Pers. Comm.) for the year 1996. This was supplemented by data from the Forest Inventory carried out by the Forestry Commission (FC) which gave estimates for forest cover both 1995 and 1980 (Forestry Commission 2000). In addition the loss of agricultural land lost to forestry was obtained from the Scottish Executives Economic Report on Scottish Agriculture (Scottish Office Agriculture and Fisheries 1984-2000).

Rates of change of the potential areas of agriculture under different climate scenarios were calculated using Arcview 3.2 and data from the Digimap resource (Edina 2003). This was in the form of Meridion 2 and Land-Form Profile DTM data sets.

3.6.4. Housing sector

Data used in the construction of the Housing sector came from the following sources. Housing stock for each of the regions, including data relating to housing below tolerable standard (BTS) and new builds, was obtained from the Scottish Office (Scottish Executive) Statistical Bulletins; Housing Series (Scottish Office Statistical Bulletin 1978-2000).

Projections relating to household composition were obtained from the Scottish Office statistical Bulletin; Housing Series, Household Projections (Scottish Office Statistical Bulletin 2002).

The housing sector also utilised the output from the population sector.

3.6.5. Water resource sector

The Areas of the three regions, in hectares, after the 1996 reorganisation of Local Government, were found at the University of Edinburgh Geography Department Website (Edinburgh University Geography Department 1998). Per capita consumption of water for the whole of Scotland was obtained from the Scottish Executive Website (Scottish Executive b 2001). Runoff as a percentage of precipitation for rivers in the three regions was found in the Hydrological Data Yearbook (Institute of Hydrology 1991b). Rates of evapotranspiration were obtained from two sources, The Monarch Report (Harrison, Berry, and Dawson 2001) and Hydrological data yearbook (Institute of Hydrology 1991b).

3.6.6. Emissions sector

Data for the emissions sector was obtained from The Statistical Compendium for the Dobris Assessment (Officer for official publications of the European Communities 1995), the research entitled Ecocraft Framework 4 (Jarvis 1999) and the U.S. Government website (DOE 1998) which deals with the carbon content of fossil fuels.

3.7. Methods; socio-economic sectors

In order to assess the impacts which the changes in climatic variables generated by the climate model might have on the socio-economic structures of the three regions, a broad socio-economic model was developed. Due to the complex nature of the model and the existence of feedback structures, this was done using Stella V5.11, a software package designed for dynamic simulation modelling. This model included the following sectors.

1. Population
2. Employment
3. Land use
4. Housing
5. Water resources
6. Emissions

In each case the relevant data was sourced (see section 3.6.) and relationships between variables sought. Initially this was achieved by graphical means and the use of correlation. Of particular interest were instances where there appeared to be a statistically significant link between climatic and socio-economic variables, as these might indicate that these would be areas sensitive to climate change. Where correlation was identified and causal links were established, regression analysis was used to provide equations which quantified the relationship.

Other non-climate relationships were similarly established, allowing the model to develop a number of connections between the sectors of the model. The construction of the model is described in Chapter 8 where the various relationships are presented in detail. An examination of the feedback loops is undertaken in Chapter 9 in order to provide further information concerning the structure of the model. Full listings of the feedback loops is provided in the appendix. Chapter 9 also gives the results of the sensitivity testing of the model.

Construction of a dynamic model represents the core of the methodology for combining aspects of the physical systems with aspects of human systems. Chapter 3.5 has given an explanation of this method and outlines the underlying concepts which are essential to this approach.

Chapter 4 Analysis of Meteorological Data.

The three regions chosen for the study (Argyll and Bute, Stirling and Fife) represent a transect running west to east across Scotland. The geography of each was described briefly in Chapter 1. The sources of the data and the ways in which this meteorological data was compiled was described in Chapter 3. This current Chapter presents an analysis of the meteorological data, relating to temperature, precipitation and wind speed, for each of the regions. The purpose of this analysis of data is to show empirically any evidence of meteorological and climatic changes in Scotland between 1970 and 2000. "Climate" is defined as the long term average of meteorological measurements, usually over a 30 year period, which in this case has been taken as the last three decades of the 20th century.

The analysis of meteorological data in order to identify trends has been carried out previously, using data from Parkhead in Stirling (Harrison 1994), (Harrison 1997). This included the use of linear regression on mean values of precipitation and temperature to establish trends. The data sets used were in some cases shorter than the three decades used in this study but identified similar trends. These studies point out that using relatively short data sets can lead to results which have to be treated with some caution. Extreme values can exert an undue influence over the gradient of the regression equation (Harrison 1997). This has been minimised in this study by firstly using data from three decades and secondly using a number of meteorological stations to produce a "regional climate". This used five sets of data for Argyll, three for Stirling and four for fife. The local variability in climate is then smoothed out by using sites which are relatively close but have different locations, aspects and proximity to the coasts.

Regression analysis is used extensively in the analysis of meteorological data. Later, in Chapter 8, regression is used to determine the relationships between meteorological variables and economic variables such as the numbers of tourists. Use of correlation and an examination of graphical output established the possibility of the existence of relationships. Correlation by itself is not adequate to establish a relationship and can exist between variables without any meaningful connection (Rogerson 2001). There needs also to be a theoretical justification for relationships which are established. To rely only on established concepts denies the possibility of uncovering relationships which have been hitherto overlooked. Performing the statistical tests first allows an examination of potential relationships. Those without any possible causal mechanism can be rejected and the remaining examined.

In order to test that linear regression was the most appropriate form, the curve estimation function of SPSS was used. This allowed a comparison of the R^2 values and the significance of the regression equations for a range of functional forms. Where data does tend to conform to a linear pattern, both exponential and logarithmic functions can produce similar results. It is only the extrapolation of these results which will generate quite distinct differences between these different functions. If no evidence for a different functional form was evident in the data, then linear relationships were used.

One potential danger with linear regression is if the data used is strongly auto-correlated. Should two variables which have unit roots be used to establish a regression equation then the results can be misleading (Koop 2000). In all of the instances where linear regression is used at least one of the dependent or independent variables is generated from the meteorological data. These data sets all show considerable variability and none can be shown to have a unit root. The problem of spurious regression (Koop 2000) is therefore avoided.

4.1. Preliminary study

The three site chosen for an initial examination of climate variations were Dunstaffnage, Stirling Parkhead and Leuchars. Their positions are indicated on Figure 4.1 and the details of each site given in Table 4.1

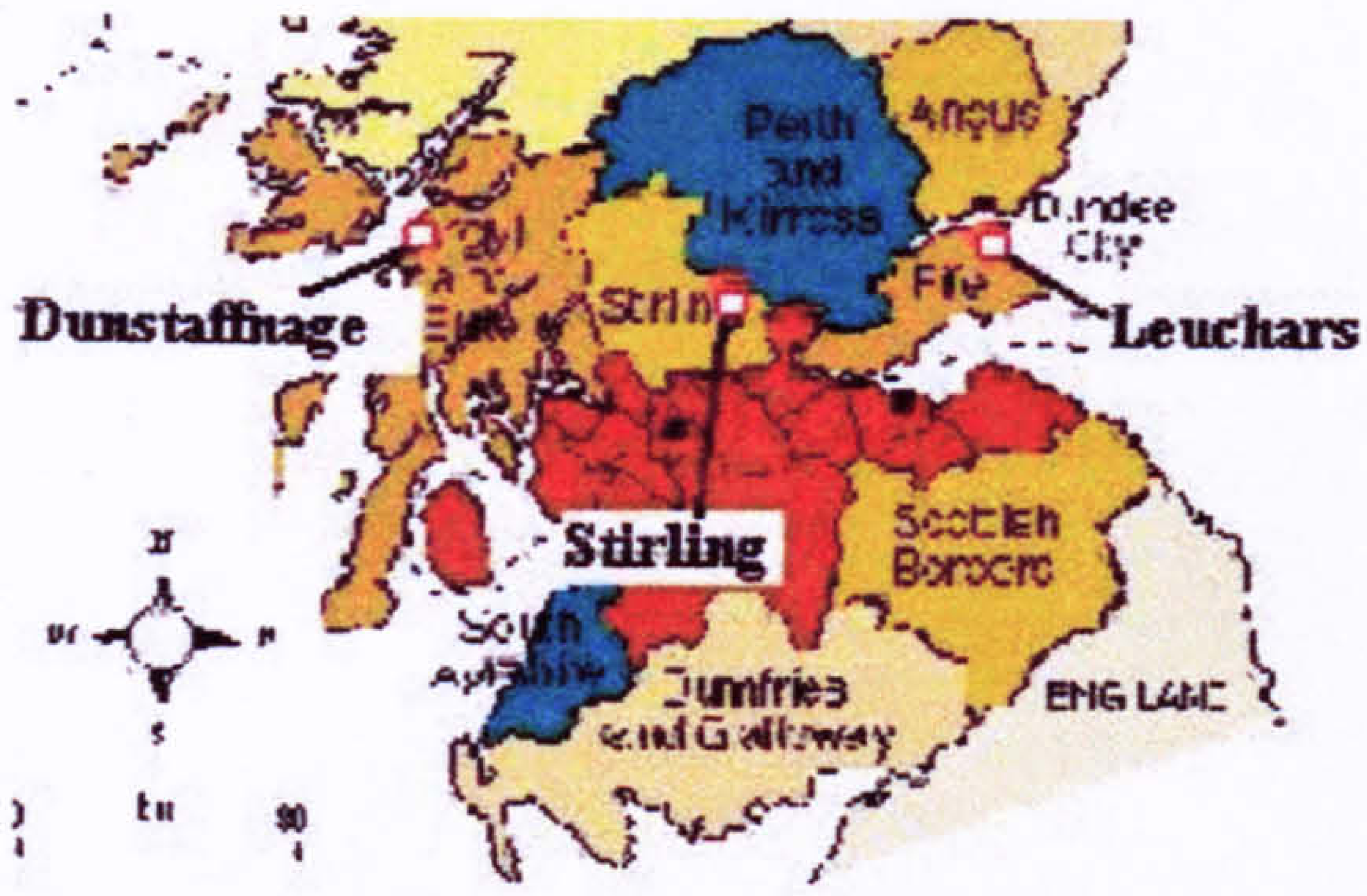


Figure 4.1 The location of the meteorological stations for the preliminary analysis

1.	
Site	Dunstaffnage
Grid Reference	NN881340
Latitude	56.450
Longitude	-5.438
Elevation	3m
2.	
Site	Stirling Parkhead
Grid Reference	NS815969
Latitude	56.150
Longitude	-3.907
Elevation	35m
3.	
Site	Leuchars
Grid Reference	NO468209
Latitude	56.377
Longitude	-2.861
Elevation	10m

Table 4.1 Details of the three sites.

All three sites have reasonably long records, with very few breaks in the continuous data. This allows for a comparison to be made for at least the last three decades.

4.1.1. Results for Temperature

Figure 4.1 shows the mean surface temperature for these three sites for a period from 1970 to 1998. This shows considerable variability in mean daily temperature for all three sites. Taking the annual figures as the dependent variable and the year as the independent variable it is possible to generate a regression equation. However this is not significant at the 5% level but does indicate a warming trend as all three sites yield an equation with a positive coefficient.

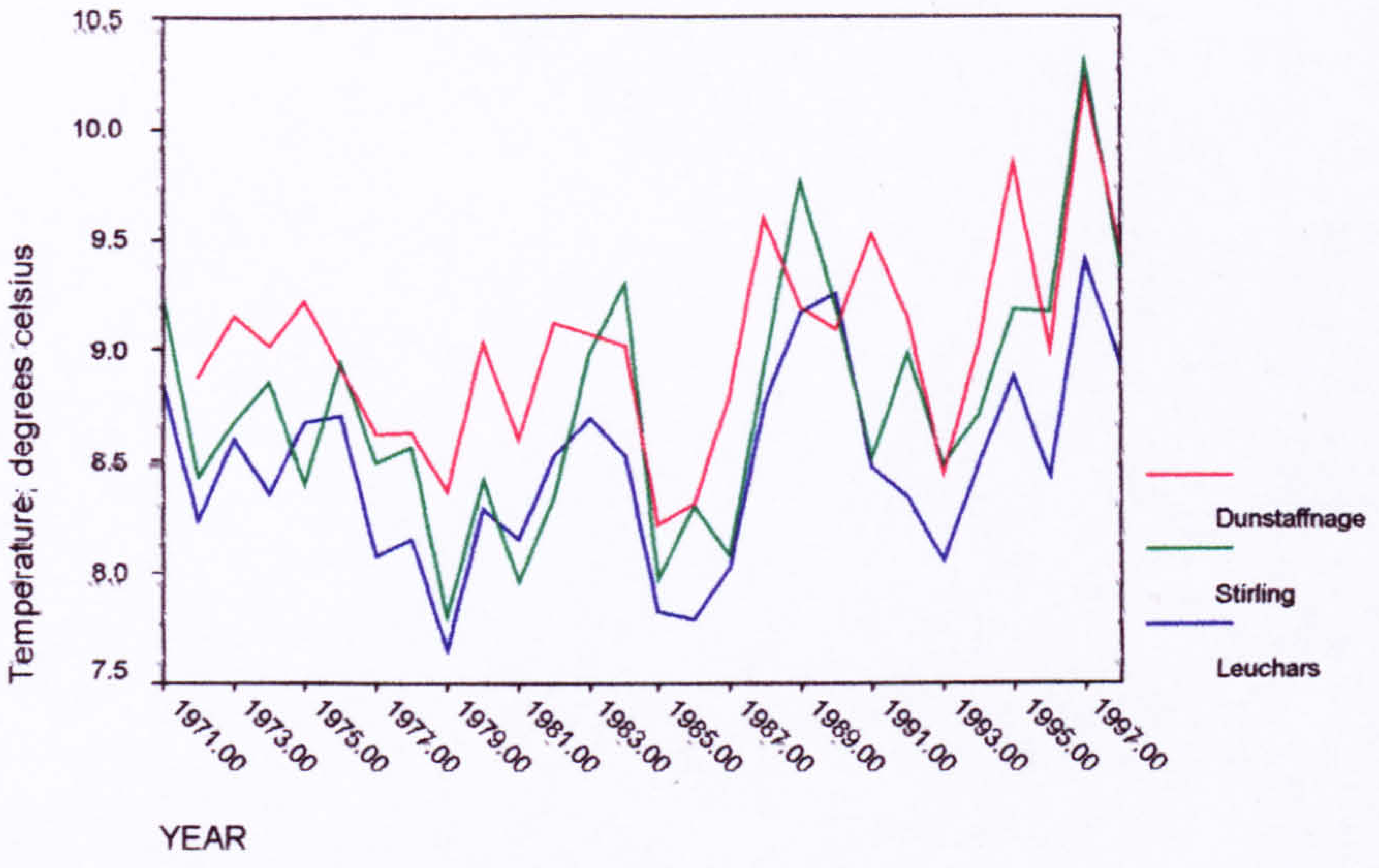


Figure 4.2 Mean surface temperature for the three sites

From a visual inspection of this graph (Figure 4.2) it is possible to make the following observations.

1. There is a visually discernible indication of a warming trend, particularly during the 1990's.
2. There is considerable variability in the data from year to year.
3. No great disparities exist between the temperature regimes of the three sites.

The west coast site, Dunstaffnage, does appear the warmest for most years, with the East coast site, Leuchars, being regularly the coldest. Table 4.2 shows descriptive statistics for the temperature data taking annual mean daily temperature for each of the sites for all years where records are complete. This shows that Argyll has the lowest range of temperatures as well as the highest mean temperature. Fife however has the lowest mean temperature but the greatest variability as measured by the range and standard deviation. All measures are in 0.1 of a degree Celsius.

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean		Std.
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
MEANTA_2	28	19.81	81.17	100.98	88.8609	.8078	4.27464
MEANTS_2	28	22.30	78.78	101.07	87.6127	.8749	4.62927
MEANTF_2	28	22.34	73.13	95.47	82.0898	.9226	4.88184
Valid N (listwise)	28						

Table 4.2 Descriptive statistics for regional annual mean daily temperature.

The moderating effect of the sea must be significant for the two coastal sites, with the warmer mean temperature of the west being the result of the difference in sea temperature which is in the region of 2 degrees Celsius in winter (Stringer E.T. 1972).

To examine the effect this might have Figure 4.3and Figure 4.4 show mean daily temperature for January and July respectively.

Again significant annual variation is visible though the temperature regime appears to be very similar throughout the country, cold winters being common to all three sites, warm summers being common to all three sites, though again Stirling shows the greatest variability.

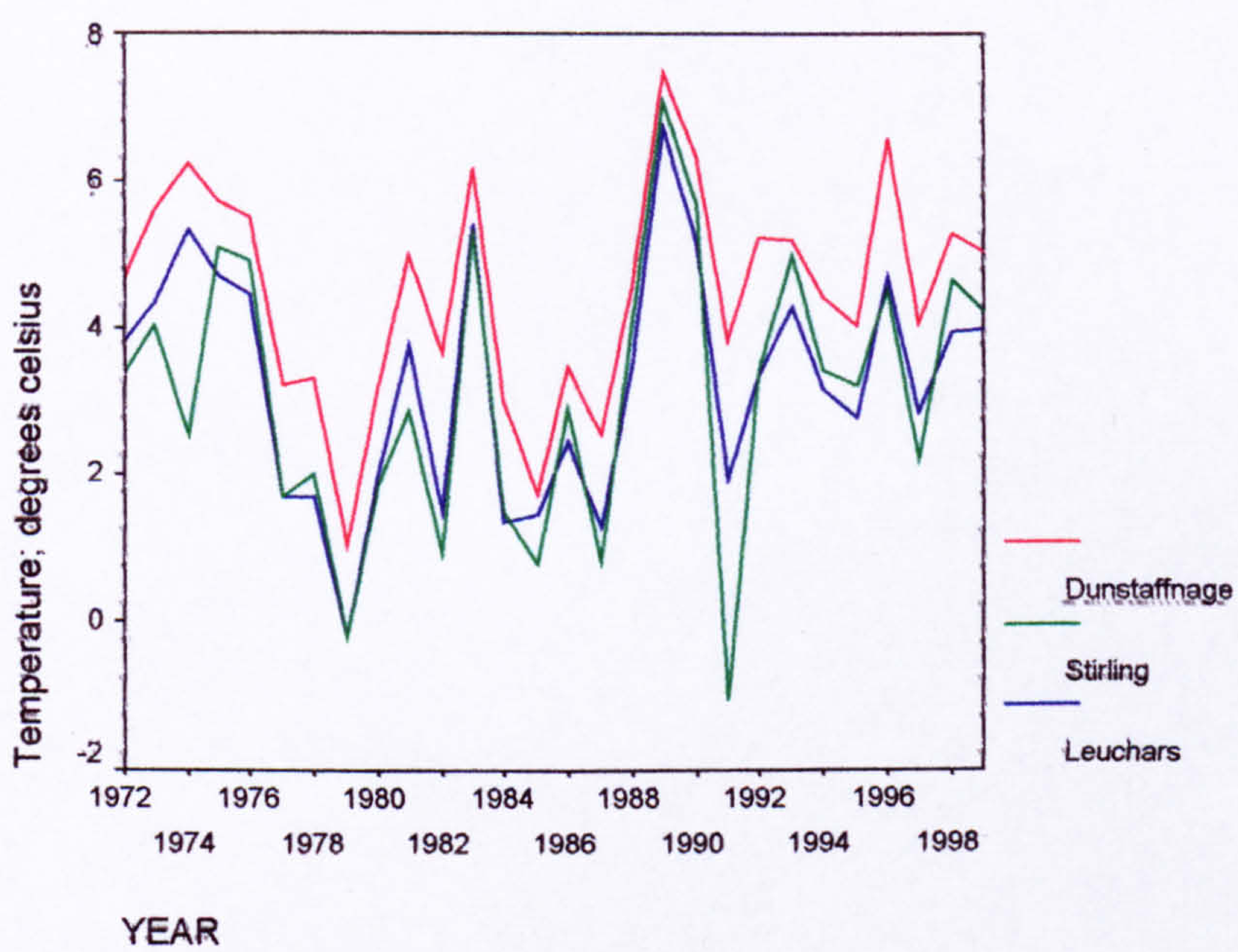


Figure 4.3 Mean daily temperature; January

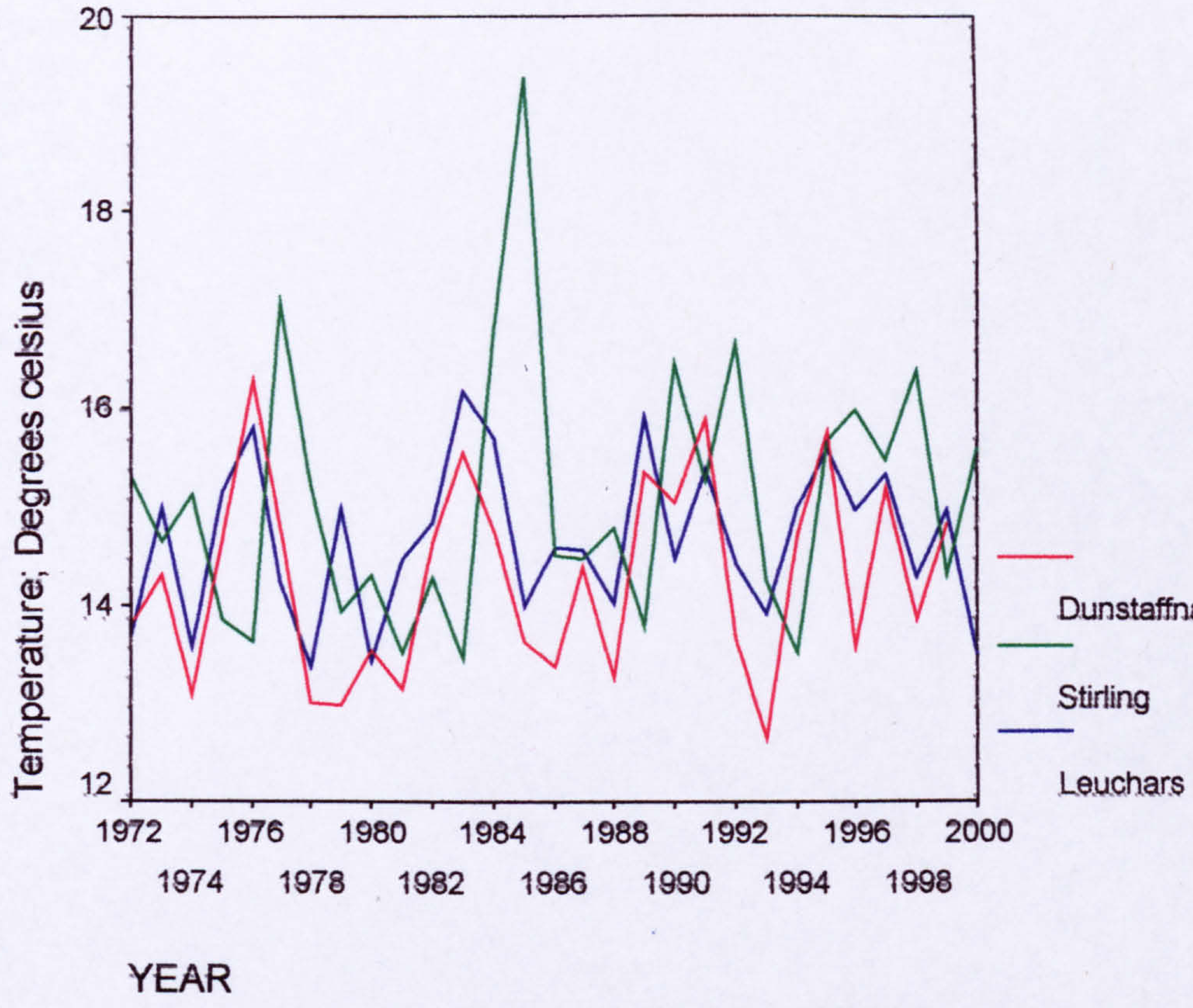


Figure 4.4 Mean daily temperature; July

The July figures show that on average the East enjoys slightly warmer Julys than does the West with Stirling again showing considerable variability. The 1985 spike in temperature has been checked and does represent a particularly warm spell inland for the month of July.

4.1.2. Regression Analysis

Rather than using a restricted number of points from annual mean temperatures a regression equation was produced using the complete data set for daily mean temperatures for the period 1971-1999. In each case the daily mean temperature was treated as the dependent variable and the year was taken as the independent variable, essentially looking at temperature as a function of time.

Temperature = f(time)

This ignores seasonal variability as a factor and as such the R^2 values of below 1% reflect how little of the variability in the data is due solely to the year. In all three cases the regression was significant at a level of 0.01. The results are summarised below in Table 4.3.

	n =	Constant	Coefficient	Significance
Dunstaffnage	10557	-514.6	0.305	0.000
Stirling	10557	-866.7	0.481	0.000
Leuchars	10557	-222.1	0.155	0.005

Table 4.3 Results of regression analysis for temperature

In each case the regression equation is significant at a level below 0.01and in each case there is a positive coefficient, suggesting that there is a definite warming trend in the data of all three sites. The value of the constant is of no significance as the use of actual dates simply means that the unit of the x-axis is one year regardless of where numbering begins. The rate at which this warming appears to be happening varies across the country, with the strongest trend being apparent in the data from Stirling.

Since the temperature data is measured in tenths of 1 degree Celsius, a gradient of 0.481 represents a warming trend of 0.481 degrees Celsius per decade, with the trend evident for Dunstaffnage and Leuchars being 0.305 and 0.155 degrees Celsius per decade respectively.

This represents considerable variation between the three sites. If extrapolated into the next century it would represent a considerable difference in mean daily temperature across the country, with inland areas warming more rapidly than the coastal regions.

Further investigation involved the seasonal breakdown of these statistics. Again the daily mean temperature was used as the dependant variable and the year as the independent. This time the results were calculated as seasonal comparisons, taking the standard definitions of seasons given above.

The results of this regression are given below in Table 4.4.

n = 82	Coefficients		
	Dunstaffnage	Stirling	Leuchars
Spring	0.276** R^2=0.005	0.431** R^2=0.012	0.275** R^2=0.005
Summer	0.206** R^2=0.003	0.447** R^2=0.020	0.116* R^2=0.002
Autumn	0.358** R^2=0.008	0.231* R^2=0.002	0.269** R^2=0.003
Winter	0.260** R^2=0.003	0.198* R^2=0.002	0.209** R^2=0.003

** denotes significant at 0.01 * denotes significant at 0.05

Table 4.4 Results of regression analysis for seasonal subsets of the temperature data.

Dunstaffnage has the strongest trend in the Autumn, with the next strongest in the Spring. Stirling Shows the strongest trend in the Summer and the next strongest in the Spring. Leuchars shows the strongest trend in the Spring with the next strongest in the Autumn.

This suggests that in all cases the months of March, April and May are showing a strong warming tendency. Autumn shows the trend on the coastal sites, but not so strongly inland, where summer temperatures show a stronger upwards trend.

All have a very low R^2 value, indicating that there is a great deal of variability around the trend line. This results from the inclusion of all daily mean temperatures for a three month period in which considerable ranges of temperature are experienced.

4.1.3. Degree-days

The effect of these trends can be seen by considering the number of degree-days, as measured at each site, over the period 1972-1999. Figure 4.5 shows the annual totals for the three sites, with regression lines fitted to the data. In keeping with the previous section, all three sites show an upward trend in the number of degree-days, with Stirling showing the strongest upward trend. Again considerable yearly variation results in a fairly low R^2 value but all three equations are significant at the 1% level.

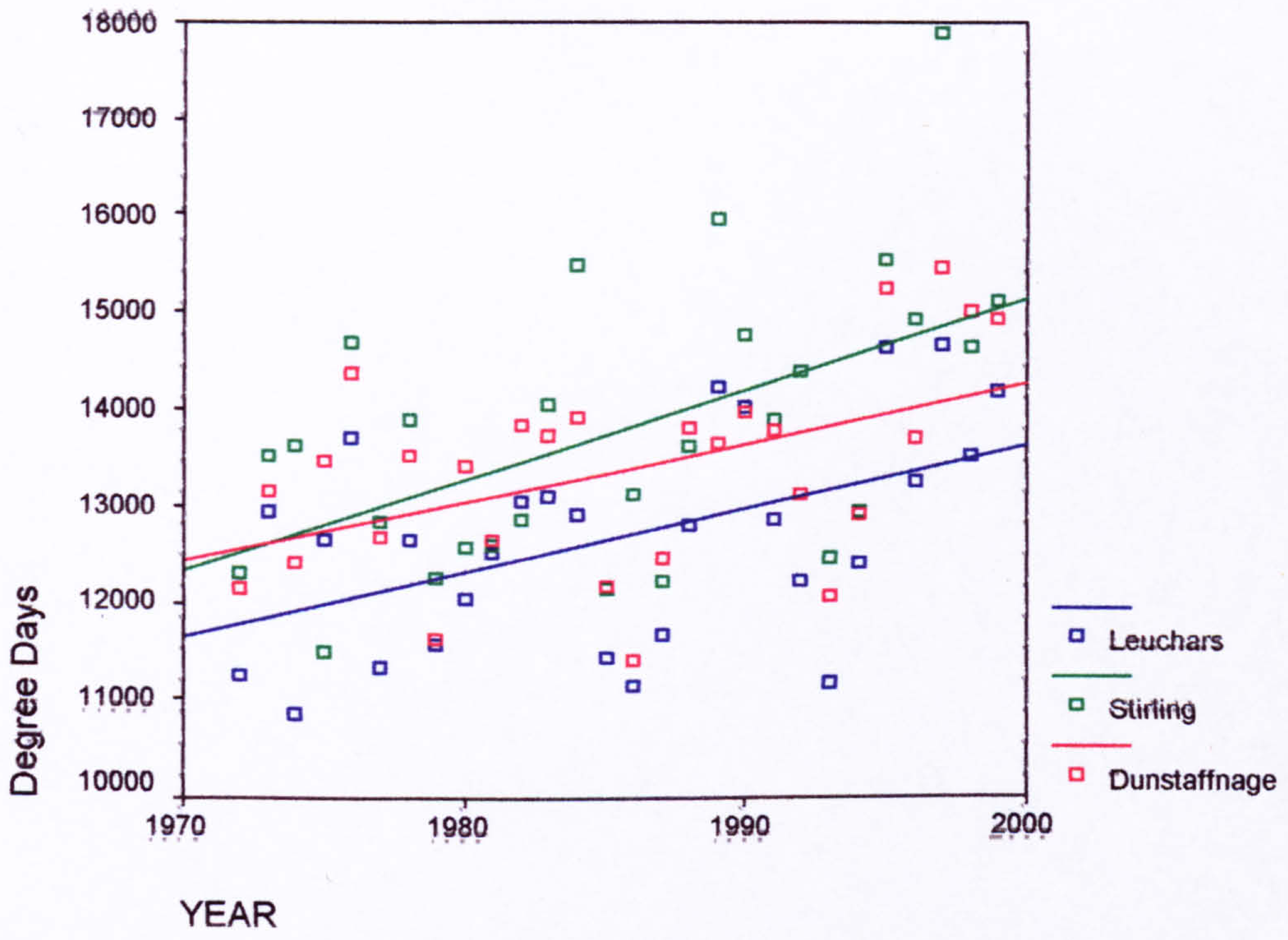


Figure 4.5 Degree days for the three sites 1970-2000

An extrapolation of these trends sees the number of degree-days increase by 81 per decade at Stirling, with Dunstaffnage and Leuchars having a projected increase of 61 and 66 per decade respectively.

4.1.4. Results for Rainfall

The West –East transect represented by the three chosen sites is designed to include the considerable variation in rainfall totals across Scotland. Figure 4.6 illustrates this, with the West coast site of Dunstaffnage receiving a mean annual total of approximately 1750mm, with Stirling receiving approximately 1000mm and Leuchars at the other extreme with a total of around 700mm.

More variability in rainfall on the West Coast is evident but no discernible upward trend in any of the data sets can be seen to exist.

A visual examination suggests a correlation between rainfall at Stirling and at Leuchars and analysis using Pearsons correlation coefficient confirms this. No significant correlation exists between Dunstaffnage and either of the other two sites, however a significant correlation exists between Stirling and Leuchars, although this is not strong. This suggests that the weather systems which produce rain in these two areas have some similarities but differ to some extent from the West Coast regime. The results are shown in Table 4.5.

An analysis of seasonal totals of rainfall shows great variability from year to year and no significant trends can be established from this data in any of the three sites

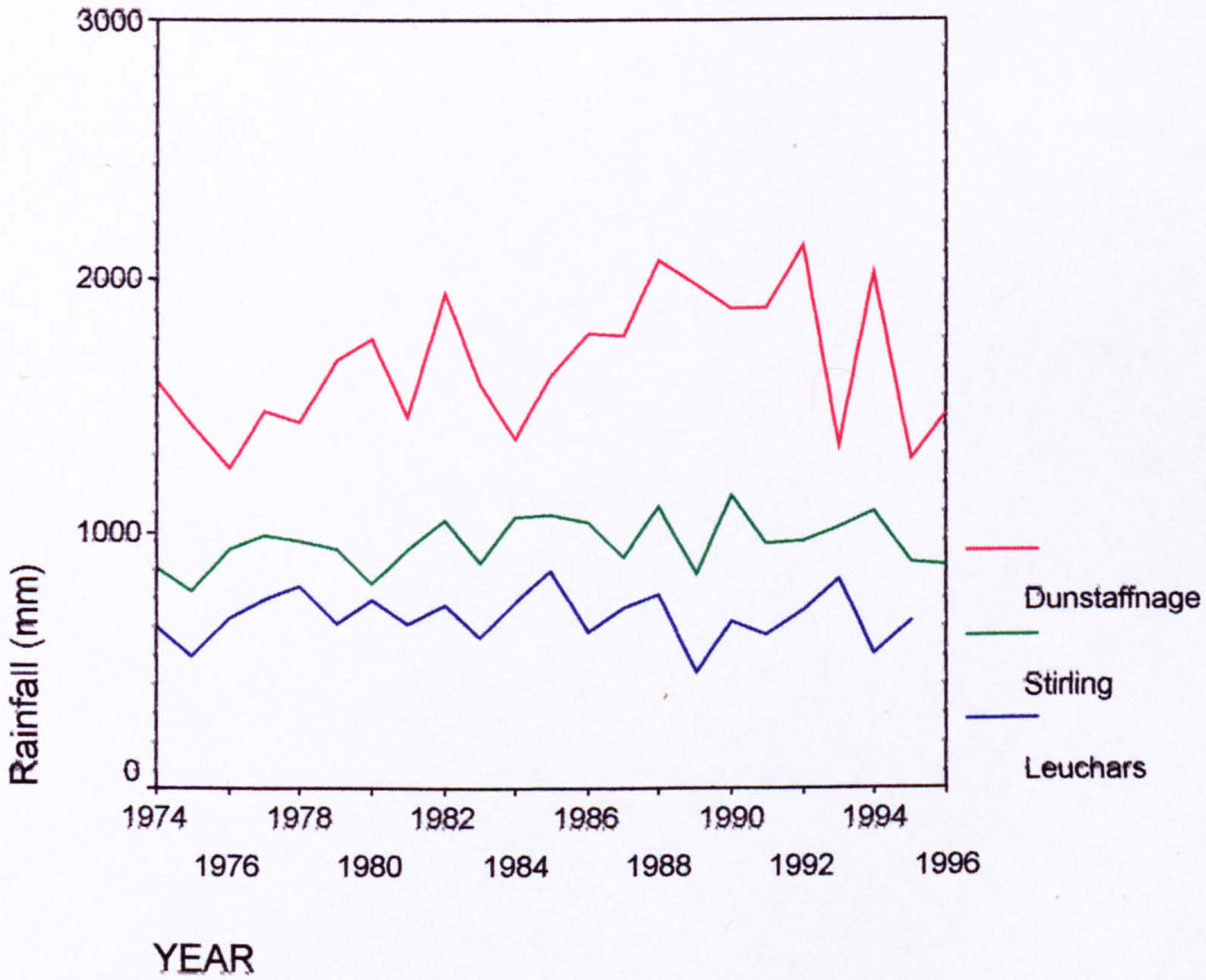


Figure 4.6 Comparison of annual rainfall totals.

Correlations

		DUNSTAFF	STIRLING	LEUCHARS
DUNSTAFF	Pearson Correlation	1.000	.215	-.009
	Sig. (2-tailed)	.	.282	.968
	N	27	27	24
STIRLING	Pearson Correlation	.215	1.000	.538**
	Sig. (2-tailed)	.282	.	.007
	N	27	29	24
LEUCHARS	Pearson Correlation	-.009	.538**	1.000
	Sig. (2-tailed)	.968	.007	.
	N	24	24	24

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.5 Correlation of rainfall statistics for the three sites

4.1.5. Thresholds

Threshold values were calculated for the three sites, on an annual basis, according to the method described in section 3.2.2. Dunstaffnage typically received 10% of its annual total in the sum of 4, 5 or 6 daily rainfall events, with the mode being 5, with 46% of years meeting the 10% quantile within the 5 largest daily events.

Stirling achieved the 10% threshold with 4 daily events 46% of the time and Leuchars showed exactly the same pattern. The year to year variability was greater in the Centre and East where the number of events ranged from 2 to 7 over the period considered.

The threshold values for the three sites were plotted, and a regression analysis performed to establish whether any linear trend was visible.

The results are illustrated in Figure 4.7, Figure 4.8 and Figure 4.9.

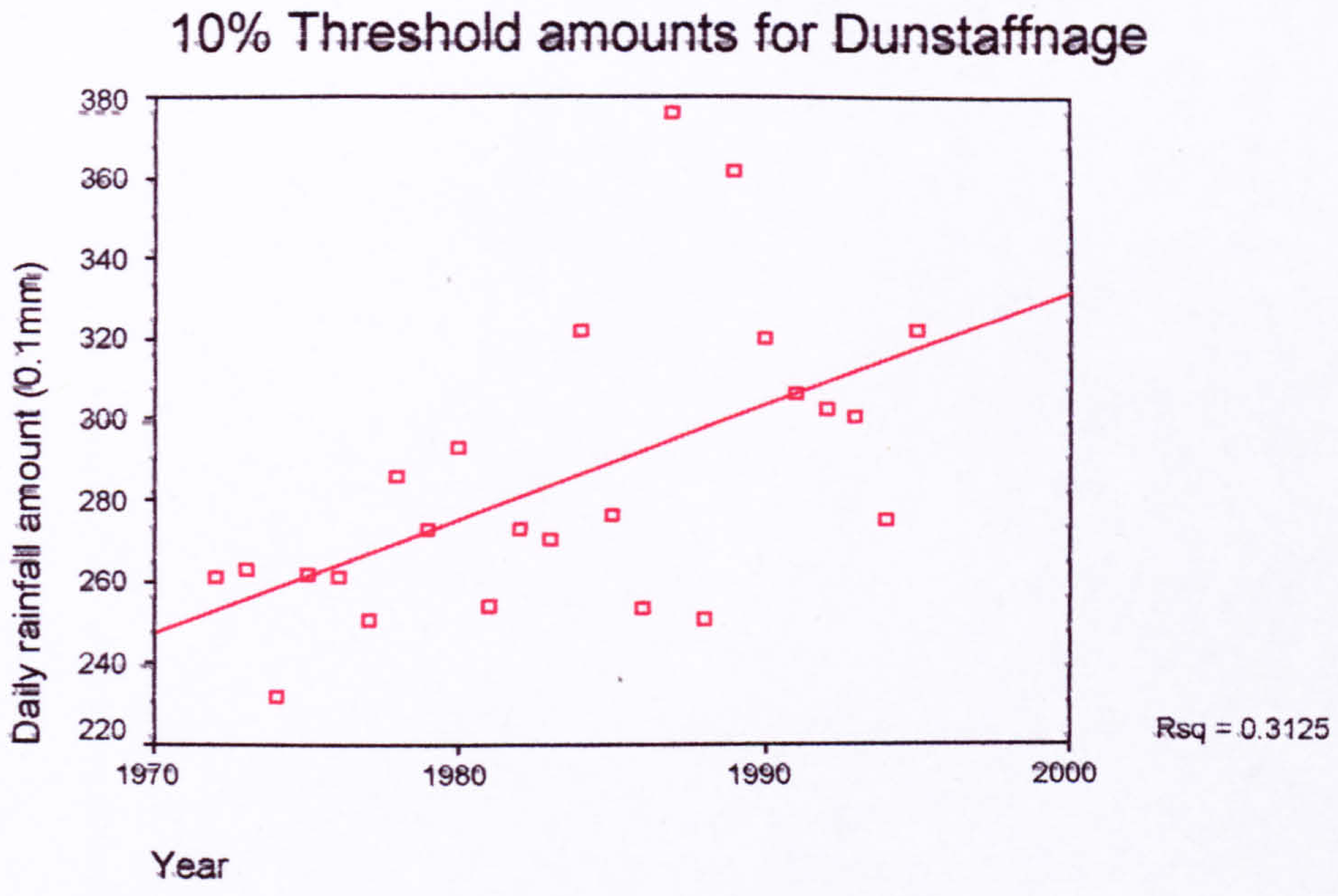


Figure 4.7 Threshold amounts for Dunstaffnage

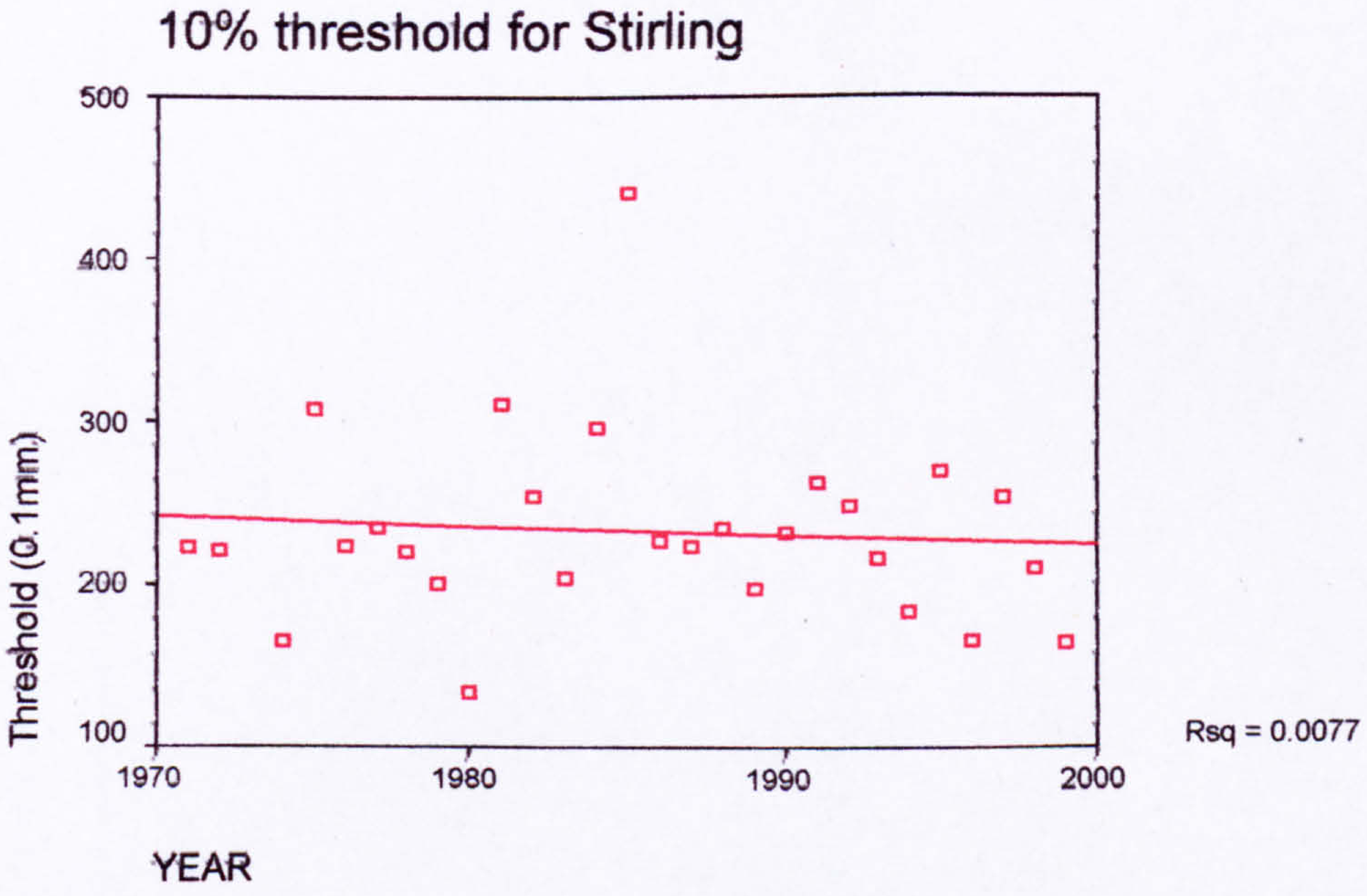


Figure 4.8 Threshold amounts for Stirling

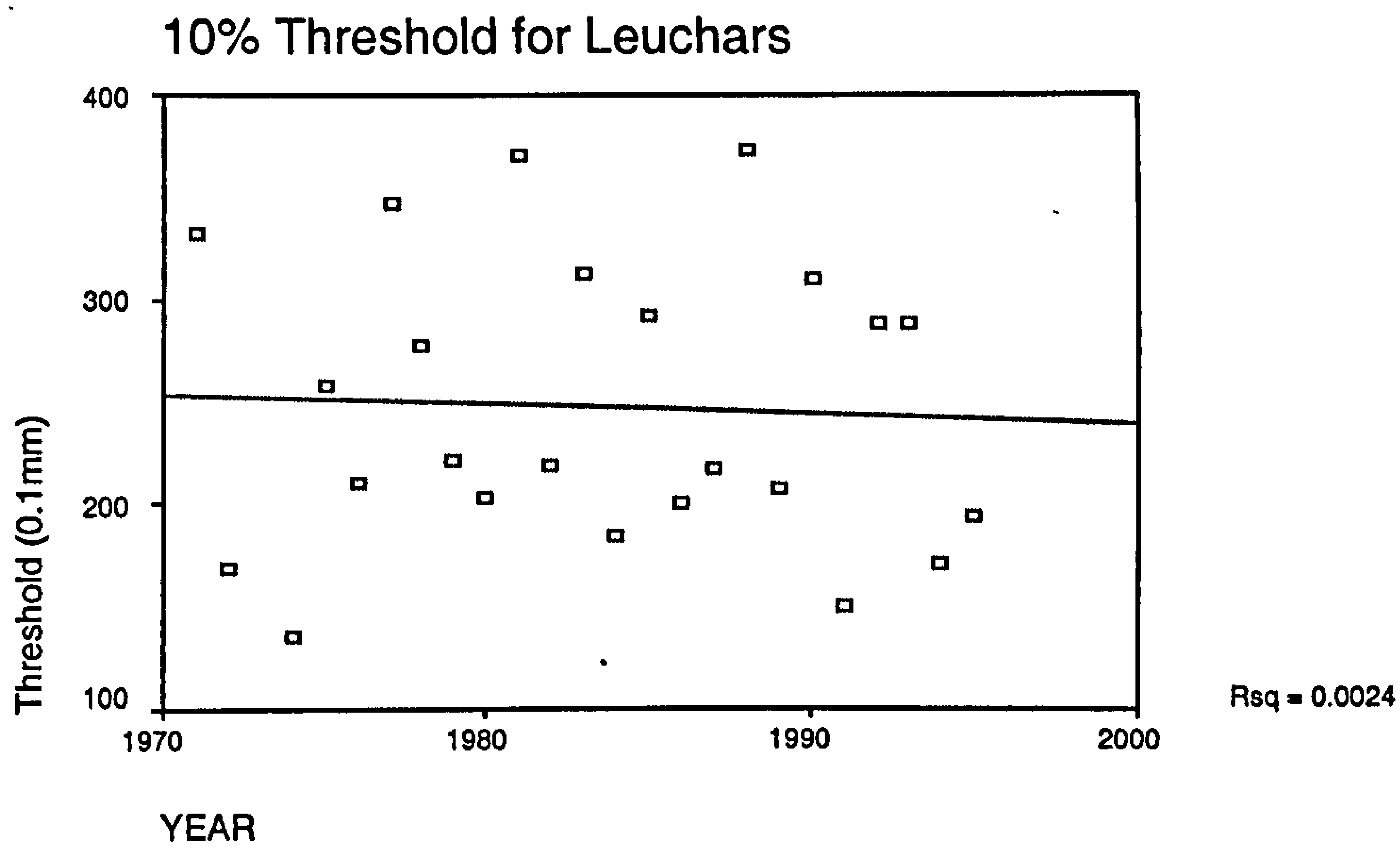


Figure 4.9 Threshold amounts for Leuchars

The linear regression equation for Dunstaffnage was significant at the 0.01 (n = 24) level and indicates an upward trend in the intensity of rainfall events, with the threshold increasing over the last three decades.

No similar trend was discernible from the statistics obtained from either Stirling or Leuchars, the trend being downwards in both cases and the significance of the regression equations being 0.675 (n = 28) and 0.675 (n = 24) respectively. This suggests that the equation is no better at predicting the threshold value than a measurement of the mean for the period under study. In both these cases the scatter graph can be interpreted as simply showing some variability around the mean value of the 10% threshold. Increased rainfall intensity appears to be confined to Dunstaffnage on the west coast.

4.1.6. Results for Windspeed

Given the quality of the data for Stirling, the analysis was restricted to the two sites on the East and West coasts. Data from Dunstaffnage was restricted to 1983-2000, whereas Leuchars had continuous data for the period 1957-2000.

Two seta of aggregated data were produced, one giving maximum, and the other mean, recorded daily windspeed. Analysis of the data from Dunstaffnage indicated no significant trends were visible, regression analysis produced a downward trend in mean daily windspeed (Figure 4.10) but this was not statistically significant. Similarly the analysis of maximum daily windspeed showed an upward trend but this was not statistically significant (Figure 4.11) (n = 16).

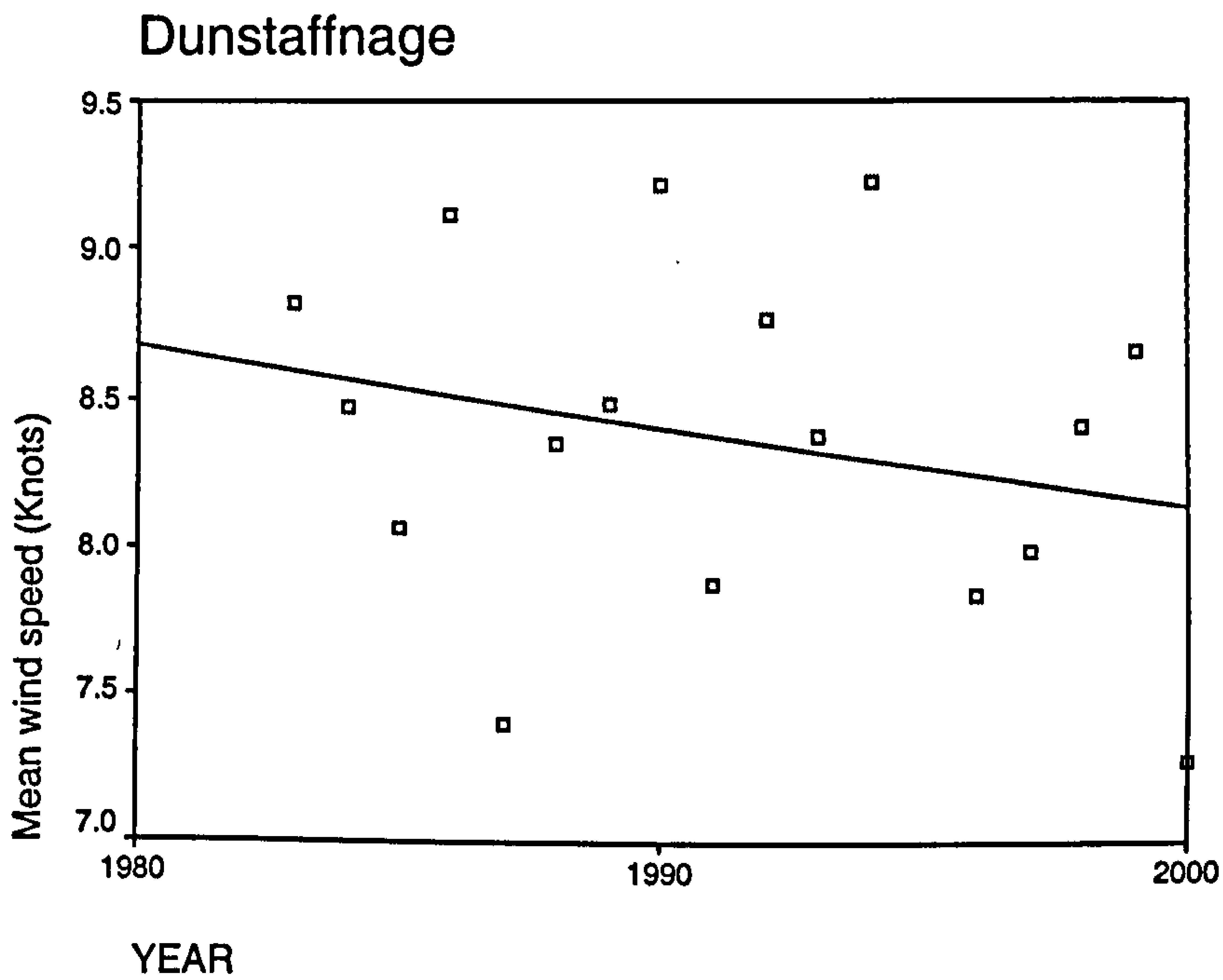


Figure 4.10 Mean windspeed at Dunstaffnage

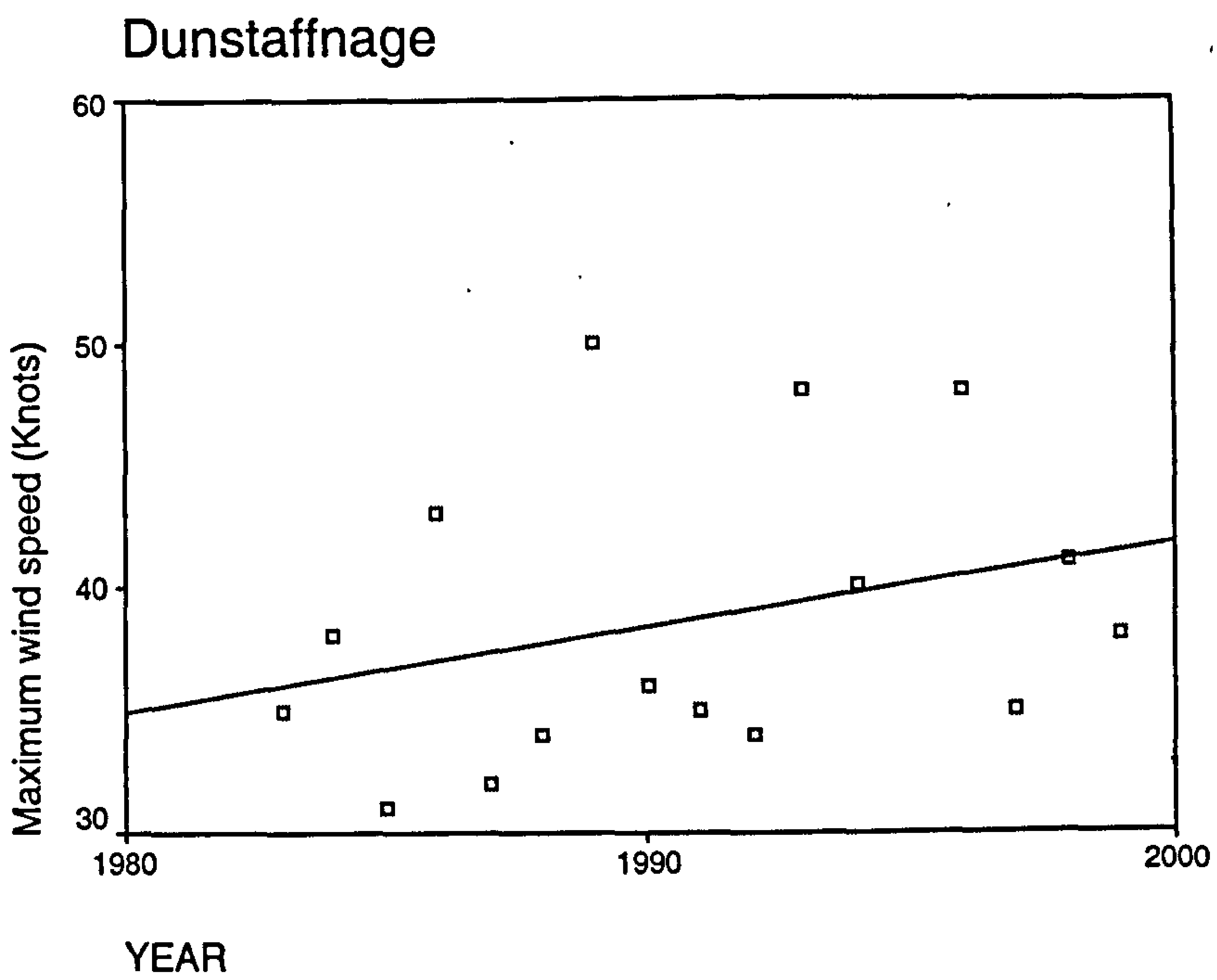


Figure 4.11 Maximum windspeed at Dunstaffnage.

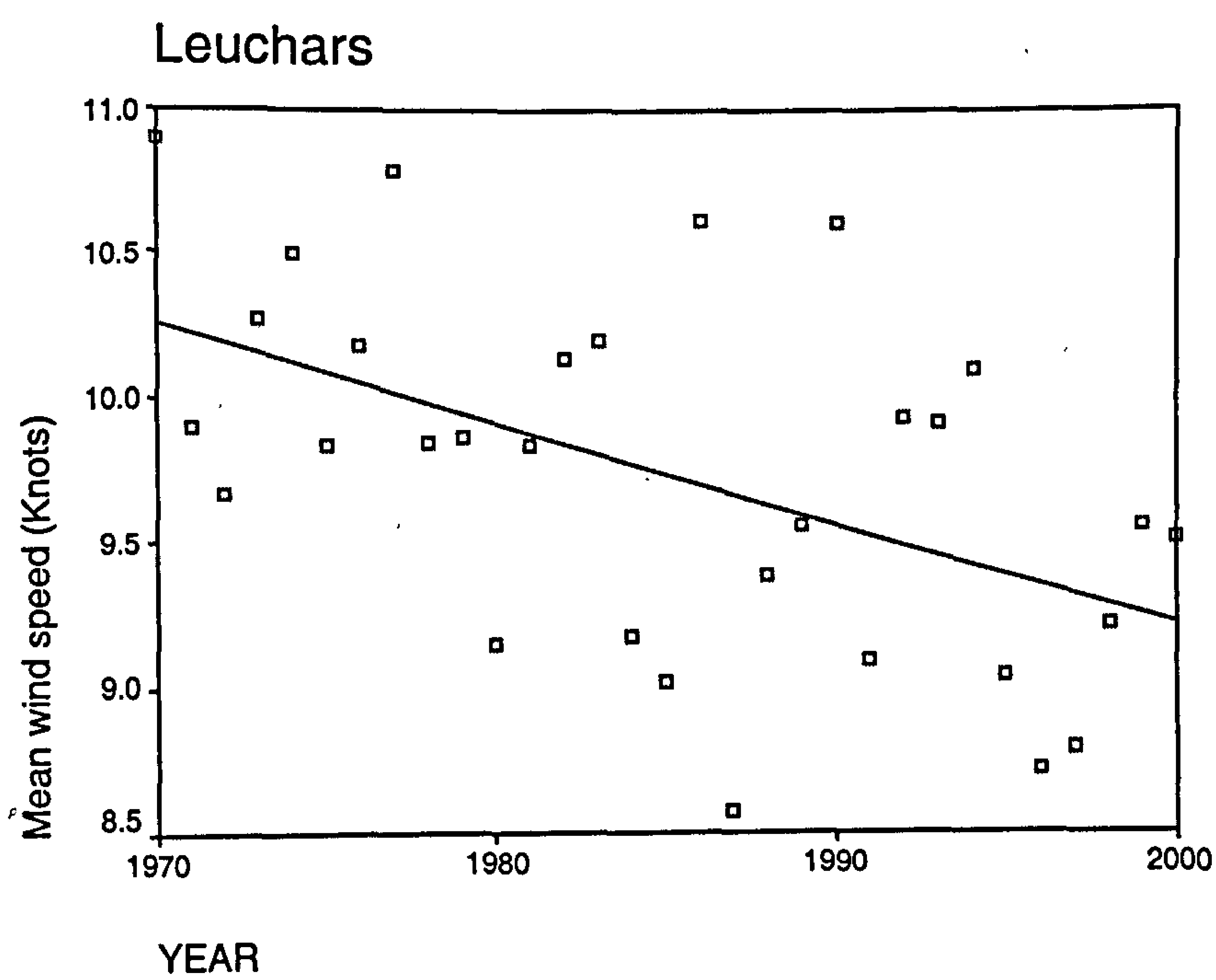


Figure 4.12 Mean windspeed at Leuchars

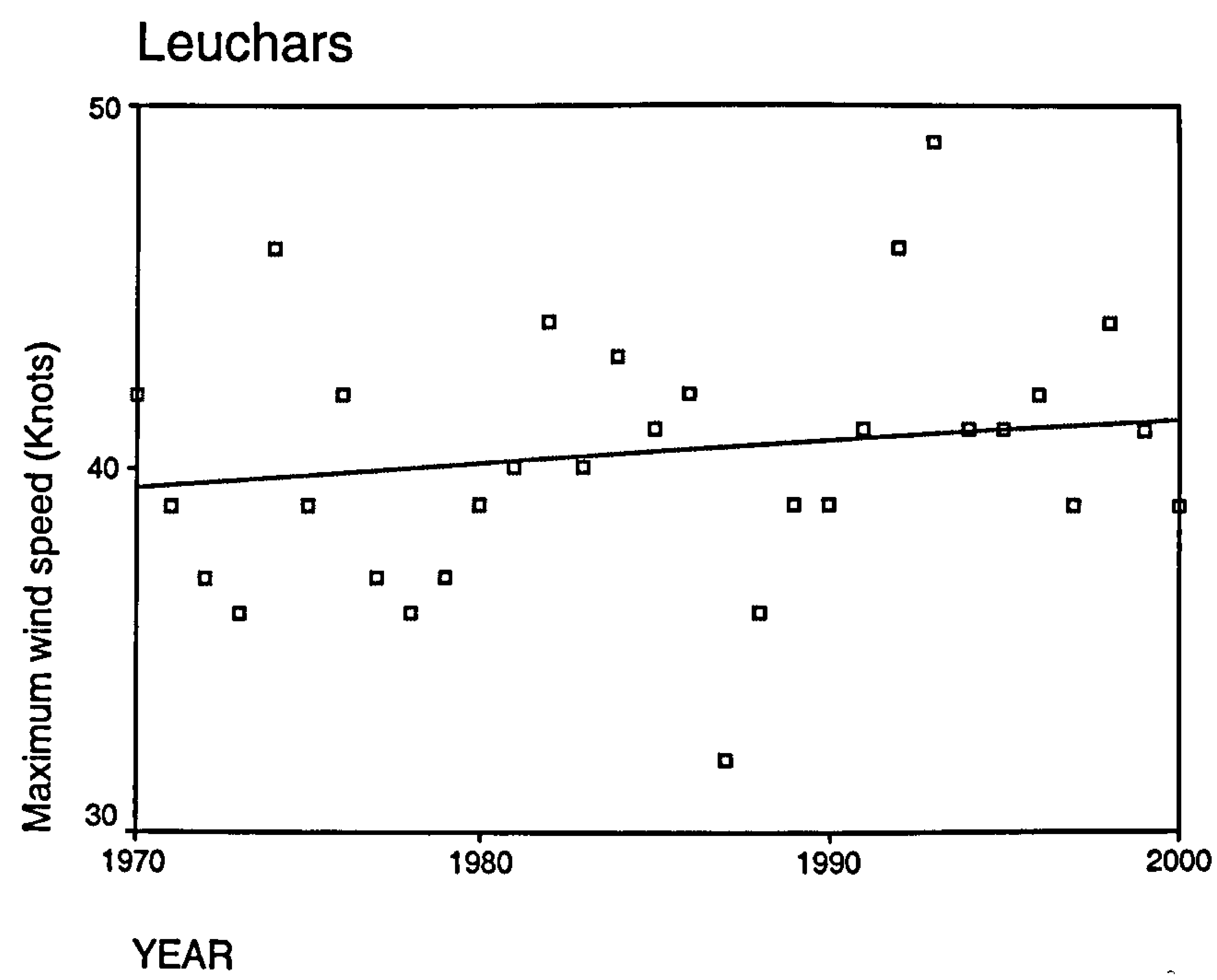


Figure 4.13 Maximum windspeed at Leuchars

This linear regression shown in Figure 4.12, was significant at the level of 0.05 (n = 31)and indicates a decrease in mean windspeed at this site.

The slight upward trend visible in the graph of maximum windspeed was, like the data from Dunstaffnage, not statistically significant (Figure 4.13).

4.1.7. Summary

The preliminary data analysis suggests that the local climate of the three regions of Scotland are indeed changing, With increasing temperatures and a longer growing season evident, increased intensity of rainfall in the west, and some suggestion of decreasing mean windspeed and increasing maximum windspeed. However this analysis must be seen as incomplete as it relies on just 3 sites. The next section involves a more detailed analysis, involving a larger number of sites from each of the regions, and attempts to identify the trends as well as the factors which are possibly influencing the climate of central Scotland.

4.2. Results of Analysis of meteorological data; Temperature

4.2.1. Argyll

The five sites used for Argyll are Dunstaffnage, Benmore, Aros, Machrihanish and Tiree. Figure 4.14 shows mean annual temperatures for all five of the sites. This shows considerable variability from year to year but also indicates the close correlation between the temperature of these sites.

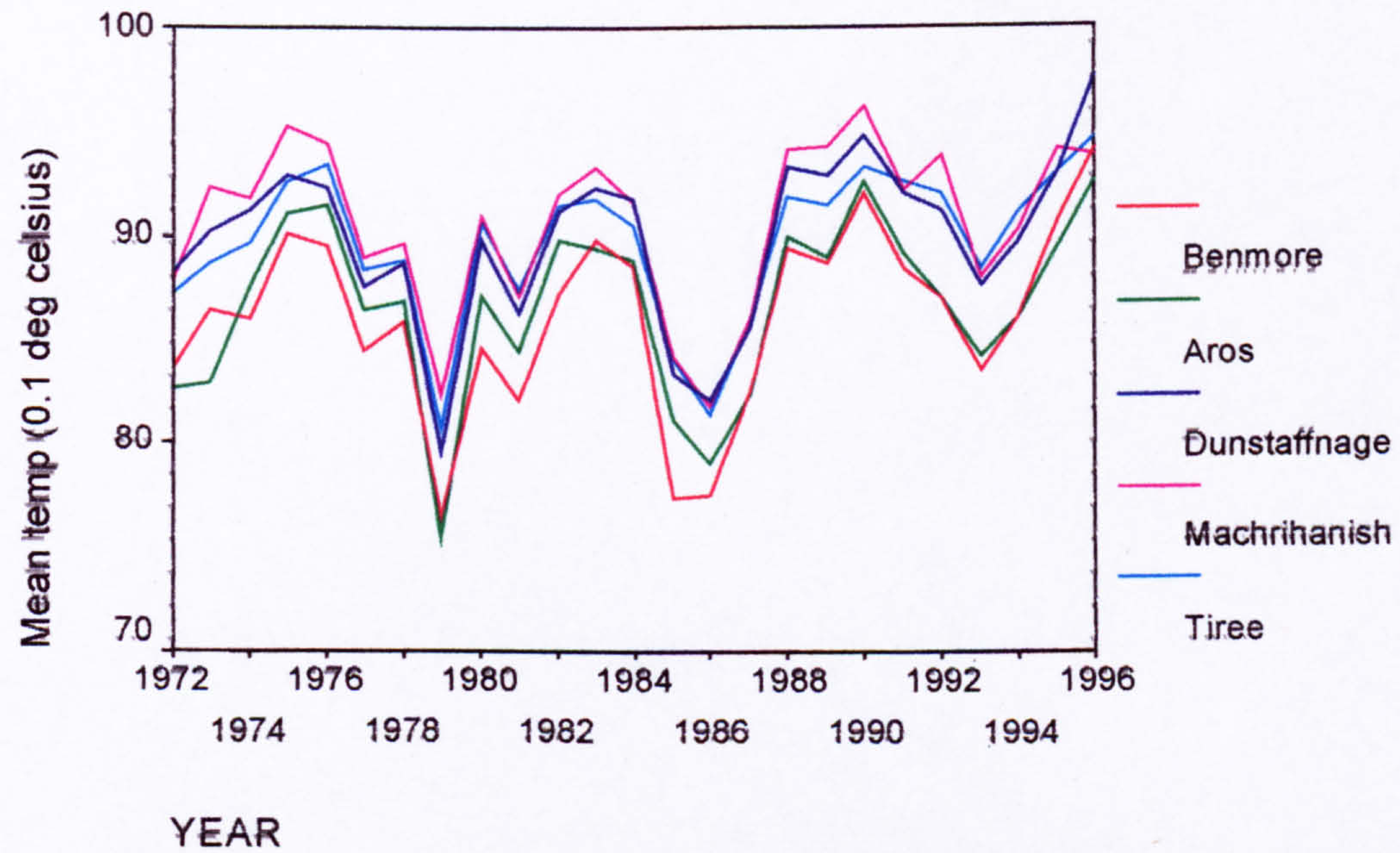


Figure 4.14 Mean daily temperature for the Argyll sites

The mean annual temperature differs by a maximum of approximately 0.5°C, with Machrihanish consistently the warmest site. Close to Machrihanish are both

Dunstaffnage and Tiree, suggesting that proximity to open water rather than latitude is the greatest influence on temperature. Benmore and Aros are both somewhat inland and are also consistently cooler.

Consideration of seasonal temperature reveals a pattern of differences between the sites and is illustrated in Figure 4.15.

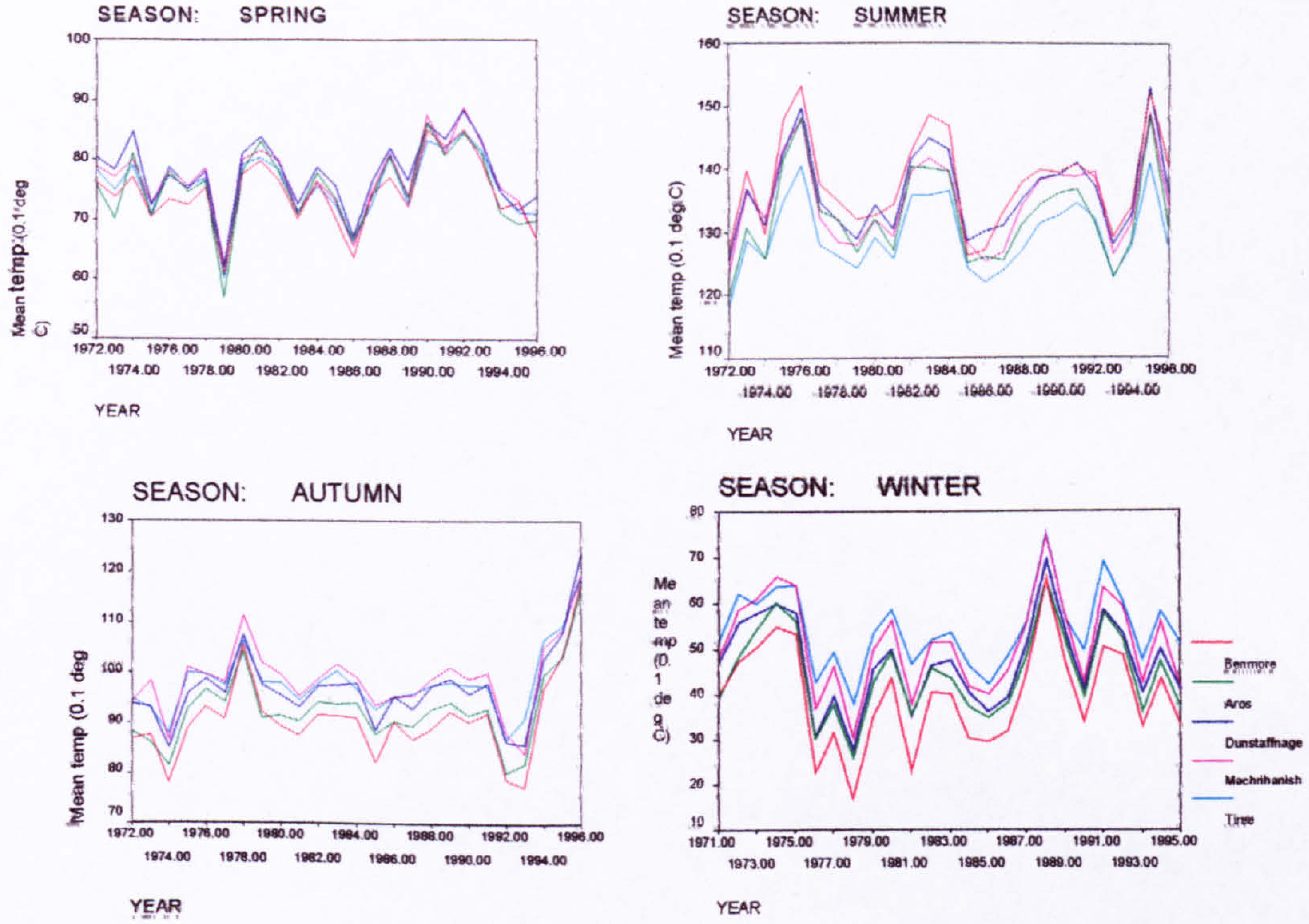


Figure 4.15 Seasonal patterns of mean daily temperature for the Argyll sites

All five sites show very similar spring temperatures, with very little variation between them. Summer however shows the more inland site of Benmore with regularly higher temperatures and the outlying site of Tiree remaining the coolest during the summer months. Autumn has the coastal sites remaining warm and the inland sites cooling more rapidly and this pattern is reflected in the graph representing winter temperatures, where Benmore is consistently the coolest and Tiree the mildest.

Although the differences in mean temperature are significant, all the sites show a similar pattern of warming and cooling, their close proximity to one another suggesting that the temperature regime across the region is very similar, without any factors affecting some sites but not others. The regional mean daily temperature was calculated by taking the arithmetic mean of the values for each of the five sites.

Figure 4.16 shows a regional mean annual temperature which will be used for future comparisons and as part of the regional profile.

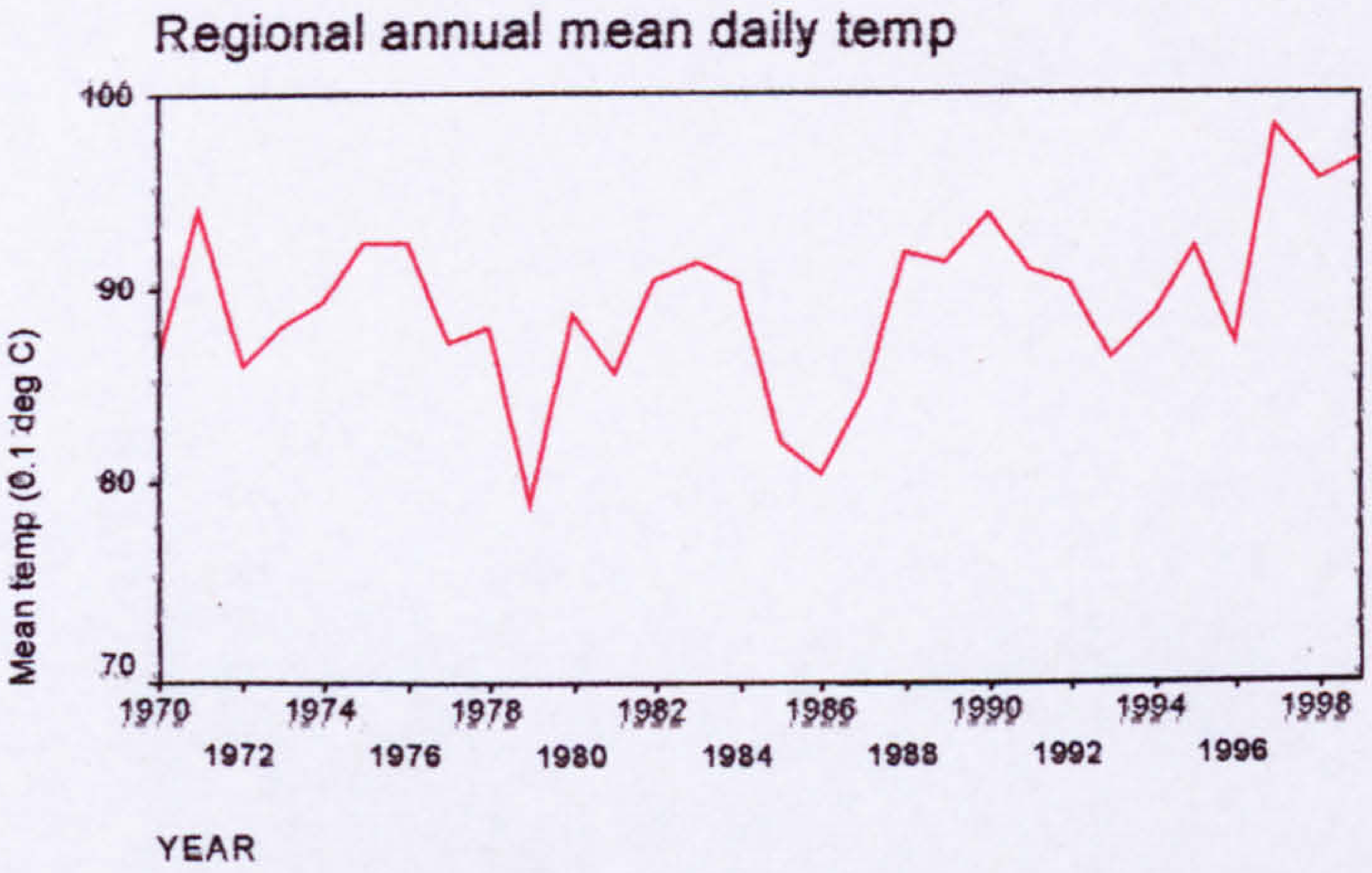


Figure 4.16 Regional mean daily temperature for Argyll

4.2.2. Trends in the temperature data

A linear regression was performed using the mean daily temperature as the dependent variable and the year as dependent. This was done for each of the individual sites, and then for the data relating to the regional mean figures. The results are shown in Table 4.6 below. The coefficient generated by the regression represents the rate of change of temperature with respect to time, (the gradient of the line of best fit).

SITE	COEFFICIENT	N =	SIGNIFICANCE
Benmore	0.182	10833	< 0.01 R^2=0.001
Aros	0.0936	9800	Not significant at 0.05 R^2=0.001
Dunstaffnage	0.267	10150	< 0.01 R^2=0.002
Machrihanish	0.0905	10955	< 0.05 R^2=0.001
Tiree	0.142	10953	< 0.01 R^2=0.001
Regional Mean	0.167	9344	< 0.01 R^2=0.001

Table 4.6 Results of regression analysis for Argyll sites; Temperature

The mean temperature of the region would appear to have been rising over the period of the study by approximately 0.17 °C per decade. All regression equations had a very low R^2 value (< 0.01) suggesting, as might be expected, that the variability of the data due to other factors, such as seasonality, is far greater than the variability due to any warming trend. To investigate the seasonal trends a linear regression was performed on the seasonal subsets of the data (n = 2666). The results are shown below in Table 4.7.

SITE	Spring	Summer	Autumn	Winter
Benmore	0.295**	0.103	0.097	0.175*
Aros	0.108	0.030	0.163	0.010
Dunstaffnage	0.250**	0.203**	0.360**	0.197**
Machrahanish	0.190**	0.116*	0.034	0.049
Tiree	0.206**	0.097**	0.170**	0.120*
Regional Mean	0.246**	0.126**	0.176*	0.145*

** denotes significant at 0.01 * denotes significant at 0.05

Table 4.7 Regression analysis for Temperature on a seasonal basis; Argyll

The strongest evidence of a warming trend comes from springtime, with all sites except Aros showing a significant increase in temperature over the period of the study. The more coastal sites also show a significant though weaker warming trend in the summer and three of the sites show a less pronounced warming trend in the winter.

The results from the mean temperature data reflects these trends, though significant warming occurs in all seasons, by far the strongest trend occurs in spring.

4.2.3. Degree-days.

The number of degree-days is often used as a measure of the growing season, giving an indication of its length and intensity, and can be used to determine which crops are suitable for a given location. Taking a figure for mean daily temperature of 6°C as being the minimum necessary for growth, all daily records are then taken and the sum of degrees Celsius above this level taken for the whole year. The number of degree days for each site is shown in Figure 4.17.

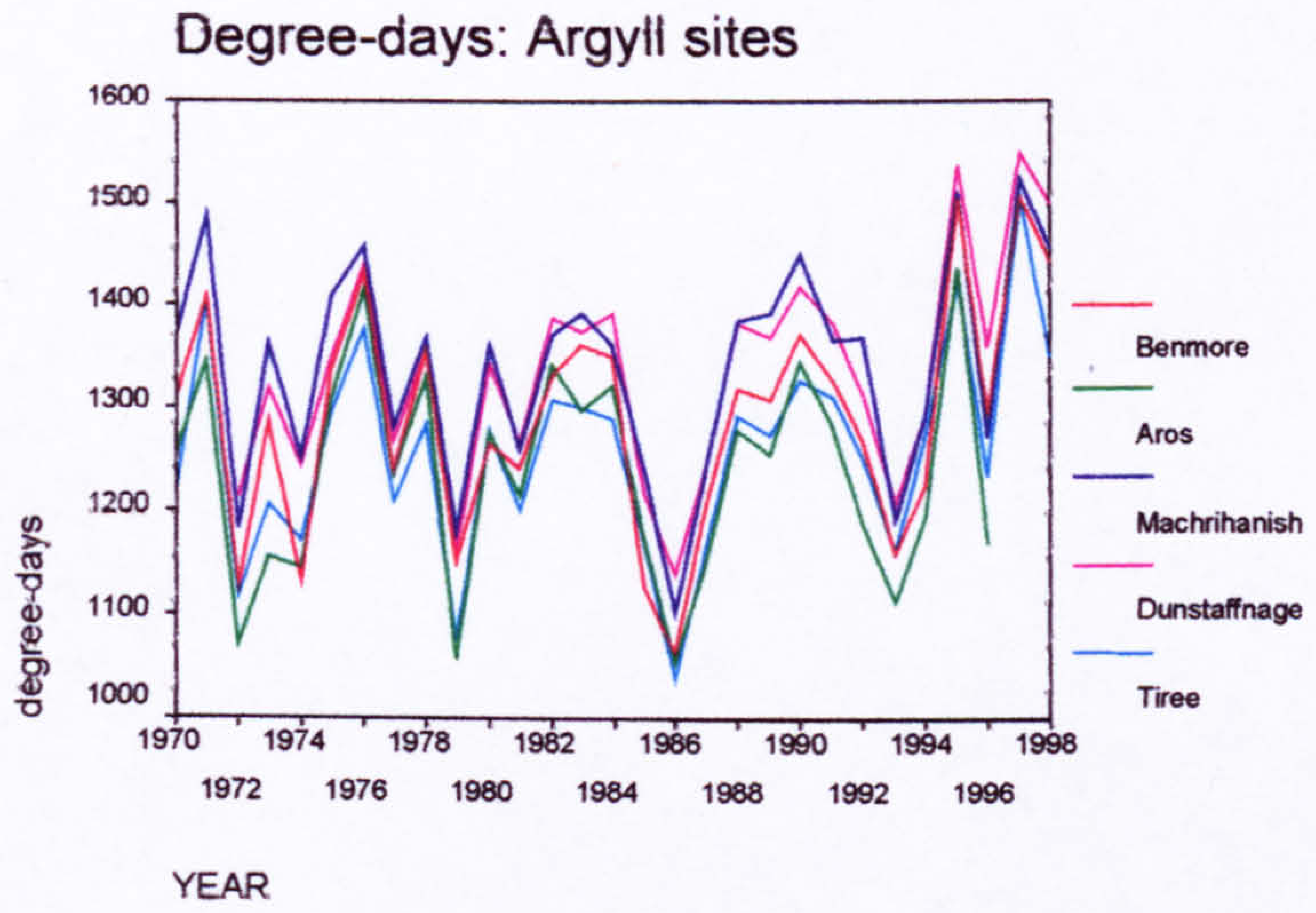


Figure 4.17 Degree days for Argyll sites

. Considerable variability is evident, as with the temperature records themselves, though if a warming trend is visible then the number of degree-days ought to be showing a similar upward trend.

Aros and Tiree are consistently lower than the other sites, with the most southerly site at Machrihanish regularly experiencing the maximum number, closely followed by Dunstaffnage.

Poor years would appear to be experienced with a regular period of seven years, with 1972, 1979, 1986 and 1993 all showing close to 1100 degree-days, whereas the maximum figure is regularly over 1300 degree-days.

Analysis of annual totals using linear regression produced trends which were significant at the 5% level for just two of the sites, Dunstaffnage and Tiree, with Dunstaffnage showing an annual rise of 5.6 degree-days and Tiree 5.1, the respective levels of significance being 0.028 and 0.039 (n = 29).

Taking the mean figure for the region, a seasonal split in the data revealed significant trends, summarised in Table 4.8. This shows the strongest trend in spring, with summer and autumn having a similar and slightly lower rate of increase.

Season	coefficient	significance
Spring	0.019	0.000
Summer	0.013	0.006
Autumn	0.012	0.033
Winter	0.003	0.254

Table 4.8 Regression analysis of degree days; results for Argyll on a seasonal basis

Analysis of monthly totals produced significant results, indicating the months in which warming is taking place (n = 29). These are summarised below in Table 4.9.

Month	Feb	March	April	July	Aug	Sept	Nov	Dec
Coefficient	0.017**	0.022**	0.019**	0.023**	0.014*	0.022**	0.021**	-0.011*

** denotes significant at 0.01   * denotes significant at 0.05

Table 4.9 Regression analysis of degree days; monthly basis

December shows a cooling trend, with fewer degree-days. All the other seven months with significant trends indicate an increase in degree-days, with March, July, September and November showing the strongest tends. This points to an extension of the growing season, starting earlier in spring and extending further into the Autumn.

4.2.4. Stirling

Figure 4.19 shows the seasonal mean daily temperatures for these sites. Aberfoyle shows the lowest temperatures for all seasons with the exception of winter, when Stirling Parkhead regularly experiences mean temperature very close to those of Aberfoyle. The difference in temperature between Grangemouth and Aberfoyle is typically around 1°C, a significant difference for two sites only 30 km apart.

The Grangemouth site is close to a major petrochemical works, and a heat island effect may in part explain the elevated temperatures. This difference in temperature appears greatest during the summer and autumn. Calculating the difference between mean monthly figures for the three sites shows a pattern of temperature differences which is not apparent from these graphs.

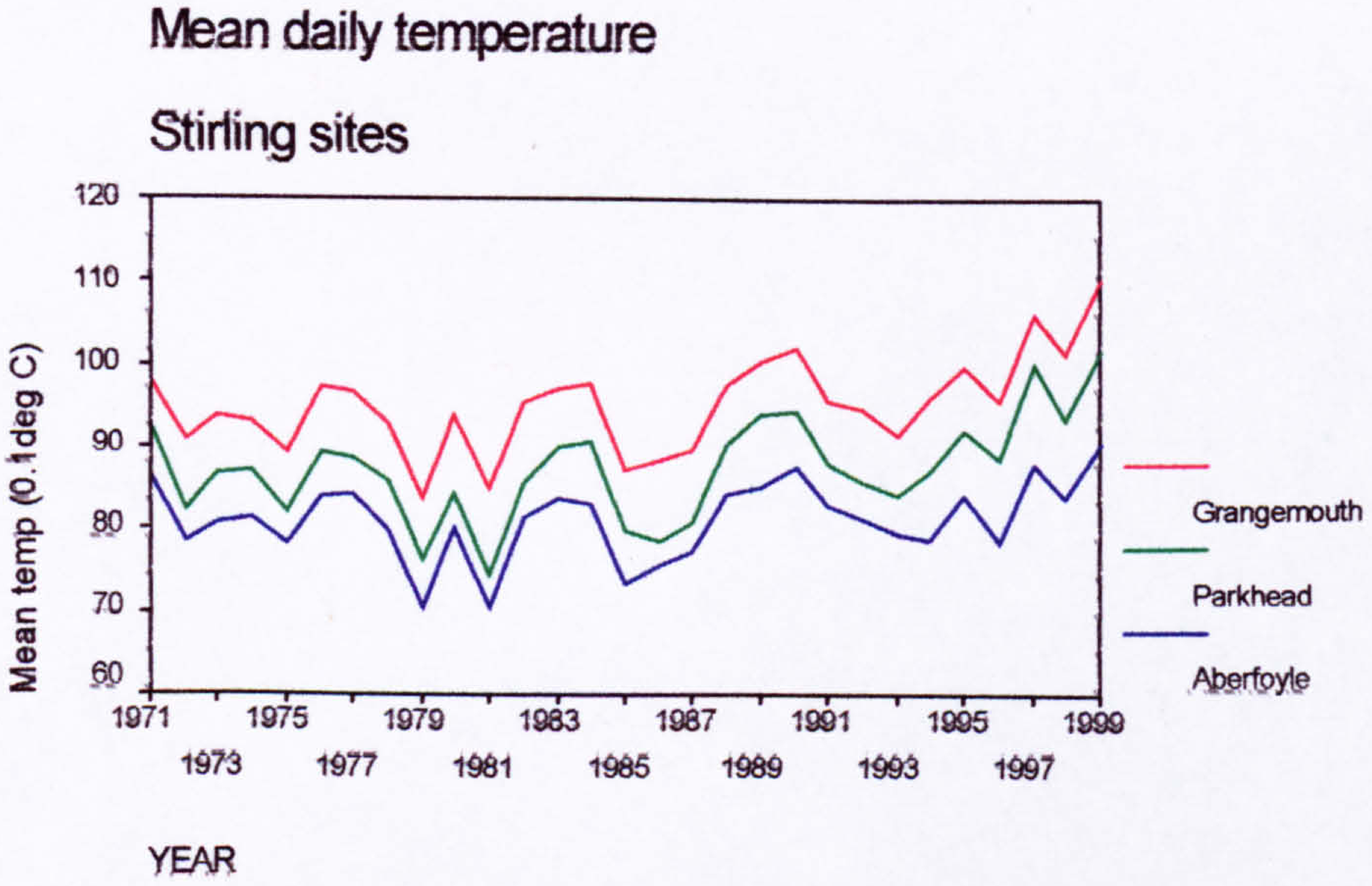


Figure 4.18 Mean daily temperature for the Stirling sites

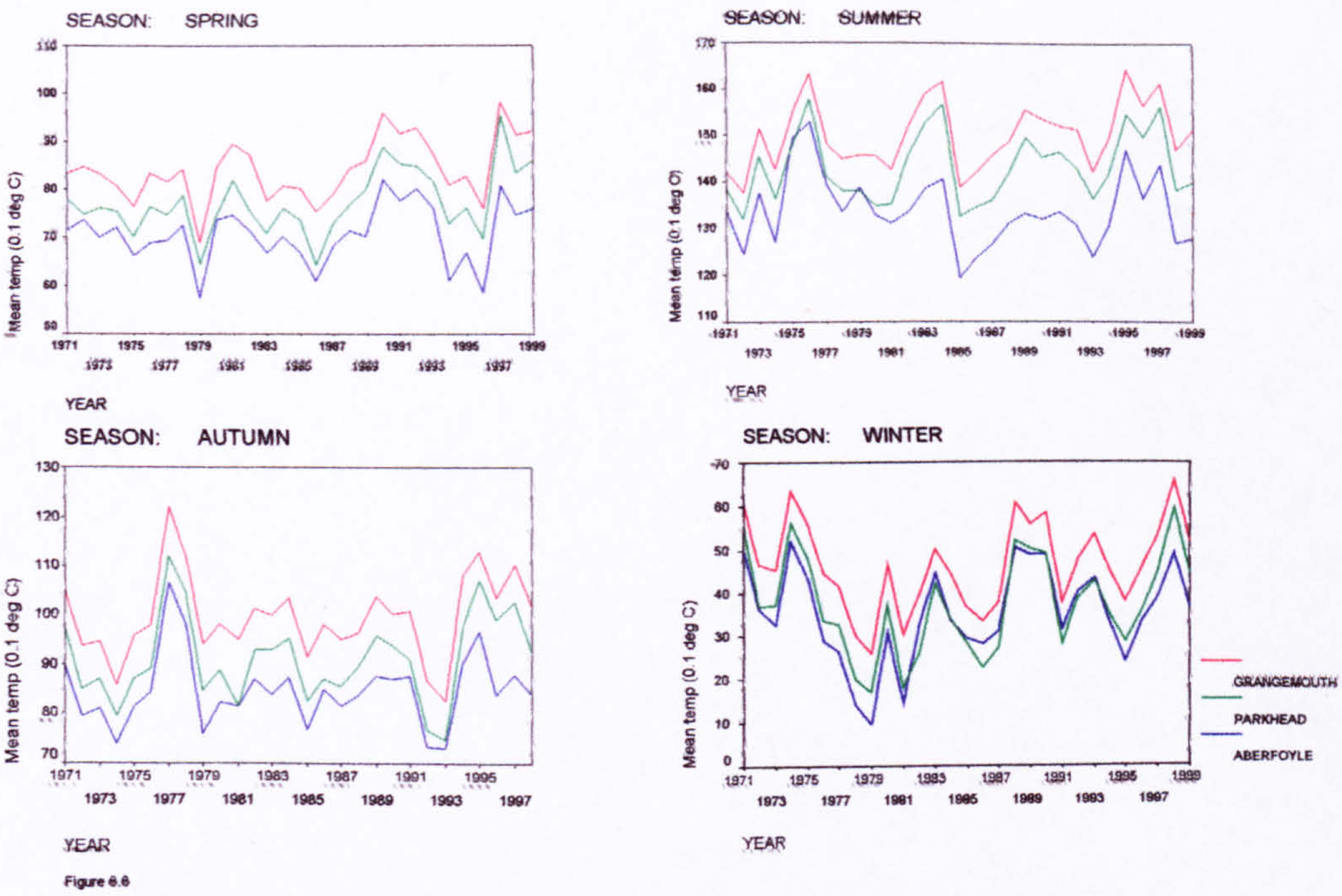


Figure 4.19 Mean daily temperature for Stirling sites on a seasonal basis

Figure 4.20 indicates that between the sites at Stirling and Grangemouth, and between Grangemouth and the site at Aberfoyle in the West, a change in the pattern of temperature emerges. Grangemouth and Stirling Parkhead show a relatively constant difference, with little variation throughout the year. Aberfoyle however shows a marked difference to Grangemouth, with the difference greatest in the late summer and early autumn. Warm summer conditions further East are not matched by the records from Aberfoyle.

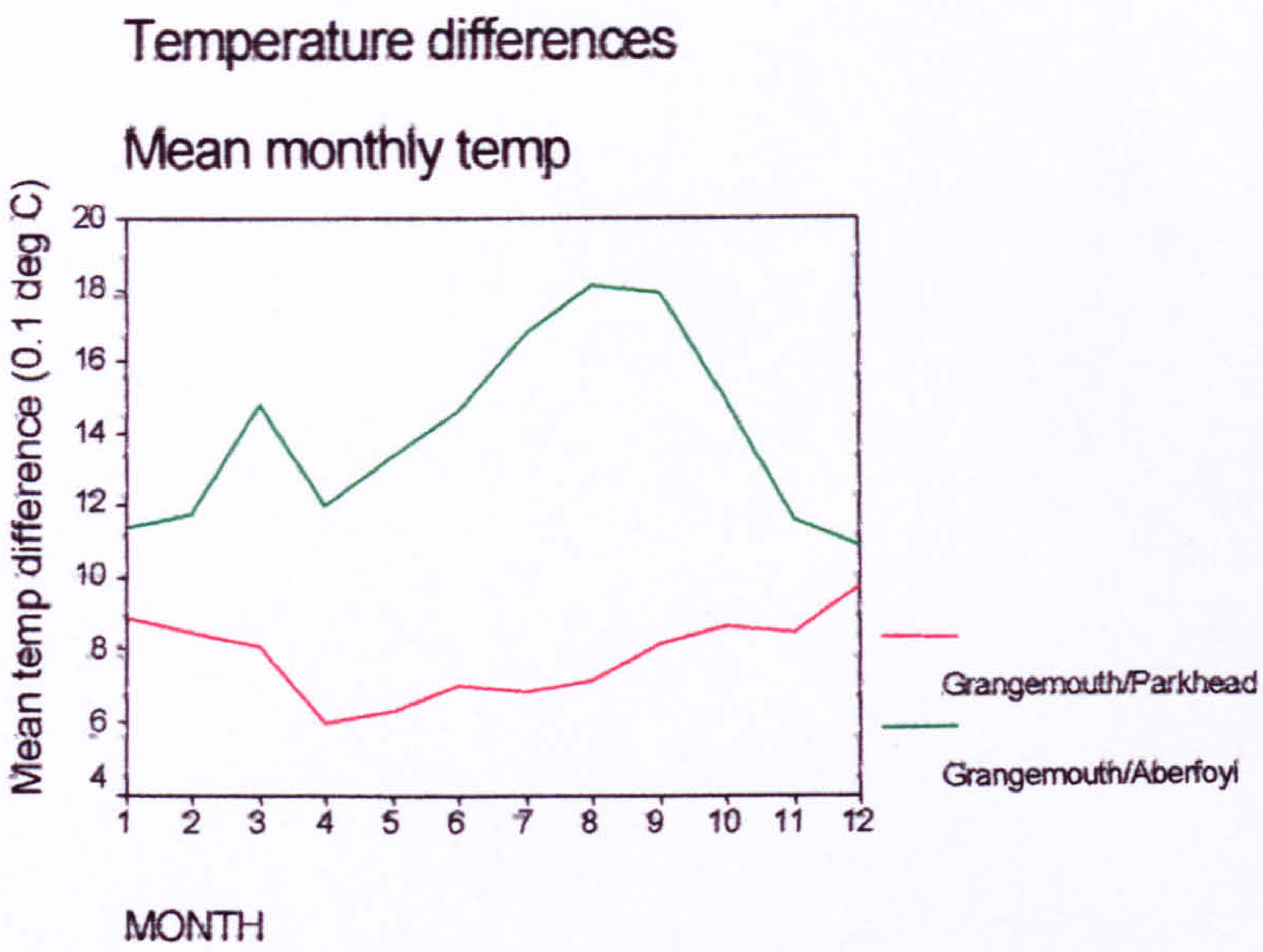


Figure 4.20 Temperature differences through the year. Grangemouth/Parkhead and Grangemouth/Aberfoyle

The mean difference in temperature between Grangemouth and Stirling is roughly 0.8°C all year round. The difference between Grangemouth and Aberfoyle however reaches approximately 1.8°C in August and September and is never less than 1°C at any point in the year. This would suggest that the length of the growing season is likely to be shorter in the more northern and western parts of Stirling district.

4.2.5. Trends in the data

Linear regression, performed on the mean daily temperature records for the region of Stirling, suggests, as with Argyll, that a warming trend exists in the data. The results are summarised below in Table 4.10. Stirling and Grangemouth show a very similar warming trend, but the data from Aberfoyle suggests that this is not uniform across this region. The figure for the mean daily temperature from the three sites shows an upward trend stronger than for any individual site.

SITE	Coefficient	N =	Significance	
Grangemouth	0.284	10555	< 0.01	R^2=0.002
Stirling Parkhead	0.272	10585	< 0.01	R^2=0.002
Aberfoyle	0.076	10555	0.186	R^2=0.001
MEAN	0.345	10496	< 0.01	R^2=0.000

Table 4.10 Regression analysis; temperature for Stirling sites

These coefficients suggest a stronger warming trend in the Stirling region than in Argyll to the west, with the mean figure showing a rise in mean temperature of 0.345°C per decade. Analysis based on seasonal subsets of the data reveals evidence of trends as presented in Table 4.11.

SITE	Spring	Summer	Autumn	Winter
Grangemouth	0.320**	0.271**	0.328**	0.183*
Stirling	0.344**	0.188**	0.324*	0.172*
Aberfoyle	0.062	-0.143*	0.186*	0.166 (sig 0.056)
MEAN	0.203*	0.105	0.285**	0.135

***** significant at 1%   * significant at 5% n = 2666***

Table 4.11 Coefficients from regression analysis for Stirling; seasonal

The results from Stirling Parkhead and Grangemouth show a similar pattern, the results from Aberfoyle being less strong and in fact giving evidence of a slight cooling trend during the summer months. When the mean figure is taken for the region this gives evidence of a strong warming trend in Autumn and in Spring with the other seasons showing trends which are not significant at the 5% level. As with the annual results there is a very low value of R^2 indicating that the regression equation does not explain much of the variability in the temperature data.

4.2.6. Degree-days

The number of degree-days for each of the three Stirling sites is show in Figure 4.21. The difference between the site with the largest total, Grangemouth, and Aberfoyle with the lowest total, is quite marked. There is a greater difference than between the sites in Argyll.

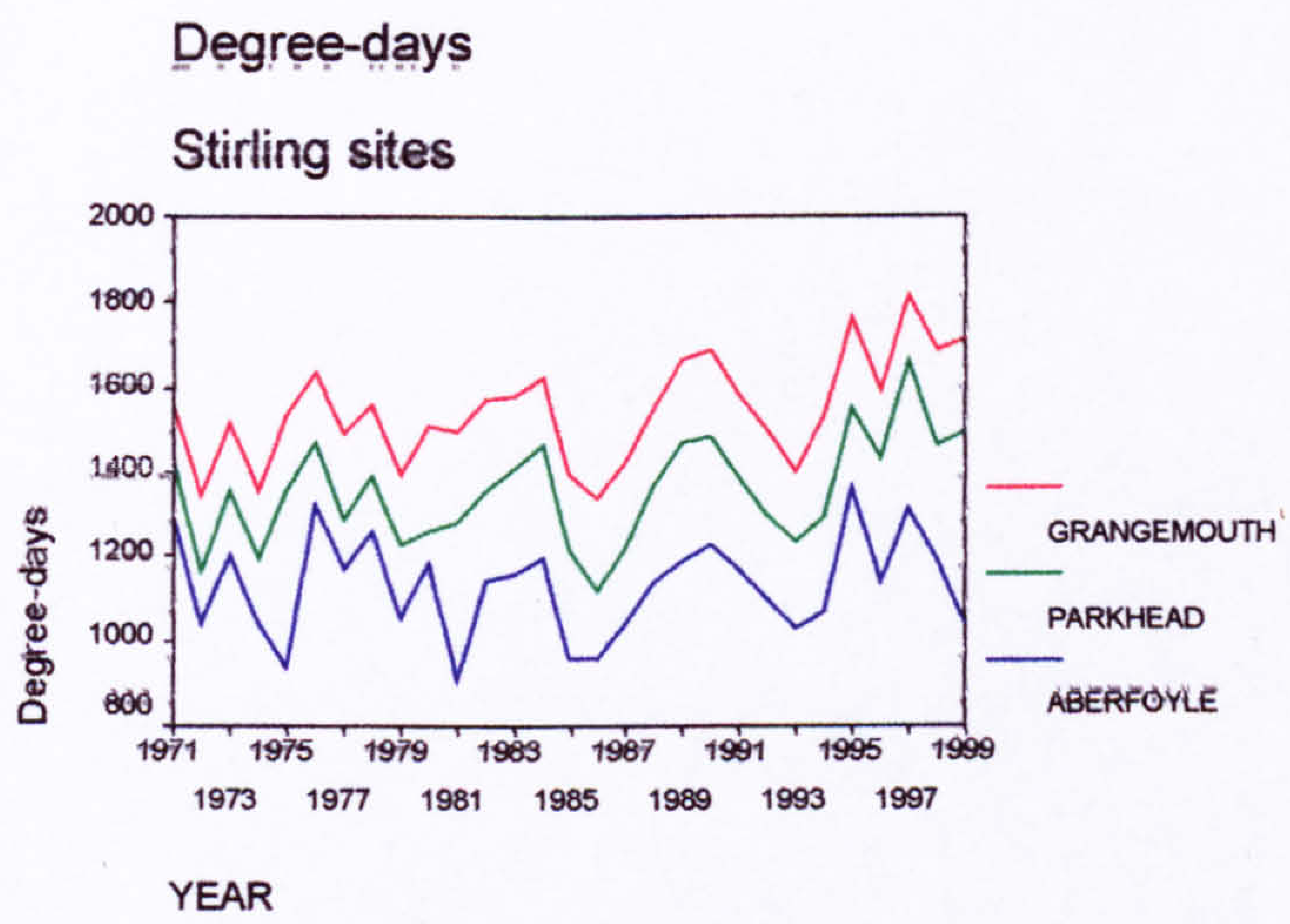


Figure 4.21 Degree days at the Stirling sites

Analysis of these annual totals using linear regression produced regression equations which were significant at the 5% level for both Stirling and Grangemouth, with coefficients of 6.29 and 7.35 respectively. This suggests that the number of degree-days is increasing by approximately 7 per annum in both sites. The data for Aberfoyle showed no significant trend.

On a seasonal basis the mean number of degree-days for the three sites showed a significant (5% level) increase in both Spring and Autumn, the coefficients and hence the strength of the trends being 0.219 and 0.212 respectively ($n = 29$).

Analysing the monthly trends produced significant trends in 7 months and these results are summarised below in Table 4.12.

Month	February	March	April	May	September	November	December
Coefficient	0.163**	0.217**	0.188*	0.249*	0.264**	0.216**	-0.119*

** significant at 1% * significant at 5% n = 29

Table 4.12 Regression analysis degree days at Stirling sites; monthly basis.

March, May, September and November show the strongest evidence of warming, and against the pattern December shows a slight downwards trend in the number of degree-days.

4.2.7. Fife

The mean annual temperature for the four sites in Fife is shown below in Figure 4.22. This shows a close similarity in annual mean for three of the sites. Kinross, with both the highest elevation and the furthest distance inland, has a consistently lower mean annual temperature.

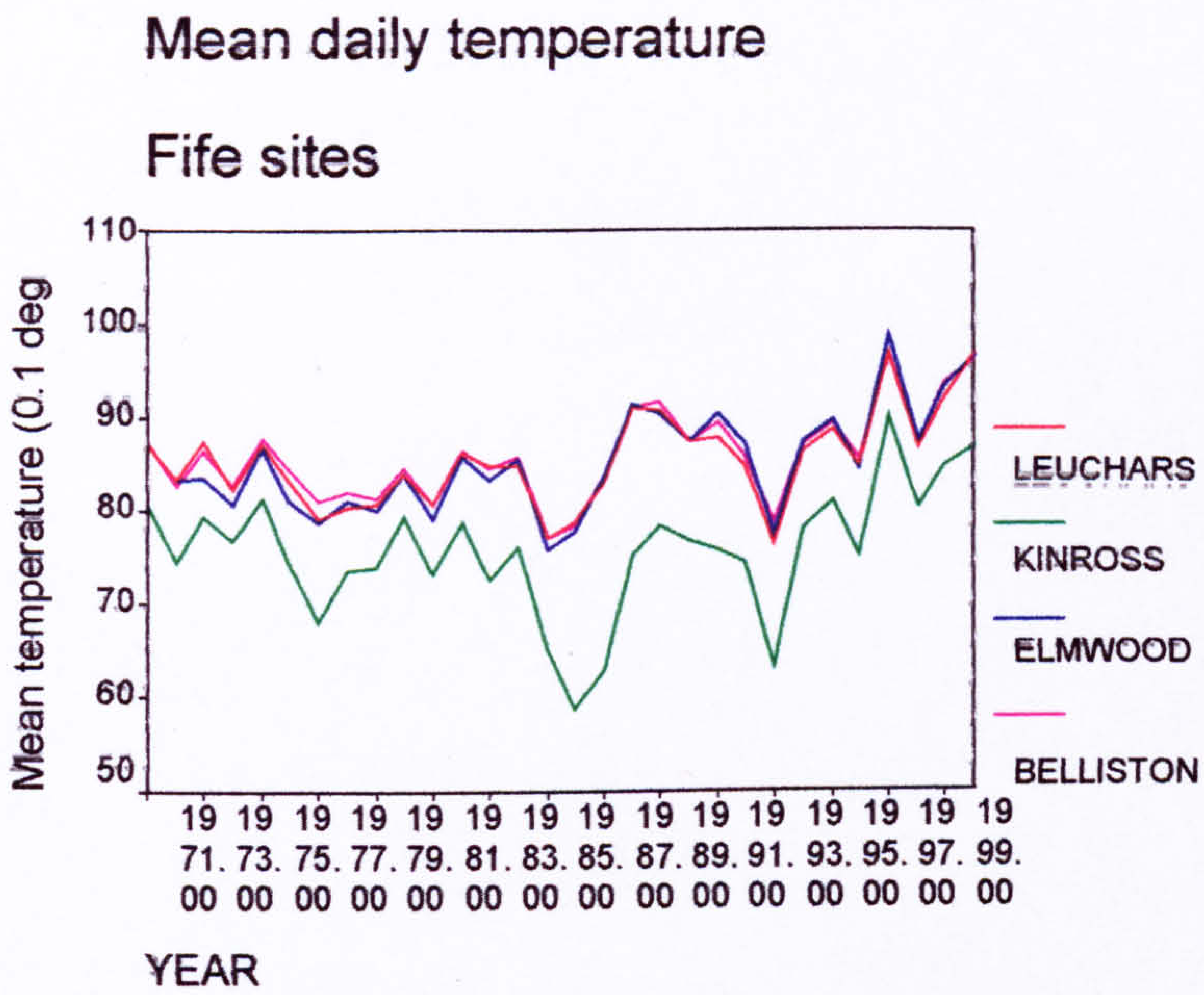


Figure 4.22 Mean daily temperature for the Fife sites

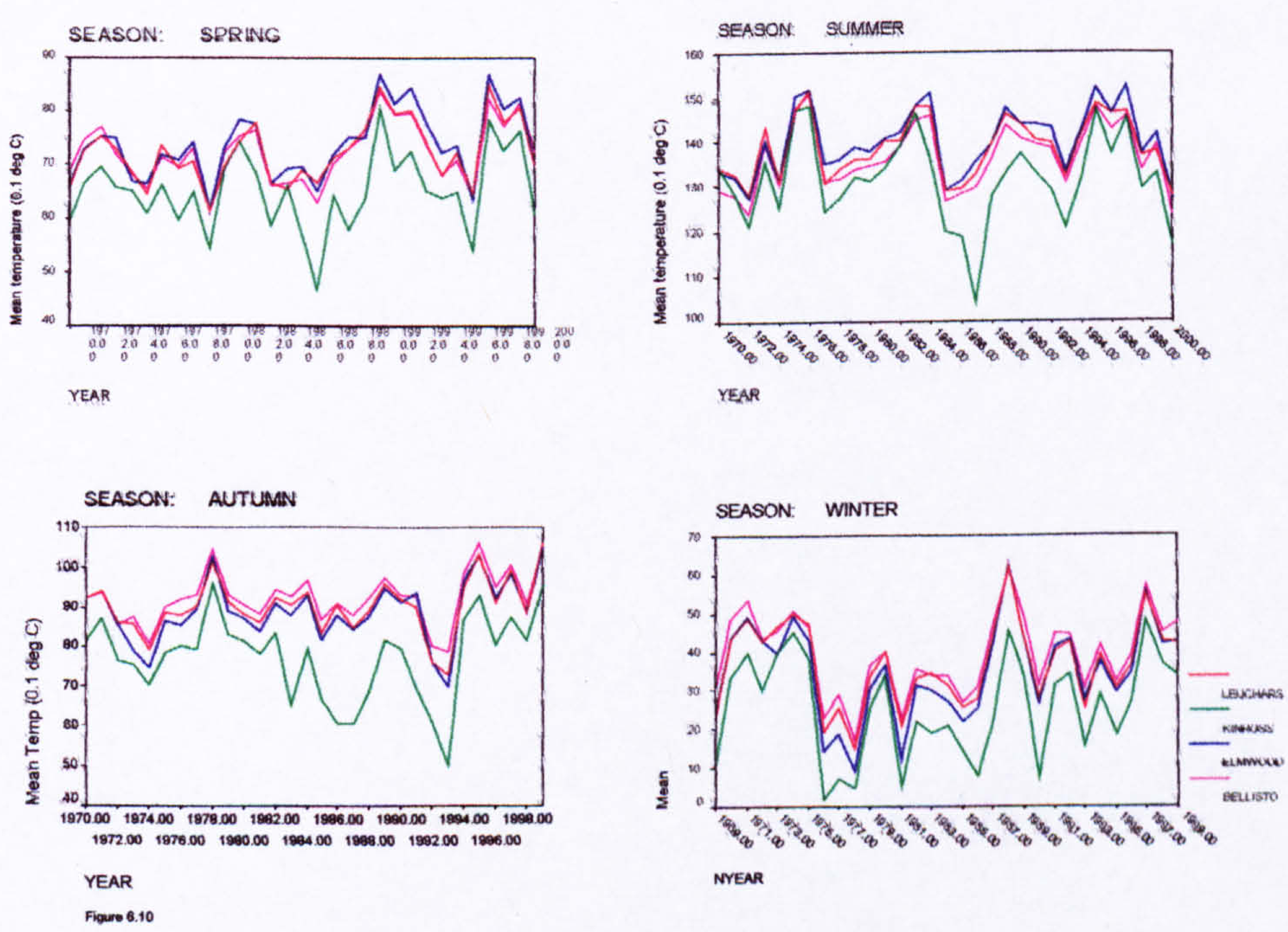


Figure 4.23 Mean daily temperature for the Fife sites on a seasonal basis

Figure 4.23 shows the seasonal mean daily temperature for the Fife sites, with Kinross showing cooler conditions for all four seasons. This is particularly noticeable in Autumn, where there appears to be the greatest difference between the sites. The similarity between the other sites is clear, with Elmwood showing greater variability, regularly being the warmest site in Spring and Summer but being the coolest in Autumn and Winter.

4.2.8. Trends in the data

Analysis of the mean daily temperature data for the four sites, using linear regression, produced evidence of warming. Taking all daily measurements regression analysis produced equations with the following coefficients, and at the given level of significance, as summarised in Table 4.13.

SITE	Coeficient	N=	Significance
Leuchars	0.271	11131	< 0.01 R^2=0.002
Kinross	0.170	10348	0.01 R^2=0.001
Elmwood	0.355	9670	< 0.01 R^2=0.004
Belliston	0.277	9828	< 0.01 R^2=0.003
MEAN	0.268	11129	< 0.01 R^2=0.002

Table 4.13Regression analysis; temperature for the Fife sites

Belliston and Leuchars show a very similar pattern, with an overall warming trend which is consistent for the East of the region. Elmwood has evidence of a stronger trend than the other sites, and Kinross has the weakest evidence of warming on an annual basis.

Consideration of the seasonal trends yields the results which are presented in Table 4.14.

SITE	Spring	Summer	Autumn	Winter
Leuchars	0.264**	0.165**	0.178*	0.122
Kinross	0.173 (sig 0.057)	0.0047	-0.015	0.140
Elmwood	0.319**	0.241**	0.258**	0.229**
Belliston	0.206**	0.198**	0.228**	0.146*
MEAN	0.241**	0.150*	0.162 (sig 0.056)	0.159*

** significant at 1%   * significant at 5% n = 2780

Table 4.14 Regression analysis; temperature for the Fife sites on a seasonal basis

The strongest evidence of a warming trend comes from the spring, with summer and autumn both indicating a warming trend at three of the sites. The data from Kinross shows no significant trends, although the data for spring comes closest and has a coefficient which is comparable to the others. The analysis of the mean daily temperature for the region suggests that, overall, spring has the strongest warming trend followed by winter and summer, with no significant trend during the Autumn. The low values for R^2 indicate the variability of the temperature data is not explained by this equation.

4.2.9. Degree –days

As with the other two regions the data relating to degree-days was analysed, Figure 4.24 illustrating the annual totals.

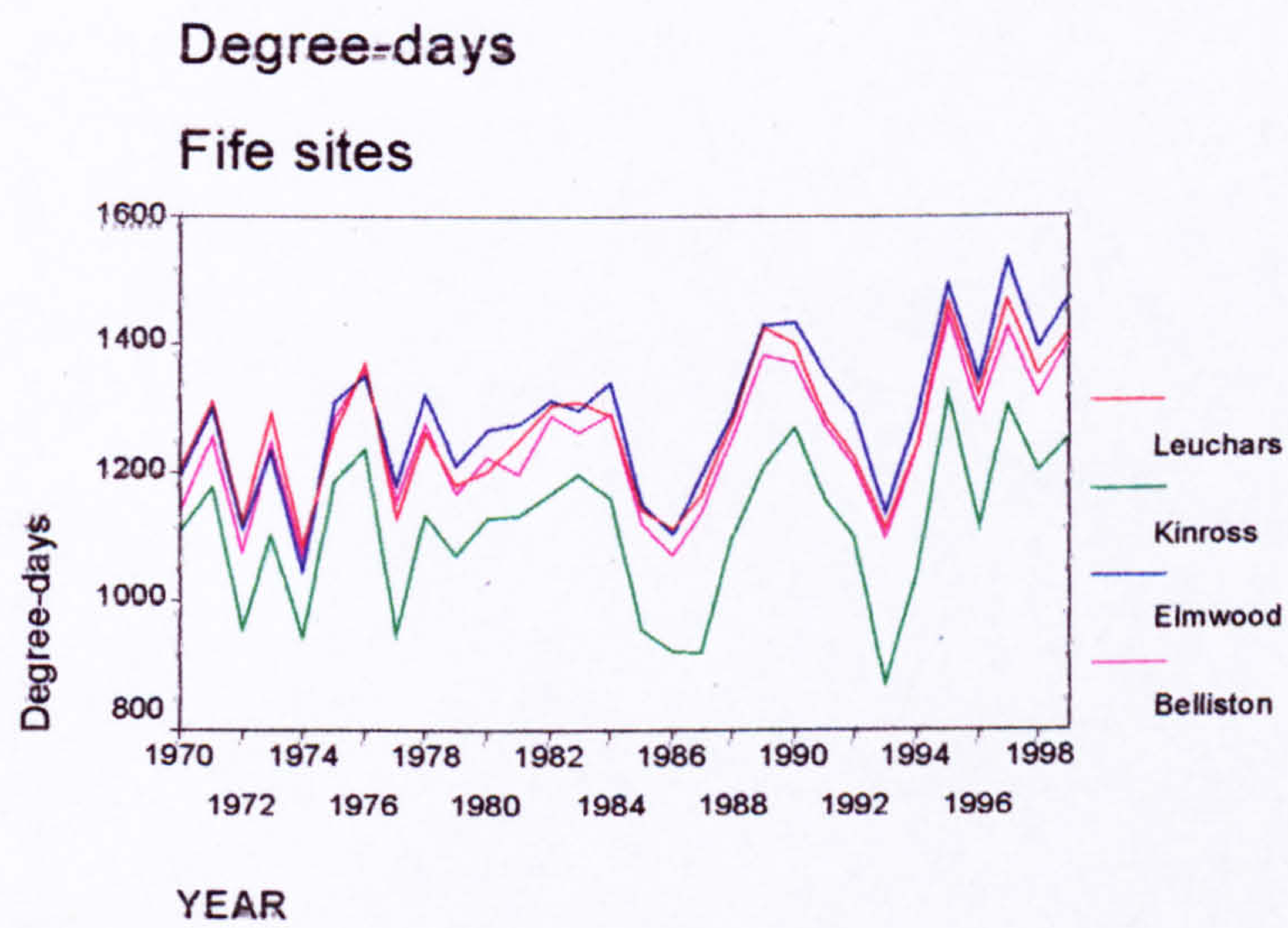


Figure 4.24 Degree days for the Fife sites

As with the temperature data Kinross lags behind the other sites, if anything the gap appears to get larger after the 1970's. Analysis, using linear regression and working with the figures for the annual totals of the mean number of degree-days across the region, produces a significant regression equation, suggesting that on average the region has experienced 5.5 more degree-days per year for the past three decades.

Taking the daily data and splitting the files into seasonal subsets before running the regression, produces evidence of the seasonal pattern. This is illustrated in Table 4.15.

Season	Spring	Summer	Autumn	Winter
Coeff	0.019**	0.013**	0.012*	0.003

** significant at 1% * significant at 5% n = 29

Table 4.15 Regression analysis; degree days at the Fife sites on a seasonal basis

Spring shows the strongest trend and summer and Autumn both show a similar and slightly weaker upward trend in the number of degree-days per annum.

Splitting the data to monthly subsets reveals 9 months which show a significant trend. These results are summarised below in Table 4.16

Month	Feb	March	April	May	July	Aug	Sept	Nov	Dec
Coeff	0.017**	0.029**	0.019**	0.017*	0.021**	0.027**	0.021*	0.017**	-0.011**

** significant at 1% * significant at 5% n = 29

Table 4.16 Regression analysis; degree days at the Fife sites on a monthly basis

March, August and September show the strongest upward trend, while, as with the other regions, December shows a slight, but significant, drop in the number of degree-days.

4.2.10. Summary

The temperature data provides evidence of a warming trend, experienced by all three regions. In all cases the strongest trends lie in the spring and autumn, with certain months showing more evidence of warming than others. March and September appear to be the most affected by the warming trend, while in all regions a decline in the number of degree-days was recorded in December. Given that very few degree-days can be expected during this month it does not represent a dramatic cooling trend.

Both September and November can be seen as having more degree-days while October does not appear to be experiencing any trend at all.

The annual figures reveal that the Argyll coast is warming at a slower rate than either Stirling of Fife, the overall figures being 0.167 °C per decade across Argyll, and 0.345°C and 0.268°C per decade in Stirling and Fife respectively.

4.3. Results of Analysis of meteorological data; Precipitation

4.3.1. Argyll

Rainfall on the west coast of Scotland varies considerably, largely due to the topography of the islands and mainland. The prevailing winds are westerly, bringing moist warm air from the Atlantic. The presence of mountainous terrain produces localised intense precipitation, as this warm air rises, cools and allows for the condensation of water vapour to form rain.

Low lying coastal areas and some of the Islands can often miss this rainfall, as the moist air is not deflected upwards. Rainfall totals reflect this varied topography and are illustrated in Figure 4.25.

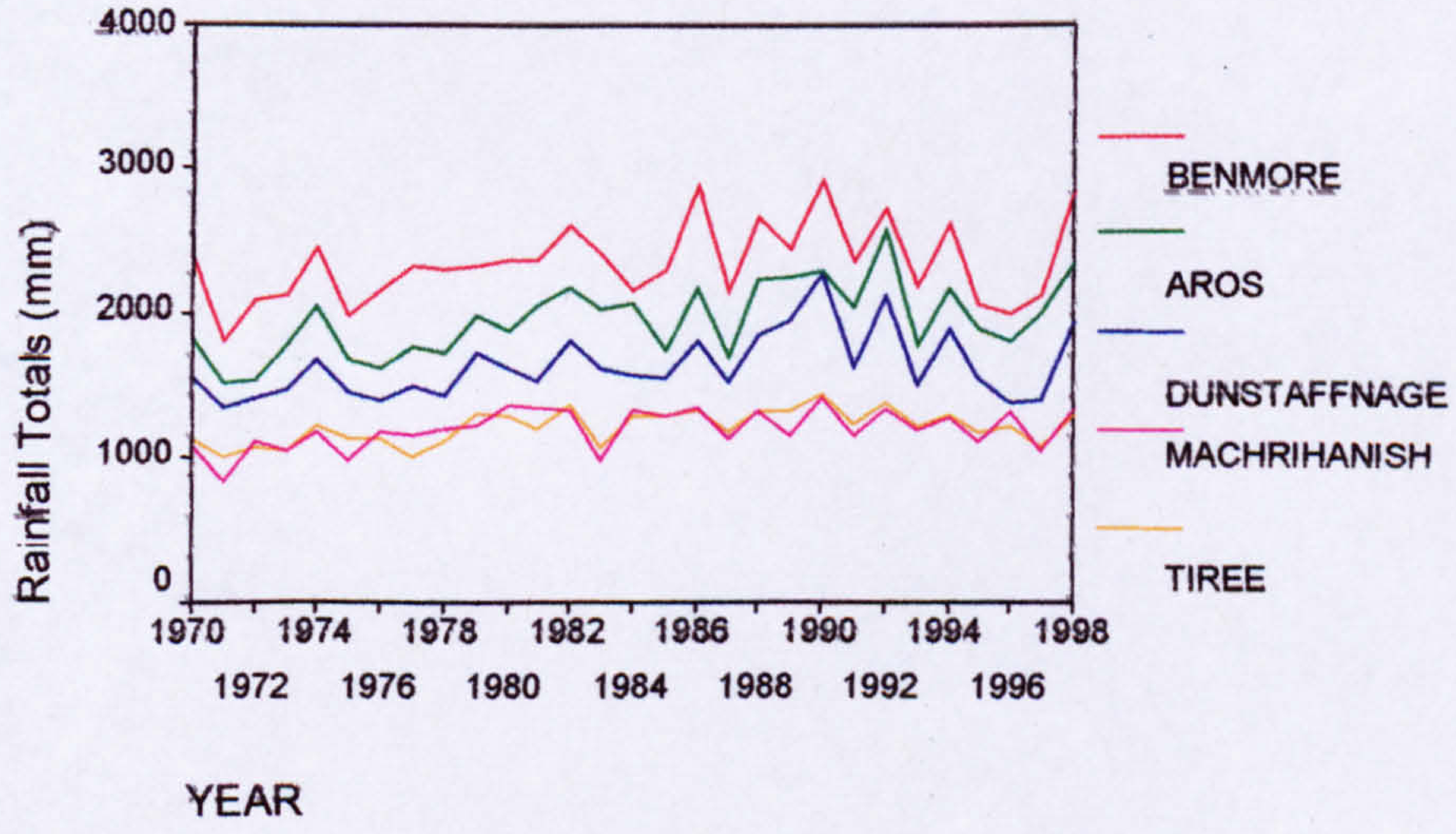


Figure 4.25 Precipitation totals for the Argyll sites

The lowest rainfall totals are for Tiree and Machrihanish, both situated to the west of the mountainous regions. The other three sites are more sheltered from the open ocean but are surrounded by hills. Aros, on Mull, and Benmore both receive approximately twice the annual rainfall of the low lying and more westerly sites.

A strong seasonal pattern exists in the timing of rainfall, with by far the largest amount occurring during the late autumn and winter. Figure 4.26 shows the monthly mean rainfall for the five sites.

All five sites show a similar pattern, with minimum rainfall during the months of April, May and June with a steady rise from then on through the summer to a peak amount during the period from October to January. It is during these months in late autumn and winter that the difference between the sites becomes pronounced.

The mean difference in monthly totals between Benmore and Tiree falls from slightly over 155mm in January, to around 48mm in June.

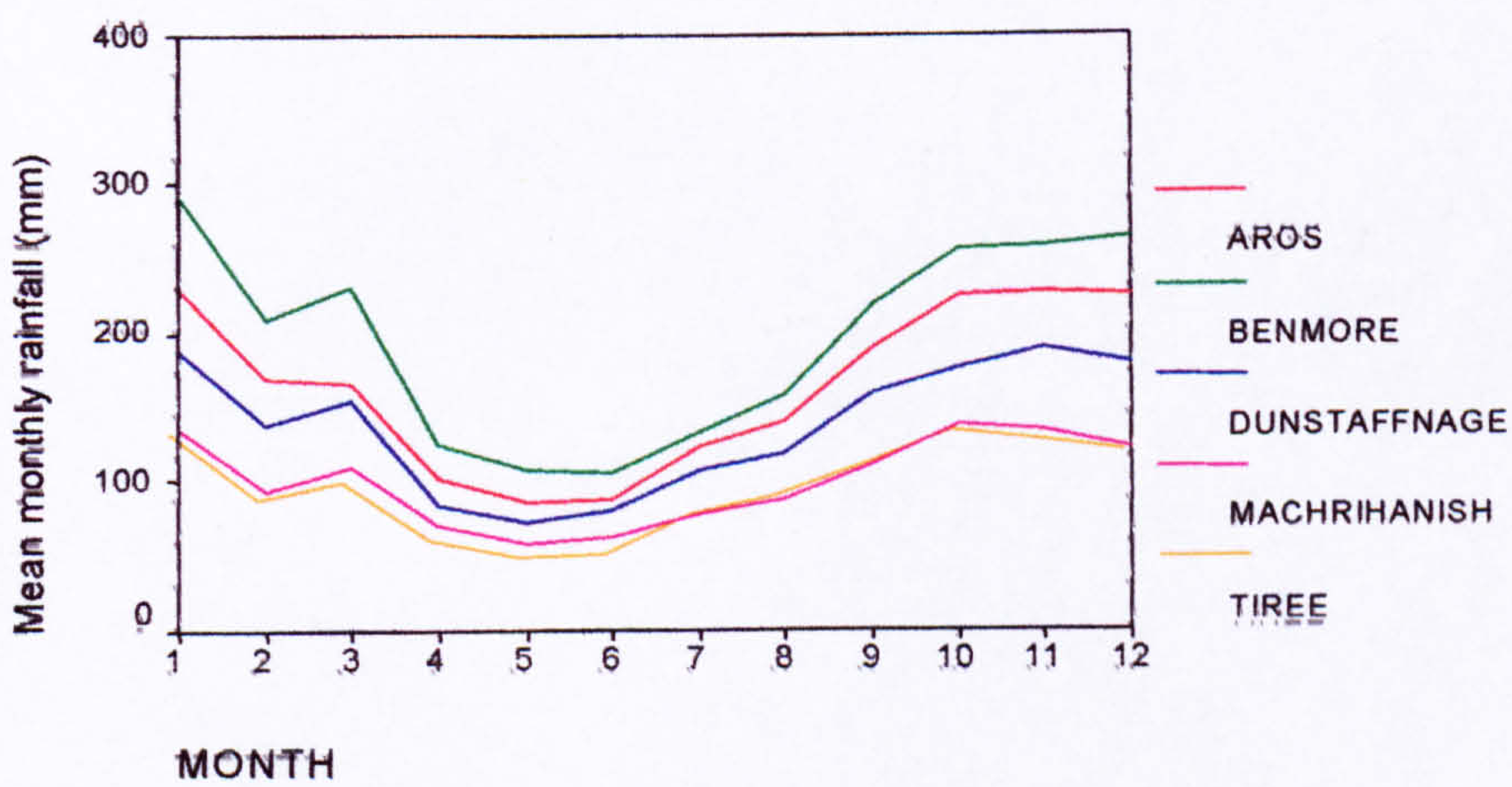


Figure 4.26 Mean monthly precipitation totals for the Argyll sites

In order to examine the data for trends, a linear regression was performed using monthly totals from all five sites. In addition, the mean monthly rainfall for the region was used. Of the five sites, three indicated a significant upward trend in rainfall, as did the regional mean.

The results are summarised in Table 4.17.

SITE	Coefficient	N =	Significance
Aros	1.547	351	0.009
Benmore	1.055	351	0.129
Dunstaffnage	1.062	351	0.040
Machrihanish	0.645	351	0.049
Tiree	0.530	351	0.107
MEAN RAINFALL	0.917	351	0.048

Table 4.17 Regression analysis of precipitation for Argyll sites

Taking seasonal subsets of the monthly totals, a linear regression produced significant equations for winter at just two of the sites, Aros and Dunstaffnage. These equations had a coefficient of 3.417 (sig 0.006) at Aros and 2.435 (sig 0.028) at Dunstaffnage. Machrihanish showed a significant equation for spring, with a coefficient of 1.017 (sig 0.047).

The data relating to mean rainfall across the region showed a significant equation for winter, with a coefficient of 1.931 and a significance of 0.044.

In all cases except Tiree, the regression equations produced for spring had significance values which were less than 0.1, suggesting that there was some evidence of an increasing trend in rainfall there also. In order to investigate further, the monthly totals were analysed independently, effectively testing for trends in the data for each individual month. As well as the five sites the mean values for the region were tested also.

The results are summarised below in Table 4.18.

SITE	February	March	April	October
Aros	6.664**		2.485*	
Benmore	5.058*	4.755*		
Dunstaffnage	4.888**	3.327*		
Machrihanish		1.675*		2.670*
Tiree	2.103*			
MEAN	3.998**	2.556*		

** significant at 0.01 * significant at 0.05 n = 30

Table 4.18 Regression analysis of monthly precipitation totals for the Argyll sites

This points to the early part of the year as the period where changing rainfall patterns are concentrated. None of the other results for the remaining months were significant at the 5% level, though September did produce lower values for the significance of the equation. In all cases this was accompanied by a negative coefficient, pointing to the possibility of a slight reduction in rainfall during September across the region.

4.3.2. Rainfall intensity.

Using the quantile method as described in the methodology section, the 10% threshold was calculated for each site on an annual basis. This gives an indication of the intensity of daily rainfall amounts and the results are summarised below in Figure 4.27.

This shows considerable variability at all sites and there is little visual evidence of a trend. However individual sites do, when the data is analysed using linear regression, indicate an upward trend in the intensity of rainfall. Both Tiree and Dunstaffnage produce significant regression equations, (significance of 0.049, and 0.005, R^2=0.141 R^2=0.312 respectively, n = 30), indicating an annual increase of 0.12 mm per decade on

Tiree and 0.28mm per decade at Dunstaffnage.

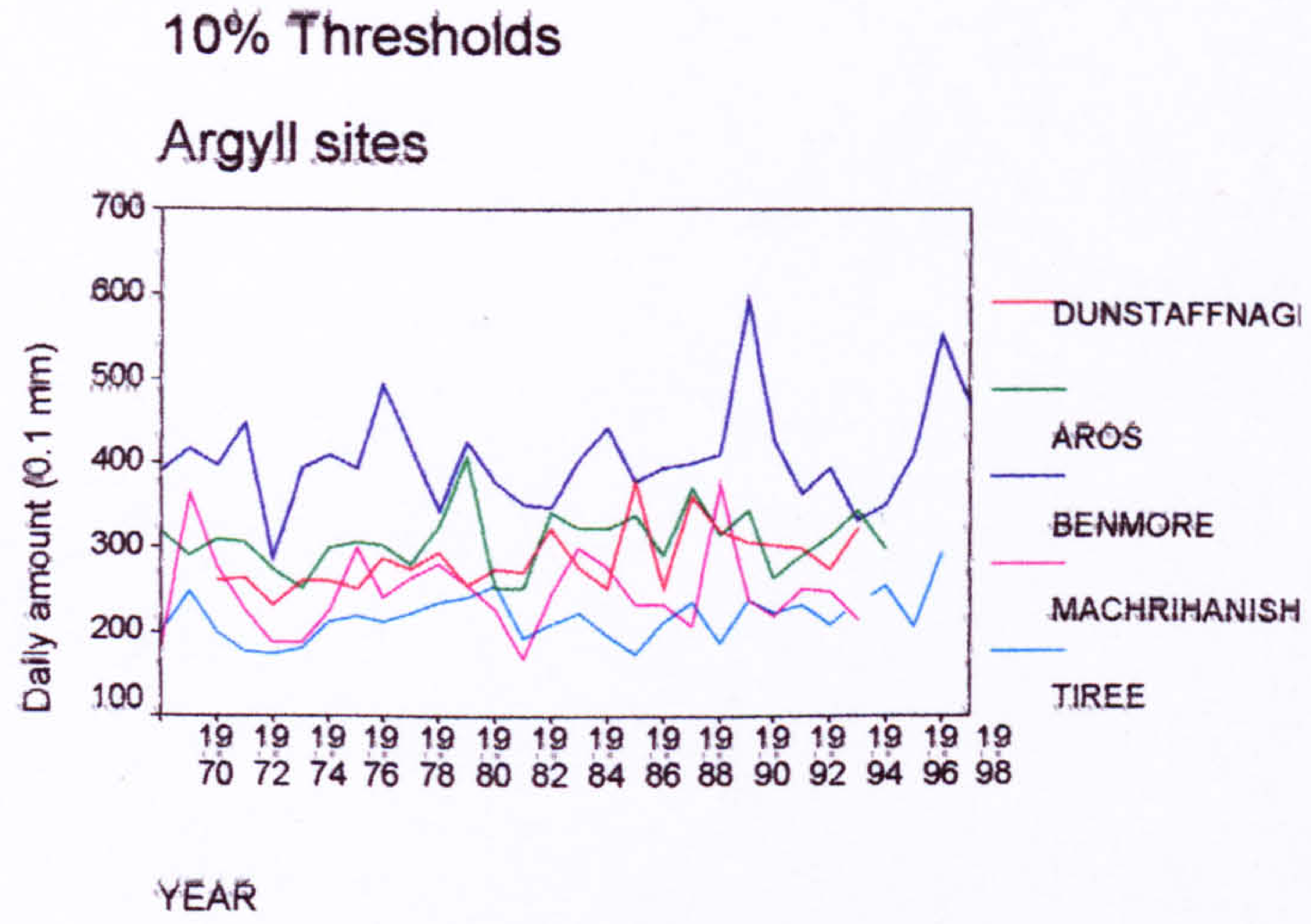


Figure 4.27 Precipitation thresholds for the Argyll sites

This represents what appears to be a relatively small increase in daily amount. However, in percentage terms, it represents approximately 5% increase per decade for Tiree, and closer to 10% increase per decade at Dunstaffnage, in the intensity of the more extreme precipitation events.

Examining these results on a monthly basis indicates that 2 months show a significant increase in rainfall intensity. This is concentrated at the beginning of the year during late winter. Both February and March show a significant trend, as illustrated in Figure 4.28. February; sig = 0.039, $R^2 = 0.144$. March; sig =0.051, $R^2 = 0.112$.(n = 30)

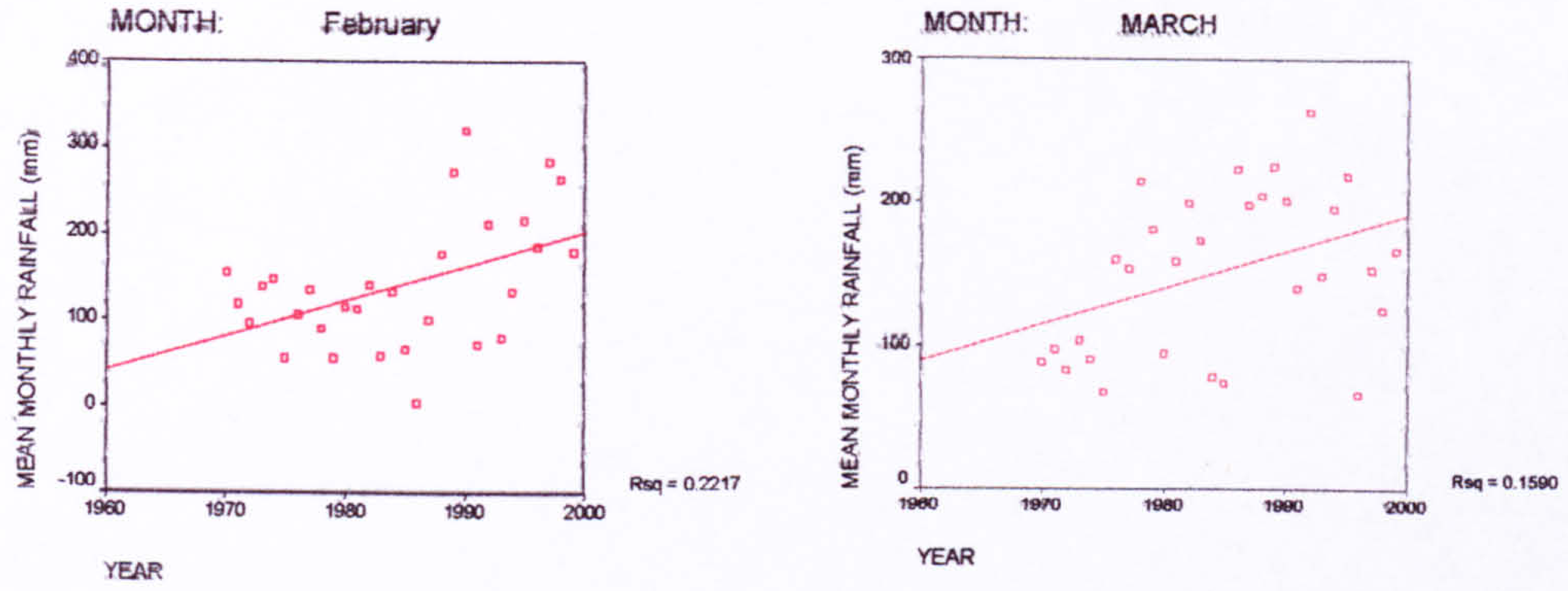


Figure 4.28 Trends in Monthly totals, Argyll

Taking the mean threshold values for the five sites yields a significant regression equation in which the coefficient is 2.713 and the significance 0.003 ($R^2 = 0.275$, n = 30). This represents an increase in percentage terms of around 0.9% per annum, given that the mean threshold is 30mm. This would indicate a regional increase in rainfall intensity of around 9% per decade, for the period of the study.

4.3.3. Stirling

The western end of the Stirling region is characterised by mountainous terrain, with several peaks approaching 1000m. The eastern end is predominately flat agricultural land on the flood plain of the river Forth. The rainfall totals represented by Figure 4.29 illustrate the contrast, with Aberfoyle in the west being situated close to the Trossachs, an area of lochs and mountains. Stirling University is situated beneath the crags of the Ochil Hills, and Grangemouth is situated on the banks of the Forth estuary.

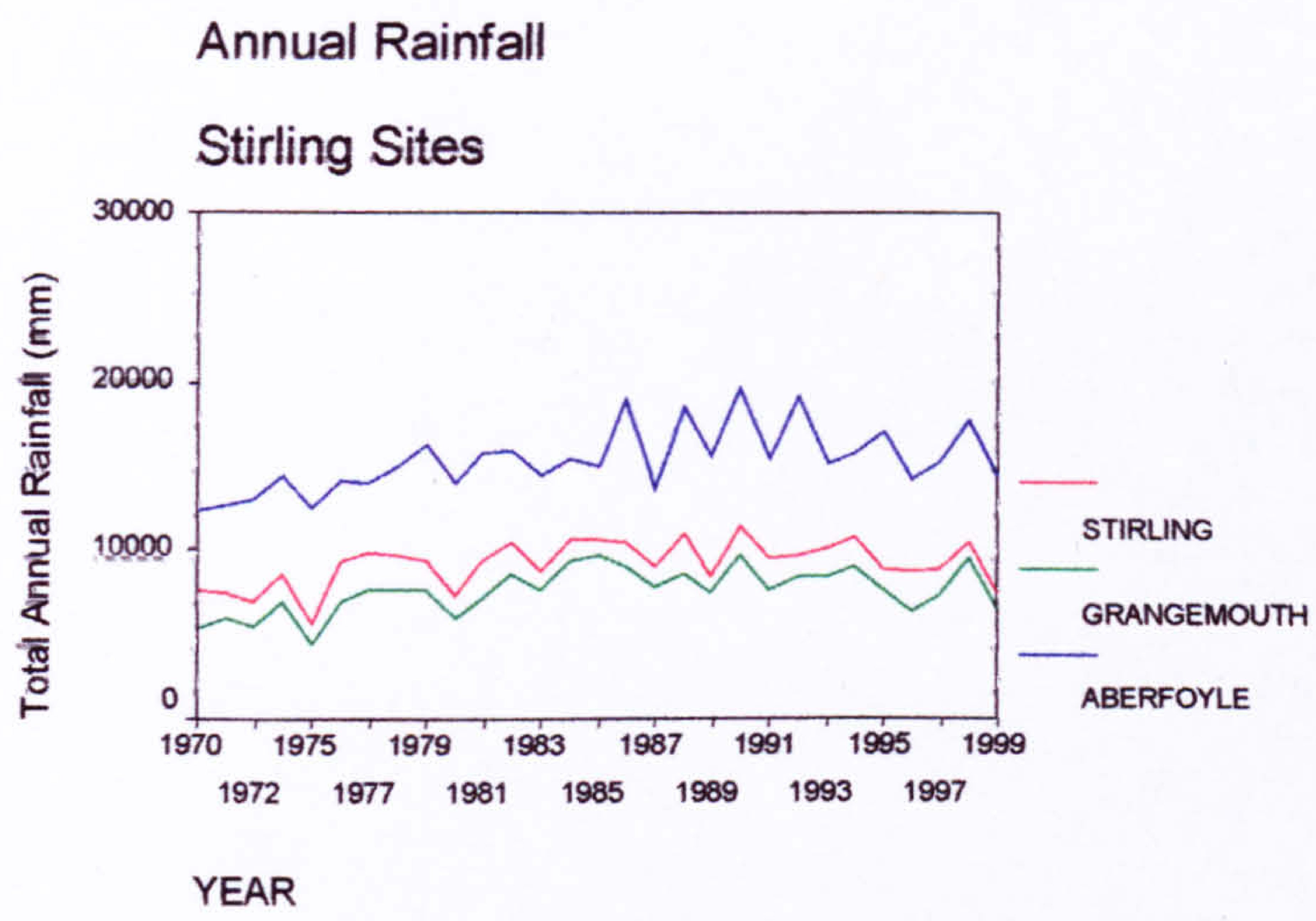


Figure 4.29 Annual precipitation totals for the Stirling sites

The rainfall totals for Grangemouth and Stirling Parkhead are very similar, showing a similar pattern of high and low years. As well as having considerably higher rainfall Aberfoyle appears to have a higher variability although the peaks and troughs appear synchronised with the other two sites.

The monthly pattern of rainfall is similar to that of Argyll, with the months of April, May and June recording the lowest rainfall totals and the Autumn and Winter recording the highest. The contrast is more marked in Aberfoyle as illustrated in Figure 4.30

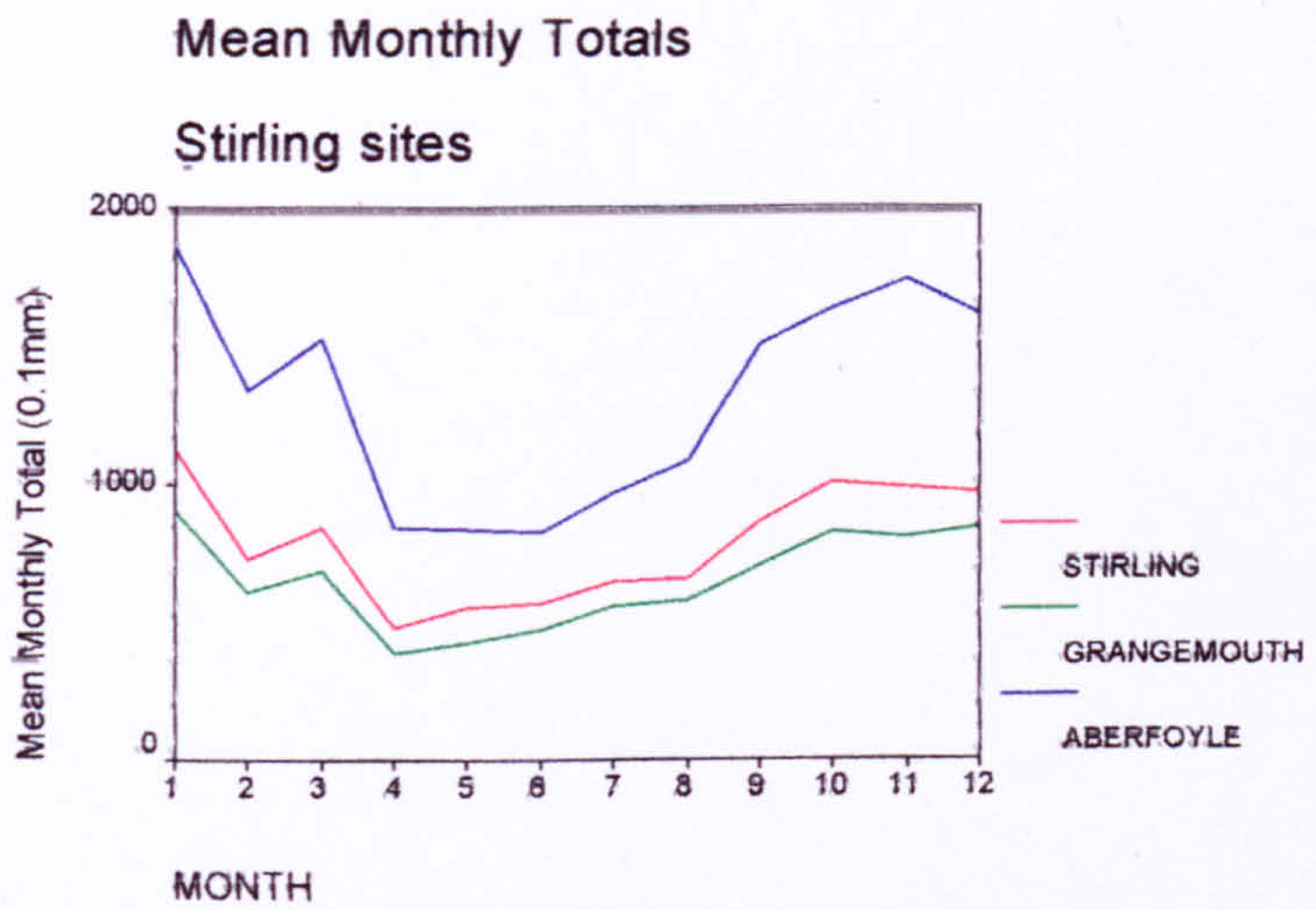


Figure 4.30 Mean monthly precipitation totals for the Stirling sites

Analysis using linear regression produces the results below in Table 4.19. This takes the monthly totals as the dependent variable and the year as the independent.

Site	Coefficient	N =	Significance
Grangemouth	5.86	342	0.016 $R^2 = 0.017$
Stirling	4.61	342	0.113 $R^2 = 0.007$
Aberfoyle	8.57	342	0.068 $R^2 = 0.01$
Mean	6.05	342	0.056 $R^2 = 0.011$

Table 4.19 Regression analysis of monthly precipitation totals at Stirling sites

All the coefficients are positive and although only one, Grangemouth, is significant at the 5% level, the mean figure is close to this level of significance. Given that the measurements are in 0.1mm this would imply an annual increase of just over 5mm per decade, a figure which represents only a very modest percentage increase of less than 1% per decade.

Taking seasonal subsets of the data indicates that the bulk of this increase is to be found in winter and spring, with winter showing the strongest trends and the lowest levels of significance. Both Grangemouth and the mean figure produce regression equations which are significant at the 5% level suggesting that the increases are most pronounced at that time. The results are shown in Table 4.20.

SITE	WINTER	significance	SPRING	significance
Grangemouth	14.0	0.011	5.30	0.125
Stirling	10.4	0.118	4.69	0.283
Aberfoyle	18.69	0.070	13.16	0.109
MEAN	14.14	0.042	7.57	0.113

Table 4.20 Regression analysis; precipitation at Stirling sites on a seasonal basis

By taking monthly subsets the increase can be seen as occurring mainly during the month of February, this recording both a relatively large coefficient as well as producing a significant equation at two of the sites. A summary of these results are below in Table 4.21, there being no other months with an equation which had a significance below 0.1.

SITE	FEBRUARY	significance	APRIL	significance
Grangemouth	18.1	0.041		
Stirling	16.8	0.137		
Aberfoyle	37.6	0.050	18.778	0.051
MEAN	22.75	0.069	10.395	0.073

Table 4.21 Regression analysis; precipitation on a monthly basis

This would indicate that for the period of the study there has been an increase in rainfall across the region, concentrated during the early part of the year but not at a level that is significant when measured against the natural variability. As with previous regression equations the R^2 values are very low, indicating considerable variability around the regression line.

4.3.4. Rainfall intensity

Using the quantile method, the 10% threshold values were worked out for the three sites. None of the sites produced a regression equation which was significant at the 5% level and the mean figures produced no evidence of an increase in intensity either. The closest evidence was at Aberfoyle, where the coefficient was 4.07 and the significance 0.061. Thus the most westerly site gave the strongest evidence of the three for an increase in rainfall intensity, but there was not sufficient evidence to suggest that across the region as a whole the intensity of rainfall had increased during the period of the study.

4.3.5. Fife

Fife lies between the estuaries of the rivers Forth and Tay, with a coastline bordering the North Sea. Much of the region is low lying although there are extensive areas of land which are elevated and provide rough grazing land. Rainfall is considerably lower than in the west of Scotland, with totals in the most easterly areas amounting to little more than 700mm per annum. Figure 4.31 illustrates the annual totals for the four sites across Fife.

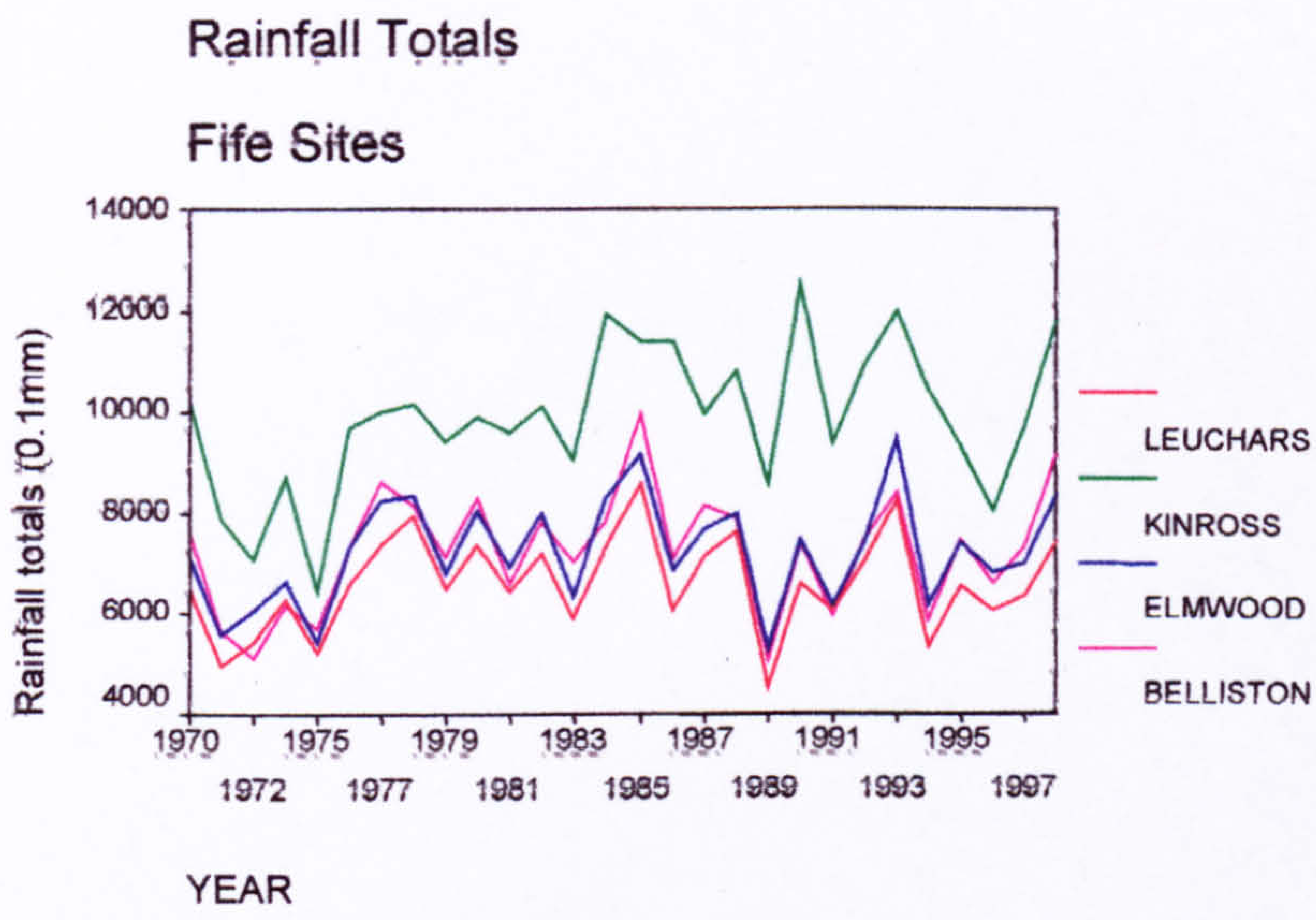


Figure 4.31 Annual precipitation totals for Fife sites

Leuchars, Elmwood and Belliston show a very similar pattern while Kinross has a higher total than the others in all years. Kinross is both further west than the other sites and is situated at a slightly higher altitude.

The monthly pattern of rainfall is illustrated in Figure 4.32. Here the pattern is noticeably different from the other two regions in that three of the sites do not show the strong seasonal contrast. Totals for much of the year remain very similar, with the period from February to August having relatively constant precipitation.

Kinross is the exception and the pattern here is more like that of the more westerly regions.

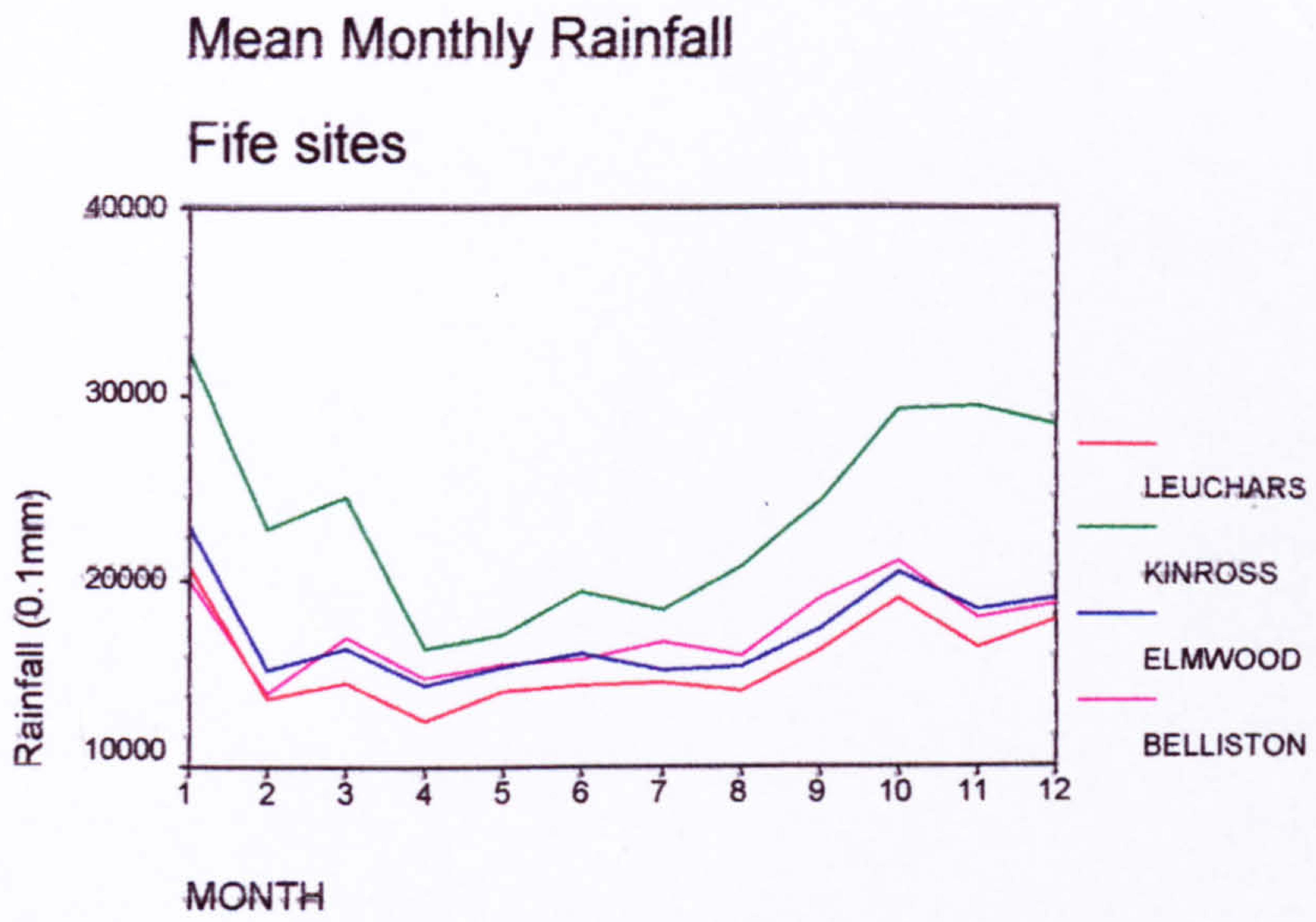


Figure 4.32 Mean monthly precipitation totals for the Fife sites

Using the monthly totals for rainfall for the four sites, regression analysis produced a significant regression equation for only one of the sites. The data for Kinross produced an equation with a coefficient of 5.8, R^2 of 0.012 and this with a significance of 0.042 (n = 342). Neither of the other sites, nor the mean figures, produced a significant equation.

Taking seasonal subsets again produced no significant equations, with the exception of Kinross where the data relating to winter rainfall showed an upward trend. The equation produced had a coefficient of 12.9 and a significance of 0.037 (n = 82). This had a very low R^2 value as a result of the variability in the data.

Reducing the data to monthly totals again produced no evidence of increased rainfall in any month, with again the exception of Kinross where the trend in September was significant (0.049) and had a coefficient of 22.4(n = 29). None of the winter months individually showed any significant trend of increased rainfall for any site and the mean figure was similarly devoid of any evidence of changing rainfall totals.

4.3.6. Rainfall intensity

Analysis of rainfall intensity using the 10% quantile method revealed no significant change in rainfall intensity at any of the sites in Fife. Regression analysis produced equations with coefficients ranging from 1.9 at Elmwood to –0.8 at Leuchars. The significance values of these equations ranged from a minimum of 0.470 at Belliston to 0.917 at Kinross. There is no evidence therefore that the intensity of rainfall has changed in any way across Fife during the period of the study

4.3.7. Summary

The West Coast has experienced an increase in precipitation over the period of the study. The strongest evidence for this comes from sites which are close to mountainous terrain, and the effect is felt inland as far as Aberfoyle in Stirling district. There is also evidence of an increase in the intensity of rainfall in the west. This pattern is not reflected in either Stirling or Fife where the strength of any signal indicating either an increase in total rainfall or an increase in intensity drops off as one move east. Fife produces no evidence of increased precipitation or an increase in the intensity of events.

4.4. Results of Analysis of meteorological data; Windspeed

4.4.1. Mean Windspeed

The lack of reliable data on windspeed requires just two sites to be considered. Leuchars on the East coast of Fife has records dating back to 1957. The site in Argyll, Tiree, had records dating back only to 1983. To make a reasonable comparison it was decided to restrict the analysis of the data from Leuchars to the same timespan as that of Tiree.

The preliminary data analysis used Dunstaffnage on the West coast of Argyll for temperature, precipitation and wind speed. Tiree is situated farther to the west, and as such is in a more exposed position. It was decided to use the data from Tiree, as this would represent the wind strength before it is interrupted by the coastline of Argyll. Tiree also had less missing data than Dunstaffnage.. The preliminary analysis in section 4.1.6 indicated that there were slight trends detectable in the annual data. The aggregated data relating to mean daily windspeed was analysed using linear regression, taking mean windspeed as the dependent variable and the year as the independent. The resulting equations are summarised below in Table 4.22.

SITE	Coefficient	N =	significance
Tiree	0.065	16	0.000 $R^2 = 0.000$
Leuchars	-0.026	30	0.031 $R^2 = 0.174$

Table 4.22 regression analysis of mean windspeed at Tiree and Leuchars.

This would suggest that over the period of the study , from 1983 –1999, the mean windspeed has increased on the west coast by a very small amount, the average annual increase being 0.065 knots. Similarly mean windspeed has decreased on the east coast by a similarly small amount of around 0.026 knots per annum.

This analysis takes all data points relating to mean daily windspeed, and includes all seasons. In order to examine the data further, linear regression was performed using monthly subsets of the data.

The results of this are summarised below in Table 4.23. Only the months in which a significant (at 0.05) regression equation was produced are included.

Site/Month	FEB	MARCH	APRIL	JUNE	AUG	SEPT	NOV	DEC
Tiree			0.199**	0.139*		-0.132*	0.197	
Leuchars	0.120**	-0.067*		-0.050*	-0.073*		-0.125**	-0.108*

* denotes significant at 5% ** denotes significant at 1%, n = 16 Tiree, n = 30 Leuchars.

Table 4.23 Regression analysis of windspeed at two sites on a monthly basis.

Tiree shows increasing windspeed in April, June and November, with a slight decrease in September. Leuchars on the other hand records a decrease in windspeed for five months and an increase only in February.

The strongest trend of any of these months is in Tiree in April and in November. The coefficients suggest that, over the course of the 17 years of data, there has been an increase in mean windspeed in these two months of approximately 3 knots. The largest change to the windspeeds at Leuchars has been a decrease of roughly 2 knots in average windspeed during November.

4.4.2. Maximum windspeed

A similar procedure to that outlined above was performed on the data relating to the records of maximum daily windspeed. Again linear regression was used to identify any trends over time. Taking the year as the predictor produced the results summarised in Table 4.24.

SITE	Coefficient	N =	significance
Tiree	0.079	16	0.000 $R^2 = 0.002$
Leuchars	-0.015	30	0.374 $R^2 = 0.000$

Table 4.24 Regression analysis; maximum windspeed at two sites

Again the west coast shows a positive coeficient and the east coast a negative one. In this case the result for Leuchars is not significant at the 5% level.

Taking the monthly subsets of the data the following results were obtained. Table 4.25 lists the months in which significant trends were identified. All had values of R^2 lower than 0.05

	JAN	FEB	APRIL	JUNE	SEPT	NOV
Tiree		0.329**	0.228**	0.181**	-0.184**	0.242**
Leuchars	-0.172*	0.431**			-0.14**	

* denotes significant at 5%   ** denotes significant at 1%, n = 16 Tiree, n = 30 Leuchars

Table 4.25 Regression analysis; windspeed at the two sites on a monthly basis

Again Tiree shows increasing windspeed for all months listed with the exception of September. February shows an increase in maximum windspeed for both sites and this is the largest change of any month. Both show a decline in maximum windspeed in September with Leuchars showing a decline in January.

This brief analysis suggests that, overall, the West Coast of Scotland has become windier and the East Coast has become less windy. The exception to this on the East Coast is the month of February, which has seen an increase in wind strength. The exception on the West Coast is the month of September which has, against the general trend, become less windy.

The following chapter attempts to determine the causes of the changes and trends which have been identified in the data, and presented in this chapter.

Chapter 5 Determinants of Climate in Scotland.

The previous section indicated that certain changes have occurred with respect to temperature, rainfall and wind speed over the past three decades. These changes have not been uniform across the country, but show a regional pattern with an East/ West divide being evident from many of the results.

Chapter 2 discussed the various factors which influence the climate over different time-scales. Of interest here would be those factors which were identified as having an impact on weather systems over the time-scale of years and decades. In order to identify which of these factors could influence the weather, and hence account for the variability and the presence of trends within the observational record, it was decided to use multiple regression. The factors which were included as independent variables include a measure of atmospheric carbon dioxide ($lnCO_2$), solar output (SOLAR) as calculated from sunspot numbers and the various atmospheric circulation patterns which are measured using pressure anomalies across the North Atlantic and Western Europe. These include the North Atlantic Oscillation (NAO), the Southern Oscillation Index (SOI), the East Atlantic Pattern (EAP), the East Atlantic /West Russia pattern (EAWR), the Scandinavian pattern (SCAND), the Polar/Eurasian pattern (POL/EUR) and the East Atlantic Jet pattern (EAJET). These were described in some detail in Chapter 3.

Rainfall, temperature and wind speed, separately for each of the regions, were used as the dependent variable and multiple regression performed to establish which of the independent variables were of significance in explaining the variability of the meteorological data.

All of the independent variables were tested for multi-correlation, including the lagged variables. This was undertaken in order to eliminate any correlation between independent variables prior to running the multiple regression. It was also of interest to establish whether the various independent variables did indeed show correlation, particularly when lagged variables were used. If such correlation existed, this could potentially indicate that forecasting of circulation patterns might be possible. In fact no such relationships were found between these variables. Auto-correlation was tested for to establish whether or not any of these time series had a unit root. None of the circulation patterns were found to show auto-correlation. This can be a problem when running regression analysis if both dependent and independent variables show unit roots. The results of such a regression cannot be considered reliable (Koop 2000). Where regression is used throughout this thesis , either the dependent or independent variables are derived from meteorological data sets. Figure 5.1 Below gives the results of a test for auto-correlation performed on the main data sets used in the regression analysis. In no case does the auto-correlation coefficient approach 1. Rainfall shows a higher set of coefficients, possibly indicating periods of high or low rainfall can persist.

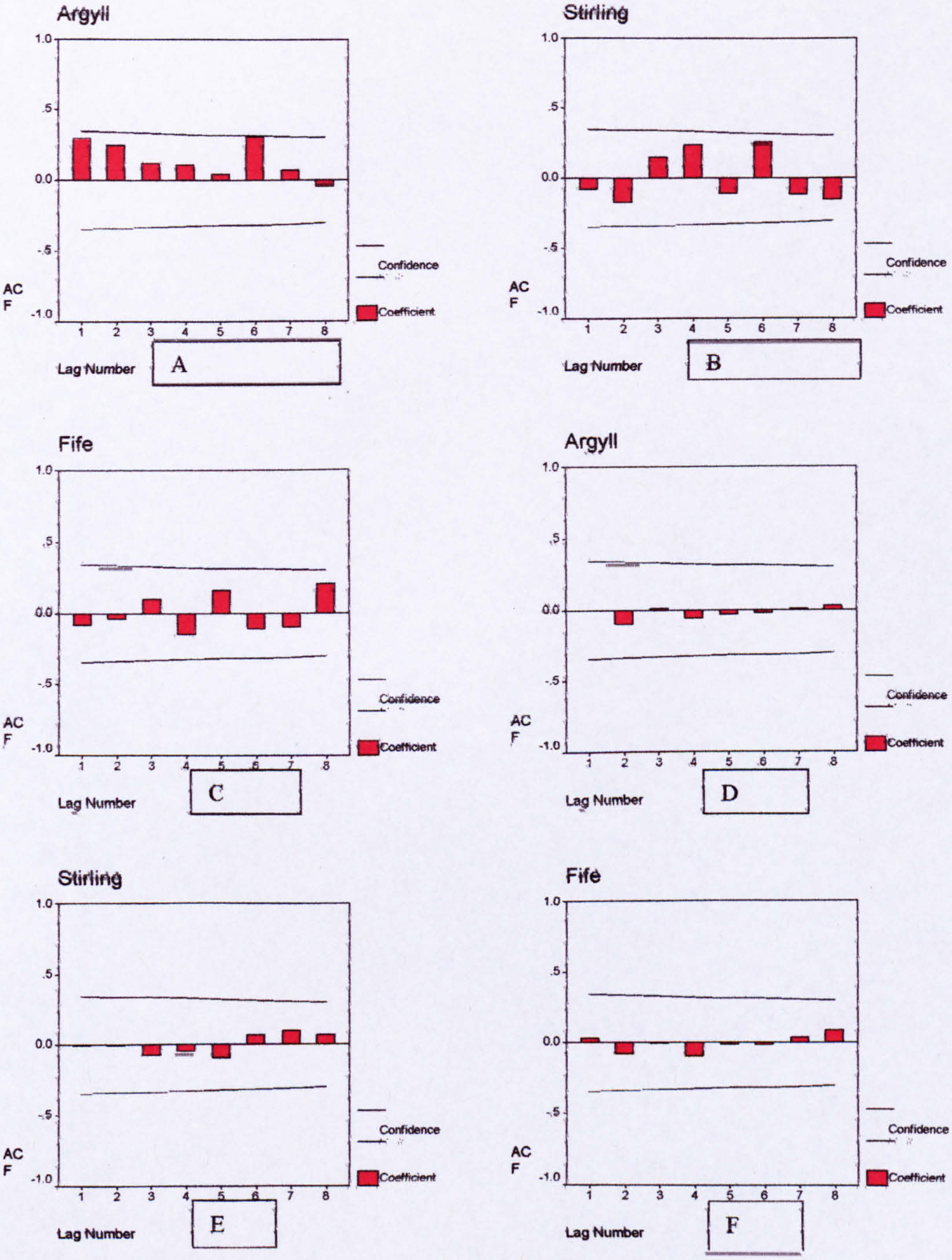


Figure 5.1 Results of auto-correlation function on rainfall(a-c) and temperature(d-f) for each of the three regions.

5.1. Results by season

Monthly rainfall totals, mean temperature and mean wind speed for each of the regions were used as the dependent variables with the independent variables listed above. Backwards multiple regression was used and all equations reported had a significance of less than 0.05. The following tables give the coefficients associated with the variables which were identified as contributing to the explanation of variance in the data. The climate of Scotland can be seen largely as a function of the circulation patterns which determine the origins of the air masses which arrive and often persist over Scotland. In addition variations in solar output cannot be discounted nor can the effects of changes to the atmospheric concentrations of greenhouse gasses. The following regression analysis takes the form of

$$C = f(\text{NAOI, SOI, EAP, EAWR, SCAND, EAJ, POL/EUR, lnCO2, SOLAR})$$

Where C is the climate variable and the independent variables are those described in Chapter 3. Only the particular indices which are in dominant mode for a particular season are included for that season. For example the East Atlantic Jet Pattern (EAJ) is only established during the summer months and so is only included for in the regression for the summer season. Backwards regression then eliminates the variables which contribute least to the equation at each step, resulting in the retention of the most significant variables which contribute most to explaining the variability of the dependent variable.

5.1.1. Rainfall

Table 5.1, Table 5.2 and Table 5.3 give details the coefficients of the various independent variables which were included in the regression equations for each of the three regions on a seasonal basis. All of the circulation patterns are standardised variables with mean zero and standard deviation one. Therefore a comparison of the relative strength of their impacts is possible.

Argyll

Variable	NAO	SOI(3)	LnCO2 (3)	SOLAR	EAP	EAWR	SCAND	EAJET
SPRING	24.9		192.6					
SUMMER	12.9							11.9
AUTUMN	27.2			-368	11.2			
WINTER	29.8		224.8			-15.9		

Table 5.1 Coefficients generated by regression analysis for Argyll

Variable	NAO	SOI(3)	LnCO2 (3)	SOLAR	EAP	EAWR	SCAND	EAJET
SPRING	13.7							
SUMMER	4.6							8.5
AUTUMN	14.2				15.5		9.6	
WINTER	15.1		194.5		10.8	-13.3		

Table 5.2 Coefficients generated by regression analysis for Stirling

Variable	NAO	SOI(3)	LnCO2 (3)	SOLAR	EAP	EAWR	SCAND	EAJET
SPRING		-3.6					8.3	
SUMMER								5.7
AUTUMN					12.4		12.9	
WINTER						-8.6	16.0	

Table 5.3 Coefficients generated by regression analysis for Fife

	Argyll		Stirling		Fife	
	R^2	Sig	R^2	Sig	R^2	Sig
Spring	0.50	0.000	0.305	0.000	0.144	0.003
Summer	0.279	0.000	0.093	0.093	0.047	0.056
Autumn	0.638	0.000	0.555	0.000	0.283	0.000
Winter	0.615	0.000	0.479	0.000	0.253	0.000

Table 5.4 R^2 values and significance of regression equations for rainfall

Table 5.4 shows the significance and R^2 values for the regression equations above. For all cases n = 75.

The North Atlantic Oscillation is picked up in all seasons in both Argyll and Stirling but is absent for all seasons in Fife. In all seasons, the coefficient associated with

Argyll rainfall is at least twice that of Stirling, suggesting that all other factors being the same, an increase in the NAO index of one unit will produce an increase in rainfall that is twice as great on the West coast as inland. Such an increase in the NAO index would have no effect on rainfall in Fife.

Fife is the only region in which the effect of the Southern Oscillation is detected on a seasonal basis and this is restricted to spring. This suggests that an increase in the southern oscillation index of one unit during the months of December, January and February would have the effect of reducing rainfall in the East Coast areas by a modest amount, approximately 4mm over the spring period.

The impact of increasing carbon dioxide levels is detected in spring and winter in Argyll, with Stirling producing evidence of an impact in winter. These figures are not comparable directly with the circulation indices as they are not standardised. For illustration, an increase in the natural log of carbon dioxide levels by one unit would increase actual carbon dioxide to well over 1000 parts per million by volume. A twenty percent increase in CO_2 levels would increase the natural log by approximately 0.2 suggesting that this would, all other factors being constant, increase rainfall during the winter months by around 45mm in Argyll. The comparable figure for Stirling would be around 39 mm.

The impact of fluctuations in solar output appears only in Argyll, and the negative coefficient suggesting that moderate numbers of sunspots will reduce rainfall totals, whereas an absence, or a very large number, will increase rainfall totals. This index has a minimum value of 1.80 and a maximum of 1.90, so the maximum change in the index, which has been produced over the last 30 years, is 0.1. Therefore the maximum impact during the Autumn months, on the West Coast, has been a change of around 38mm.

The East Atlantic pattern has a similar impact across all regions during Autumn, the impact on rainfall being slightly greater inland where it appears to impact on winter rainfall as well.

The East Atlantic Jet and the East Atlantic/West Russian patterns affect all regions in summer and winter respectively, the impact declining gradually on an east west gradient.

Whereas the NAO appears to be the dominant circulation pattern in Argyll and Stirling, it is the Scandinavian pattern which dominates in Fife. With the exception of summer time, the greatest impact on the rainfall of Fife comes from the Scandinavian pattern, which is included in none of the regression equations for Argyll, though autumn rainfall in Stirling is affected. This would appear to confirm the east/west split with Stirling picking up elements from both systems.

5.1.2. Temperature

The results of the backward regression are listed in Table 5.5, Table 5.6 and Table 5.7. For Spring and Autumn in both Stirling and Fife, regression analysis finds that a constant explains a greater proportion of the variability in temperature than any equation involving the independent variables. This is also true of Autumn temperatures in Argyll.

	NAO	SOI(3)	LnCO2 (3)	EAWR	EAJET
SPRING	-2.4			4.2	
SUMMER	12.9		108.7		-5.8
AUTUMN	const	const	const	const	const
WINTER	3.7	4.1		3.6	

Table 5.5 Coefficient from regression equations for Argyll

	NAO	SOI(3)	LnCO2 (3)	EAWR	EAJET
SPRING	const	const	const	const	const
SUMMER	2.6		129.9		-7.0
AUTUMN	const	const	const	const	const
WINTER	4.4	5.3		3.8	

Table 5.6 Coefficient from regression equations for Stirling

	NAO	SOI(3)	LnCO2 (3)	EAWR	EAJET
SPRING	const	const	const	const	const
SUMMER	4.1		155.5		-7.1
AUTUMN	const	const	const	const	const
WINTER	4.5	5.4		3.5	

Table 5.7 Coefficient from regression equations for Fife

Argyll			Stirling		Fife	
	R^2	Sig	R^2	Sig	R^2	Sig
Spring	0.074	0.046	const	-	const	-
Summer	0.173	0.002	0.206	0.001	0.261	0.000
Autumn	const	-	const	-	const	-
Winter	0.026	0.151	0.032	0.115	0.043	0.156

Table 5.8 R^2 and significance of regression equations

In all cases n = 75

The influence of the North Atlantic Oscillation on temperature is positive in summer and winter, positive values of the index producing increased temperatures in all regions. Spring temperatures in Argyll are reduced by a positive index, where increased rainfall, as identified above, tends to lower temperatures. The summer temperatures of all three regions are influenced by a greater amount by the changes in the index of the East Atlantic Jet, positive values of this index being associated with a reduced temperature (Climate prediction center 2001).

The Southern Oscillation Index is picked up in winter in all regions, and this three month lagged variable appears to be of greater significance than the NAO in all regions. Positive values of the SOI tend to increase temperature, whereas they were associated with reduced rainfall in Fife during the spring.

The East Atlantic/West Russian pattern contributes to the regression equations for all regions during the winter, though it's impact is slightly less than that of the NAO and SOI in all cases.

Of significance is the correlation between summer temperatures and the CO_2 concentrations, which is included in the regression equations for all regions. The impact is not uniform with a gradient rising from west to east. Although not directly comparable to the coefficients of the circulation patterns, it can be calculated that a 20% rise in CO_2 levels would induce an increase of approximately 0.2 in the natural logarithm. An increase of 0.2 would translate to an increase in summer temperatures of 2.2°C for Argyll, 2.6°C in Stirling and 3.1°C in Fife.

5.1.3. Wind speed

The results of the backward regression are shown in Table 5.9 and Table 5.10. With the exception of Argyll in summer, both regions show a positive correlation between the NAO index and wind speed. The effect is greater in the west than in the east and strongest in the spring.

Wind speed in summer is more strongly influenced by the East Atlantic Jet than by the NAO and again the effect is greater in the west.

The Scandinavian pattern is included in the regression equations for Fife, for all seasons with the exception of summer. It is not included in any season for Argyll. This reflects the situation with rainfall where a separate pattern of influences appears from west to east.

The EA/WR is implicated in the variability of wind speed in the west in winter and spring, but not in the east where the effect of the SOI is picked up during autumn and winter.

Carbon dioxide levels appear to be correlated with wind speed, positively in the west and negatively in the east. For comparison a 20% increase in CO_2 concentrations would have the effect, all other factors remaining constant, of an increase in mean summer wind speed of 4.1 knots in Argyll and a decrease of 2.3 knots in Fife.

Greater solar output is associated with an increase in mean wind speed in Argyll during the spring but appears nowhere else.

	NAO	LnCO2(3)	EAWR	EAJET	SOLAR
SPRING	1.3		-0.5		17.9
SUMMER		20.6		0.8	
AUTUMN	0.8				
WINTER	0.9	22.0	-0.4		

Table 5.9 Coefficients from regression equations for Tiree

	NAO	SOI(1)	SOI(3)	LnCO2(3)	EAJET	SCAND
SPRING	0.7			-10.3		-0.3
SUMMER	0.2			-11.4	0.3	
AUTUMN	0.5	-0.3		-16.3		-0.3
WINTER	0.6		0.5			-0.4

Table 5.10 Coefficients from regression equations for Leuchars

	R^2 Leuchars	Sig Leuchars	R^2 Tiree	Sig Tiree	N =
Spring	0.486	0.000	0.559	0.000	T= 24, L=75
Summer	0.287	0.000	0.372	0.000	T= 24, L=75
Autumn	0.428	0.000	0.482	0.000	T= 24, L=75
Winter	0.439	0.000	0.438	0.000	T= 24, L=75

Table 5.11 R^2 values,number of cases and significance of equations for Tiree (T) and Leuchars (L)

5.2. Effects on climate.

The technique of multiple regression is in essence a method by which variability in the dependent variable (temperature, rainfall or wind speed) is explained in terms of variability in the independent variables (circulation pattern indices, carbon dioxide, solar output). Variables are included where this provides a statistically significant improvement to the final model. As such, it is statistical relationships which are uncovered, not necessarily causal relationships. Where a lot of variability exists in the data, as with the records for individual months over a thirty year period, the results of the multiple regression show quite considerable differences between the equations generated for different months. Where seasonal subsets are used, the variability is reduced from year to year, and the regression equations are simpler. Only the results for seasonal analysis have been included here.

Temperature across the three regions is influenced by broadly similar factors, especially if the seasonal results are considered. The North Atlantic Oscillation is an important contributor to the temperature regime across Scotland, the impact being greatest in the West and especially during summer and winter. The state of the Southern Oscillation during the autumn months appears to be an influence on winter temperatures in all regions, and winter and spring temperatures are influenced by the East Atlantic/West Russian pattern. Summer temperatures are influenced also by the East Atlantic Jet pattern and by carbon dioxide levels. In general terms, temperature is largely controlled by a combination of circulation patterns and the level of CO_2 in the atmosphere.

Rainfall shows greater regional variability than does temperature. The factors which are identified as contributing to rainfall totals also show more variability between the regions. Argyll and Stirling appear to be largely similar, though Fife appears different at most times of the year. Of major importance here is the effect of the NAO, strong effects in the west declining in Stirling and absent in Fife. Within Fife, the Scandinavian Pattern seems to be more important in determining rainfall totals. The influence of increasing carbon dioxide levels is apparent in Argyll during winter and spring, during winter only in Stirling and is absent in Fife, where earlier analysis showed no detectable changes to rainfall. The effect of solar output on rainfall is detected in the west, with maximum solar output being associated with reduced rainfall totals in Argyll during autumn.

A different pattern of wind speeds exists between the west and east coasts. The NAO influences both at most times of the year, but the east also is influenced by the Scandinavian pattern. The effect of rising CO_2 levels appears to be an increase in wind speed in the west but a decrease in all seasons, with the exception of winter, in the east.

In broad terms the "climate" of Scotland can be seen to be the result of the interaction of certain atmospheric circulation patterns, carbon dioxide levels in the atmosphere and variations in solar output.

Solar activity tends to follow a fairly regular cyclical pattern associated with sunspot activity (period approximately 11 years), and as such is not likely to be responsible for any rising trends over a 30 year period. The trends identified in Chapter 4 can therefore be explained by either the increase in carbon dioxide levels or identifiable trends in the circulation patterns which influence the climate. It is clear that carbon dioxide levels have been rising but it is worth examining the behaviour of the circulation patterns over the period of the study to see if these could be contributing to the trends which are apparent in the data.

From the regression equations above it can be seen that the following conditions would have to exist in order to influence climatic variables in the direction indicated.

5.2.1. Warmer

Season/trend				
SPRING	NAO +ve	EA/WR +ve		
SUMMER	NAO +ve		EAJ -ve	
AUTUMN	NAO +ve	EA/WR +ve		
WINTER	NAO +ve	EA/WR +ve		SOI +ve

Table 5.12 Value of indices required for "warmer"

5.2.2. Wetter

Season/trend					(Fife only)	(Fife only)
SPRING	NAO +ve				SCAND +ve	SOI -ve
SUMMER	NAO +ve	EAJ +ve				
AUTUMN	NAO +ve		EAP +ve		SCAND +ve	
WINTER	NAO +ve			EA/WR -ve	SCAND +ve	

Table 5.13 Values of Indices required for "wetter".

5.2.3. Windier

Season/trend				(Fife only)	(Fife only)
SPRING	NAO +ve	EA/WR -ve		SCAND -ve	
SUMMER	NAO +ve		EAJ +ve		
AUTUMN	NAO +ve			SCAND -ve	
WINTER	NAO +ve	EA/WR -ve		SCAND -ve	SOI +ve

Table 5.14 Values of Indices required for "windier"

If a warming trend was the result of circulation patterns alone this would suggest that the NAO and EA/WR would have to show a rising trend for all seasons throughout the period of he study. A steadily falling EAJ during summer and a rising SOI (lagged 3 months) during winter would help to explain the warming trends. The following graphs, Figure 5.2 to Figure 5.7 give the seasonal mean value for each of these variables. Included with each scatter graph is a linear trend line to give an indication of any overall change in the values of the variable.

5.2.4. Spring

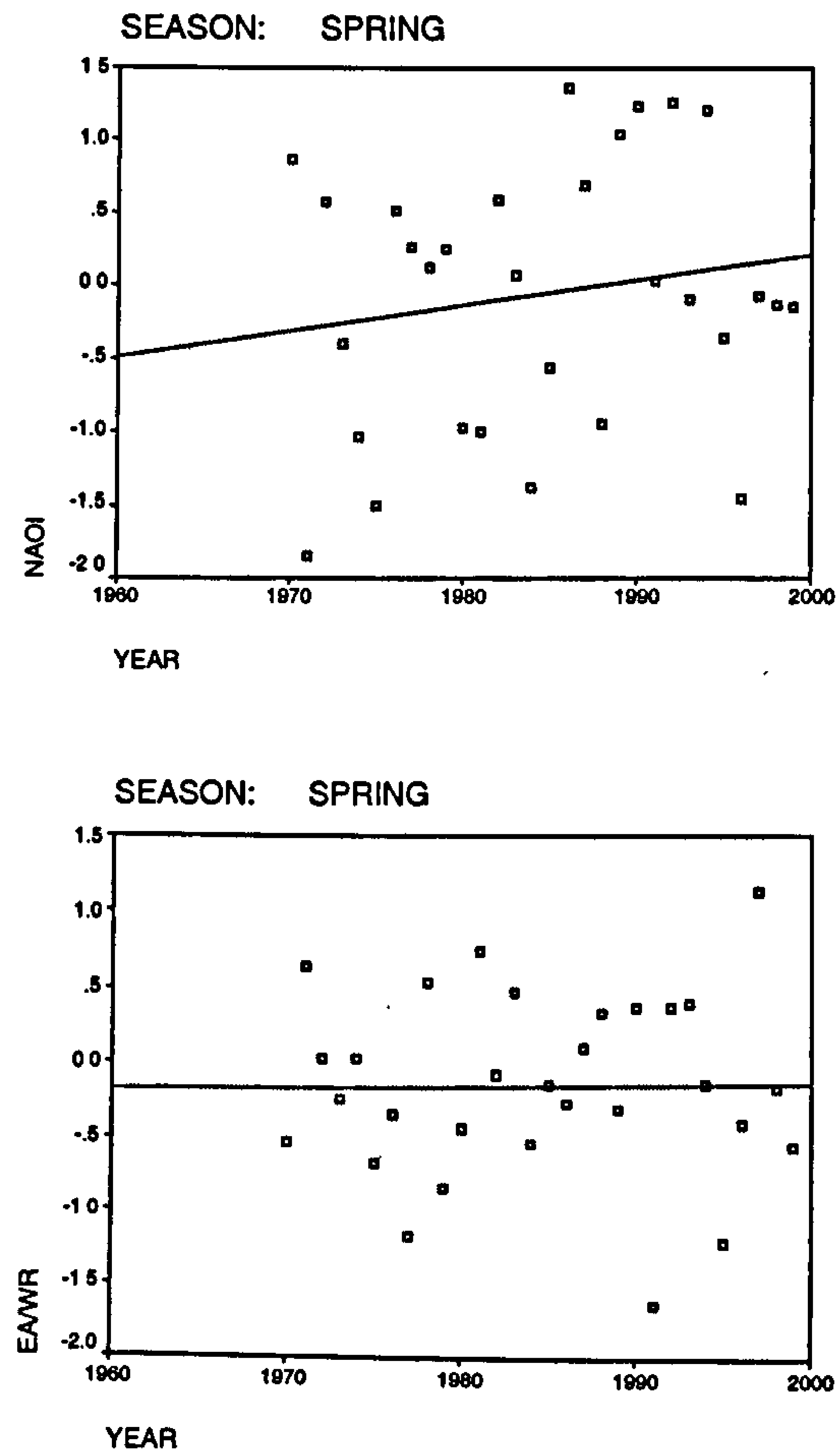


Figure 5.2 Trends in the NAO and EAWR pattern 1960-2000; Spring

The NAO has a slight upwards trend during spring over the past 30 years, no such trend is evident in the graph of the EA/WR. This upward trend in the values of the NAO would tend to increase temperatures in Stirling and Fife but according to the regression equations would tend to decrease temperature in Argyll.

Rainfall in Argyll and Stirling is linked to the NAO and this could help account for an increase in rainfall in the west. Rainfall in Fife shows no change in amount or intensity, the factors identified as influencing this are the Scandinavian pattern (downward trend) and the SOI (downwards trend). Given that the signs of these coefficients are opposite, the influences over time may well cancel out. The effect on wind speed is slightly positive.

5.2.5. Summer

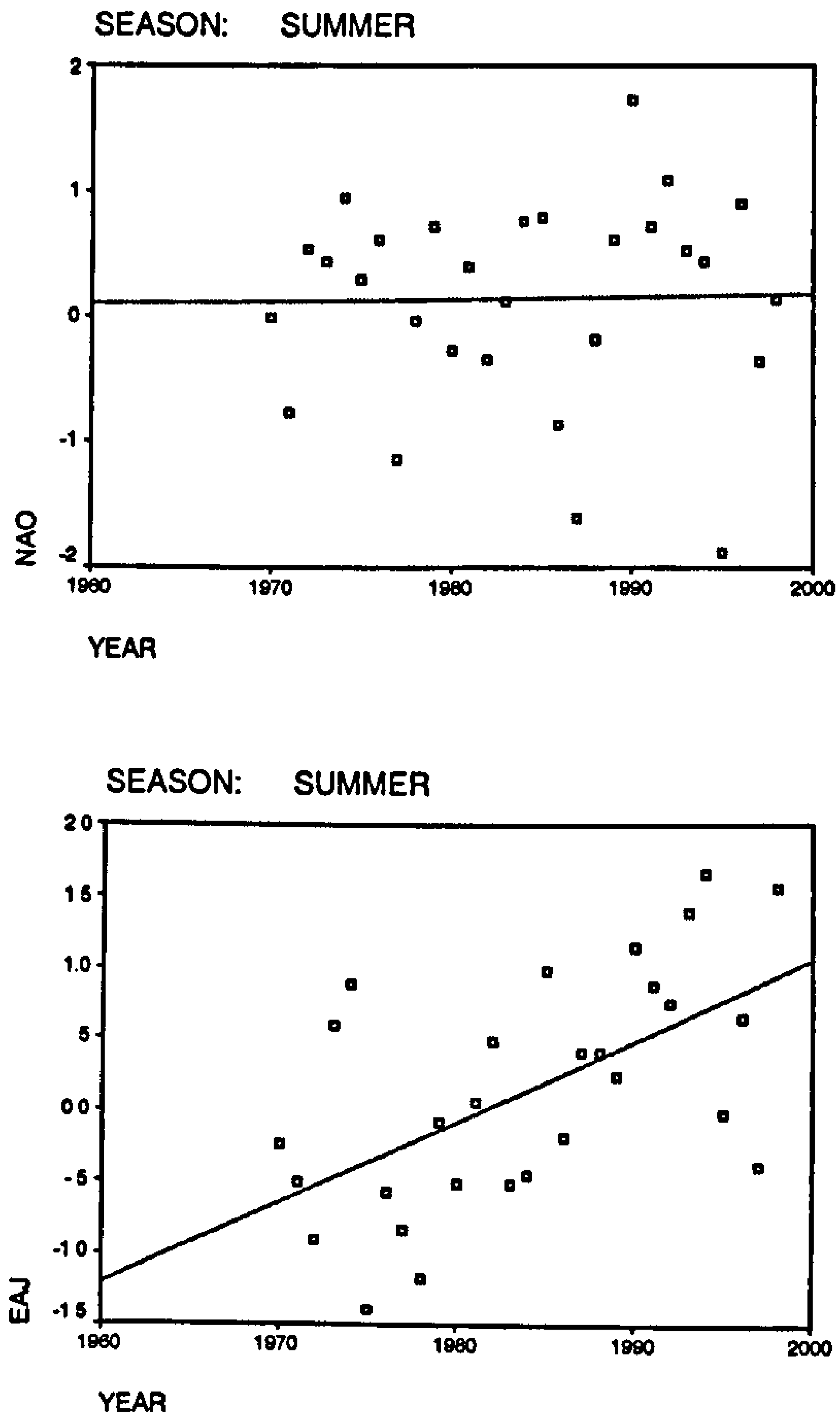
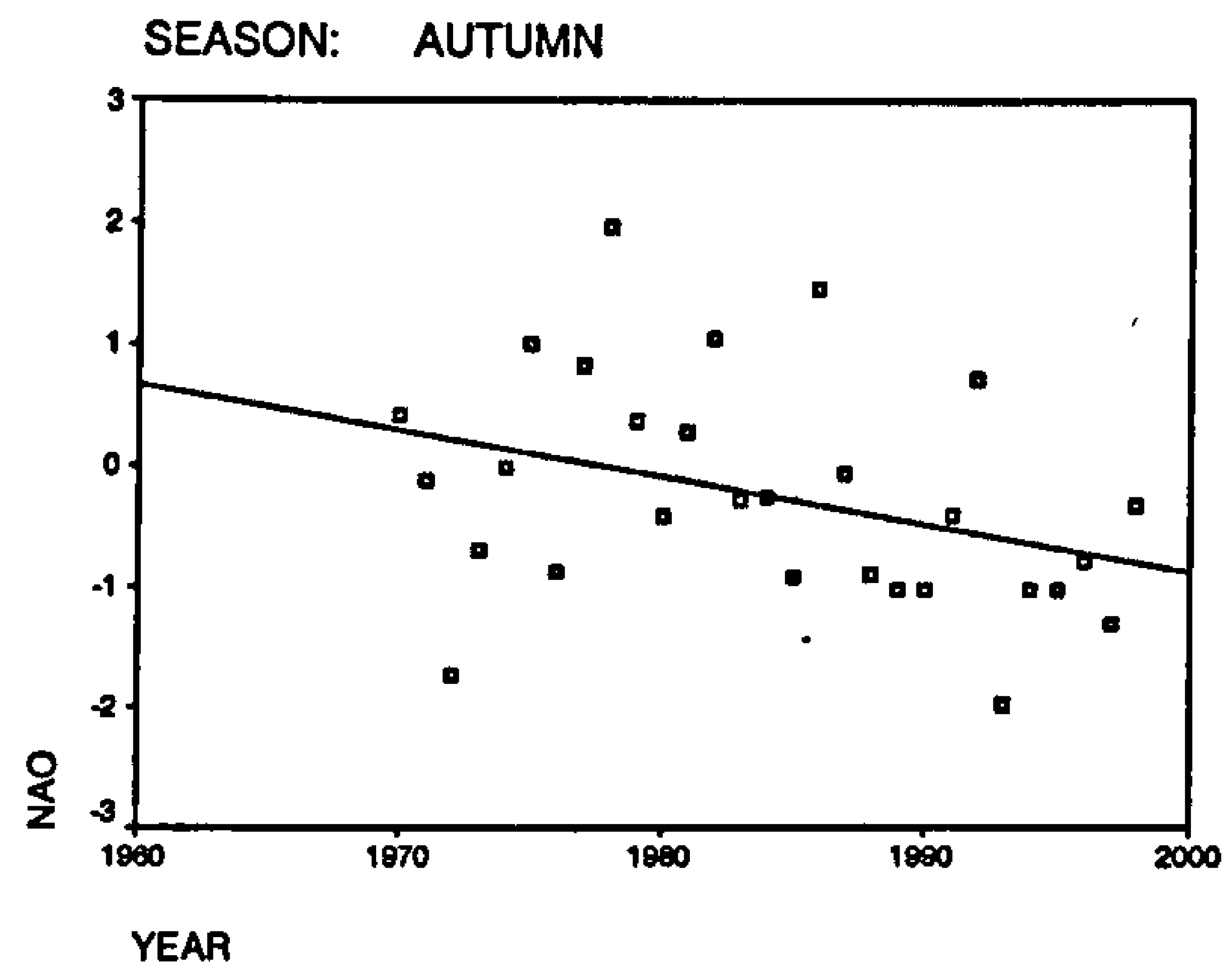


Figure 5.3 Trends in the NAO and EAJ pattern 1960-2000; Summer

The NAO has no upward trend during the summer months for the period of the study. There is a strong upward trend in the figures for the East Atlantic Jet pattern. As the coefficients of this variable in the regression equation are negative, it suggests that the overall effect of these two variables on summer temperature ought to be to introduce a downwards trend in temperature over the period of the study.

The EAJ is included in the regression equations for rainfall in all three regions with a positive coefficient. The strong upward trend in this variable could help to explain any increase in rainfall during the summer months. The effect on windspeed both east and west is positive

5.2.6. Autumn



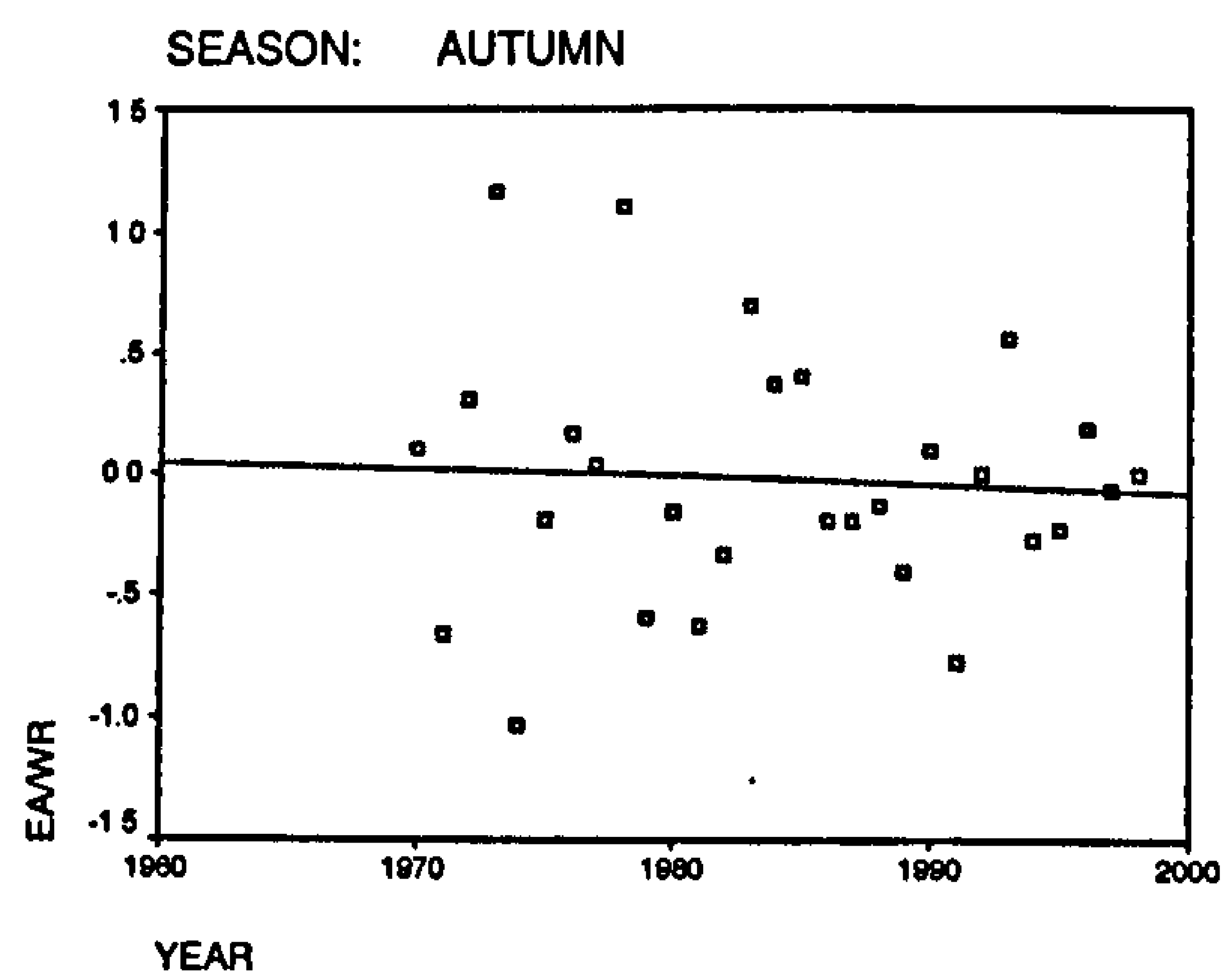


Figure 5.4 Trends in the NAO and EAWR pattern 1960-2000; Autumn.

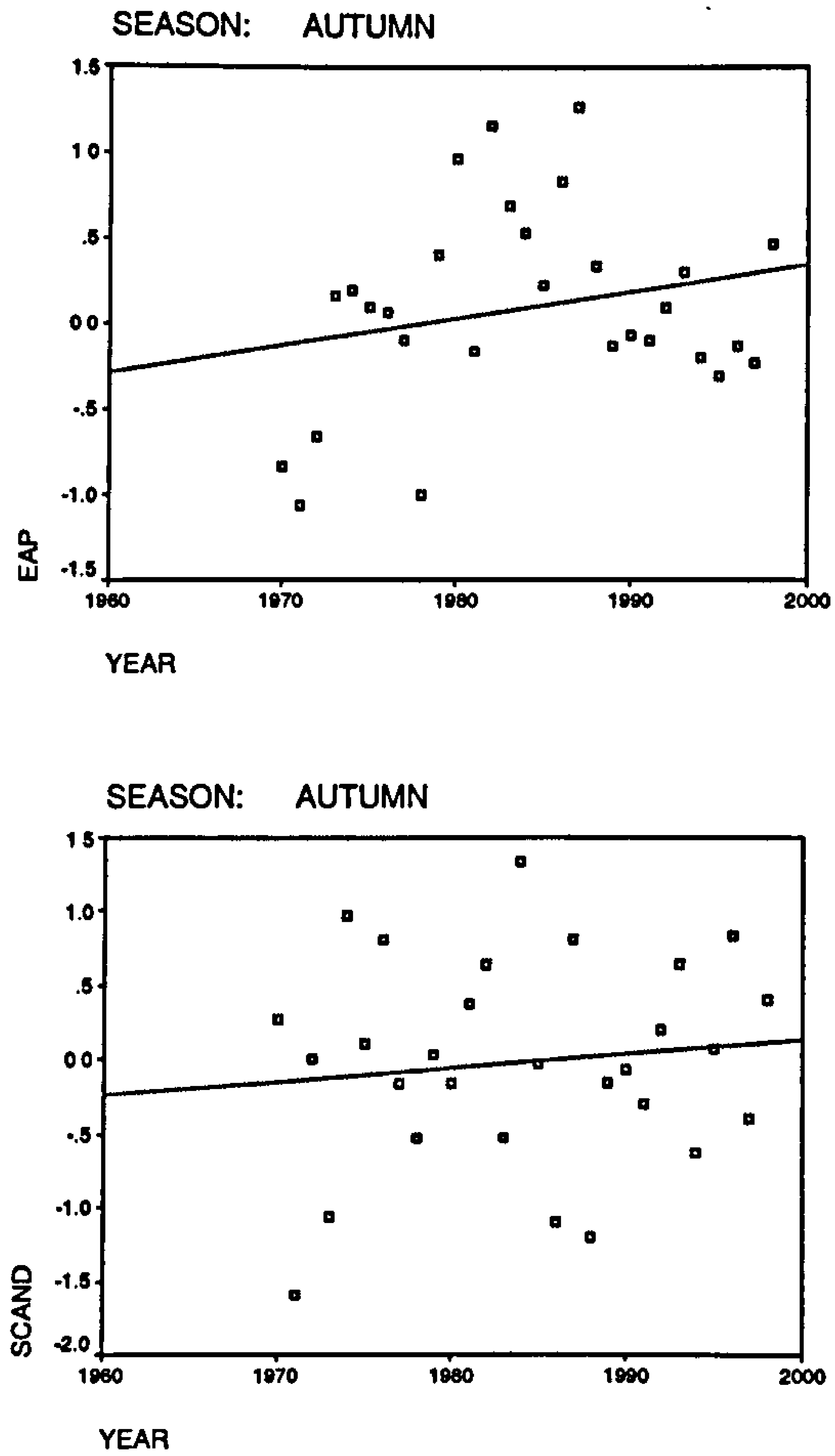


Figure 5.5 Trends in the EAP and Scandinavian Pattern 1960-2000 Autumn.

For autumn, the mean values for the NAO and EA/WR show no upward trend over the period of the study. Indeed the NAO shows a downwards trend. This ought to give a combined cooling effect

For rainfall, the NAO dominates in Argyll. The EAP is included in all regression equations and has a higher coefficient in Stirling than the NAO which is not included for Fife. Stirling and Fife also include the Scandinavian pattern. Both of these indices show a slight upward trend over the period of the study and could help to account for any increase in Autumn rainfall. The effect on wind speed should be downward.

5.2.7. Winter

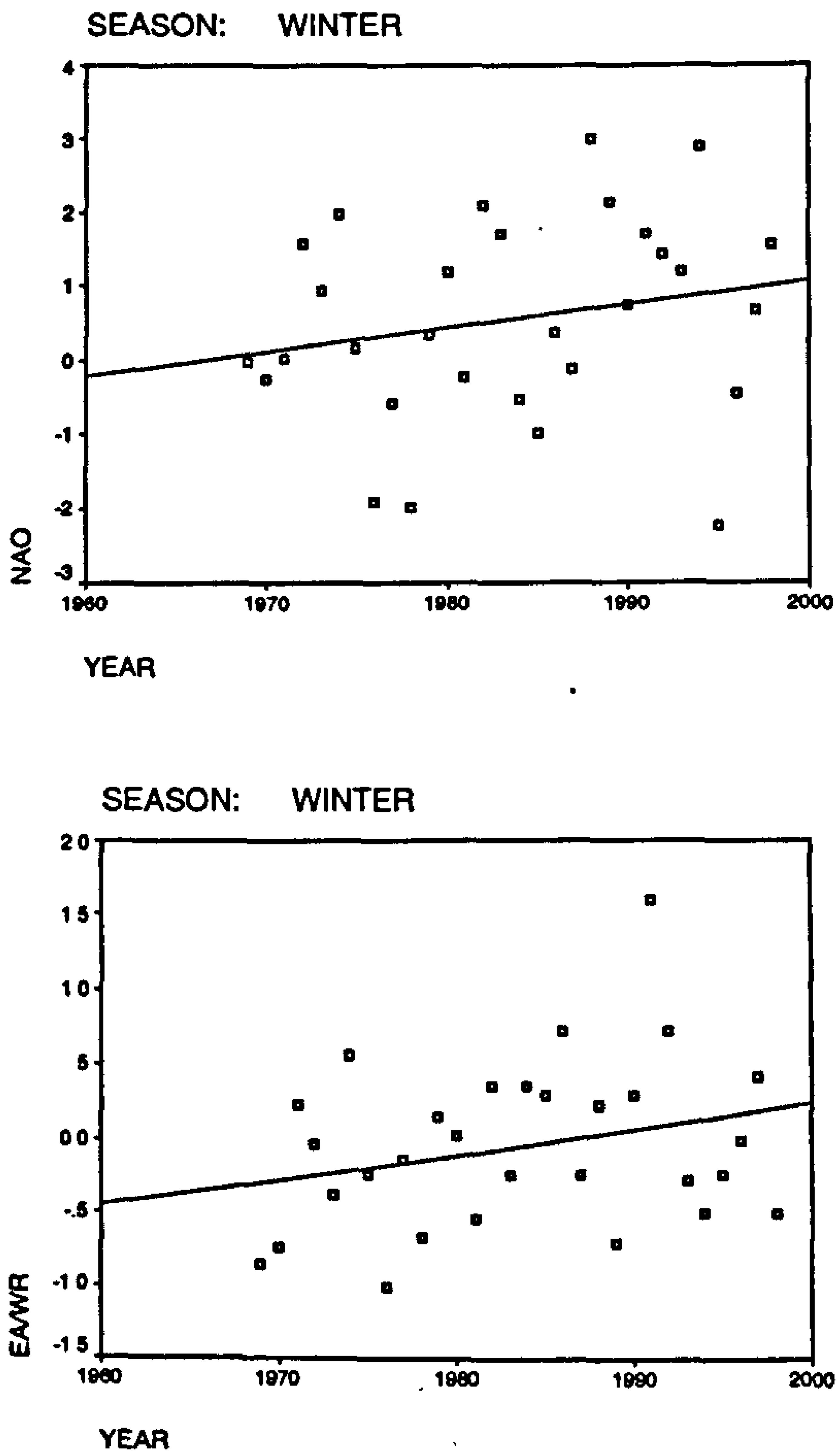
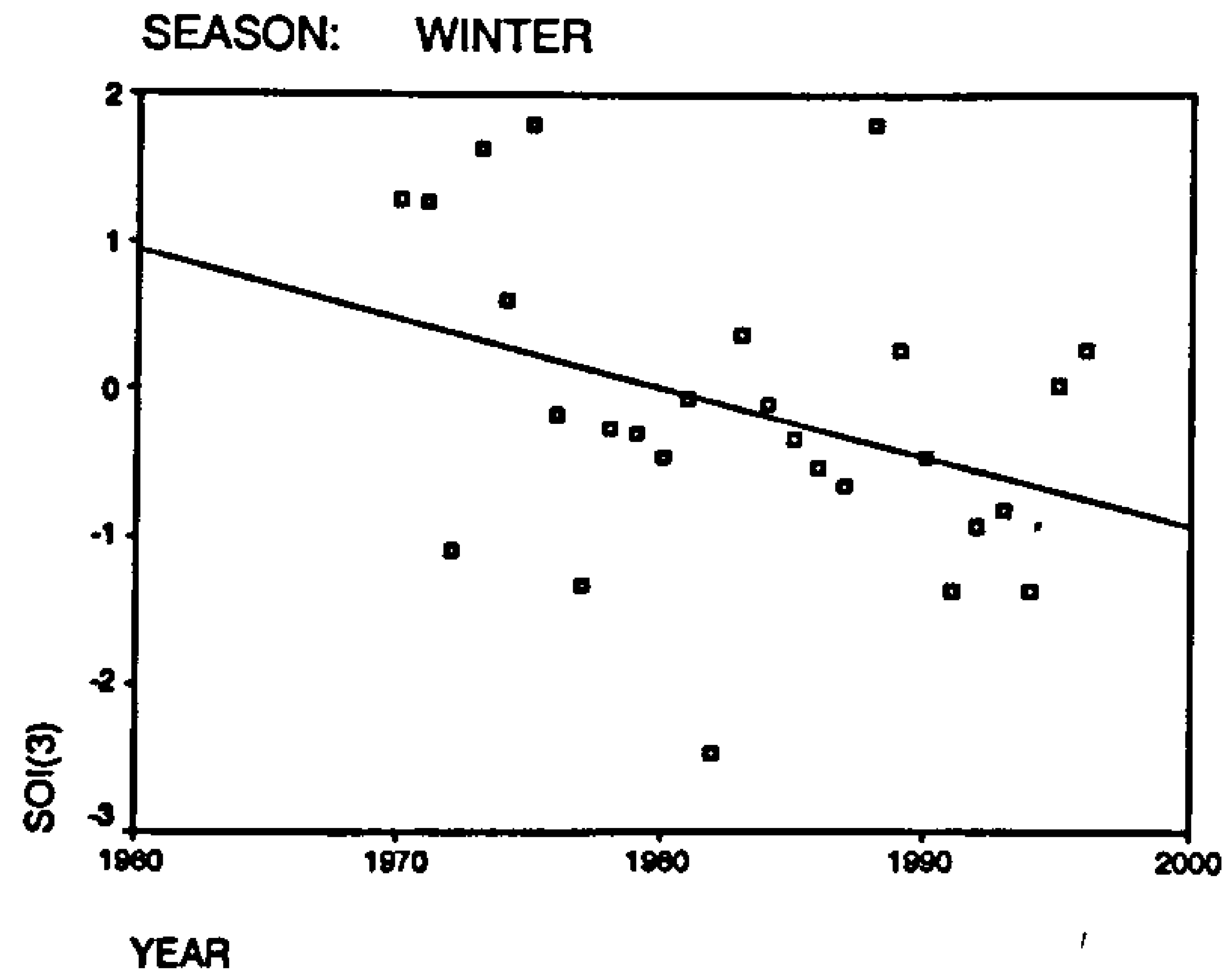


Figure 5.6 Trends in the NAO and EAWR pattern 1960-2000; Winter



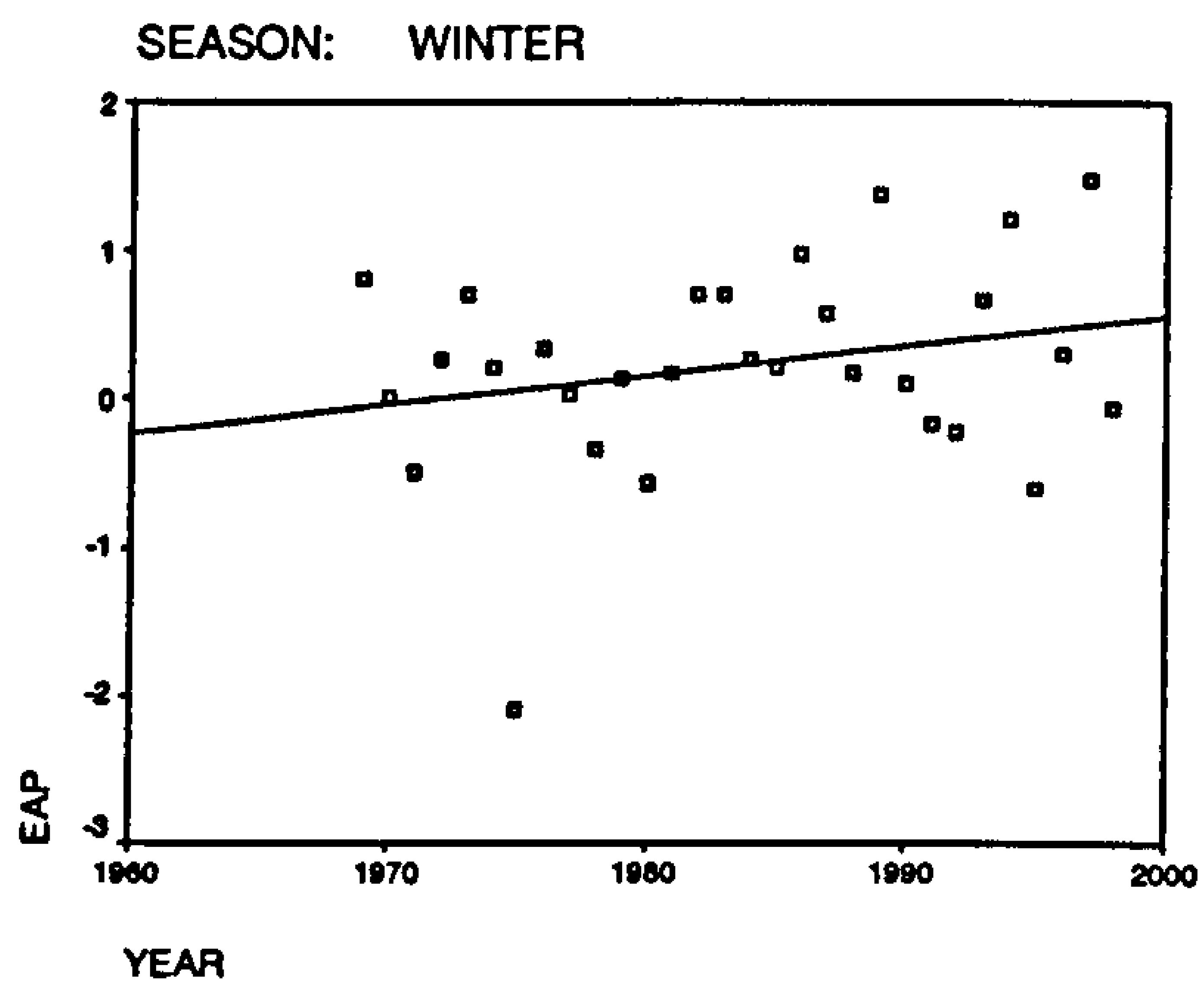


Figure 5.7 Trends in the SOI (3) and EAP 1960-2000; Winter

The winter mean values of the four circulation patterns which are implicated in winter temperatures are shown above. For an increase in temperature they should show an upward trend since all have positive coefficients in the regression equations. In the regression equations for all regions it is the SOI which has the largest coefficient, and it is clear that the trend with respect to this variable has been downwards over the period of the study. This corresponds to strong negative phases of the SOI (El Nino events) and the trend has been towards more negative values during the latter part of the year. The other two variables show an upward trend, the NAO having the stronger trend during the winter months. The warming influence of the NAO and EA/WR should, at least in part, be lessened by the effect of the SOI over this period.

Rainfall in winter is positively correlated with the NAO (Argyll and Stirling) and negatively with the EA/WR in all regions. Fife shows a positive correlation with the Scandinavian pattern and Stirling a positive correlation with the EAP. In each region therefore there is one upward influence (two in Stirling) and one downward influence on rainfall over the period of the study.

Wind speed in the west should increase with these influences, the east should show a decrease.

5.3. Conclusion.

Trends in rainfall and temperature cannot be explained solely by reference to the circulation patterns. At times of the year when warming is evident, for example during the summer months, the influence of the important circulation patterns cannot explain an upwards trend in the data.

Trends in circulation patterns can, at least in part, help to explain rainfall distribution and in all seasons would point to a wetter climate in the west. The importance of the NAO in determining rainfall in the west is perhaps the most noticeable feature, where, with the exception of the summer months, the coefficients of the NAO are all at or above 25.

The correspondence between changes over time to circulation patterns and wind speed does not explain all of the observed trends. Thus the importance of other factors cannot be ignored.

Broad trends in the values of several indices can be identified at certain times of the year but they do not necessarily correspond to the observed changes in the meteorological data. The importance of CO_2 in the atmosphere cannot be excluded, as it is not only important in many of the regression equations, but can be seen as important in the sense that no other variables can effectively explain long term upward trends in the data. This is true in particular for temperature across all regions of the study, and wind speed on the west coast.

Chapter 6 A simple climate model

6.1. Outline

A simple climate model was constructed covering the three regions in order to provide simulated seasonal temperature and precipitation figures under conditions of increased atmospheric carbon dioxide levels. When this work was undertaken the only climate models available were those AGCM's based on a resolution of approximately 300x250km. One grid square of, for example, the UKCIP98 model covered the majority of the Scottish mainland. It was felt that the resolution of the model would have to take into account at least some of the climatic differences between the regions identified in Chapter 4. This simple climate model will be designed to produce simulated temperature and precipitation on a seasonal basis for each of the three regions of the study. These will be used as one input to a socio-economic model as potential drivers for economic change.

The model was constructed using StellaV5.1.1 and is essentially a stock/flow model, in which solar radiation is tracked as it enters the atmosphere. Here a proportion is stored, some is reflected back to space, and some carries on through to be absorbed by the Earth. This model attempts to capture the dynamic interactions of these two stores of energy in the atmosphere and the planet's surface.

This simple model is based on the flows and stores of energy outlined above and which were described in more detail in Chapter 2. As such it has a thermodynamically sound structure. The modelling process was discussed in Chapter 3, where it was stated that with all models there is necessarily a simplification of the system being investigated. Chapter 2 described several feedback loops which exist within the climate system. This simple model retains the major feedback loops which exist in connection with the flows of energy between Earth and Atmosphere. In order to retain a simple structure many of the minor feedback loops have not been included. There is still debate between climatologists as to the exact nature of some of these feedback loops. For example, an increased concentration of water vapour in the atmosphere is considered likely, as global temperatures rise. Water vapour acts as a greenhouse gas, the effect should therefore be to increase the warming effect in a positive feedback loop. Water vapour also condenses to form clouds. The existence of cloud cover, particularly in the tropics, increases the reflectance of the Earth to incoming radiation. This should therefore act as a negative feedback loop, stabilising the Earth's temperature.

Leaving out such loops simplifies the structure of the model but retains the overall balance of energy in the system. Chapter 11 discusses some of the ways in which the model could be developed in order to reflect the more complex nature of the climate system.

Initially a basic temperature model was constructed, which generated mean surface temperatures for the planet as a whole, with and without carbon dioxide. This was then modified to represent a region of the planet at 56 degrees north of the equator, with a seasonal range of temperatures which correspond to those identified from the empirical records for central Scotland, when appropriate values of CO_2 concentrations were introduced.

Arrays were then introduced to allow different values to be generated for each season and for each region of the study. The model was then capable of generating a three (region) by four (season) matrix of values for each successive calculation interval in simulated time (dt). For this model the calculation interval, or dt, was set at one year.

Crucial for the model were future values of atmospheric carbon dioxide concentrations, for which the IPCC Special Report on Emissions Scenarios (IPCC 2000) was used.

This led to four versions of the model being constructed, each with an identical structure but differing only in the projected rates of change of atmospheric CO_2. These four models represent the Low, Medium Low, Medium High and High scenarios used by the Hadley Centre for the UKCIP02 model (UKCIP 2002).

An additional sector was added to the model, which took the predicted changes in precipitation from the UKCIP02 report, and used the increases in CO_2 for each of the scenarios to generate seasonal rainfall patterns for each of the regions.

Thus the model was capable of generating seasonal temperature and precipitation figures for each of the three regions of the study, under the four different scenarios of future increases in atmospheric carbon dioxide.

6.2. Method of construction

The model is constructed in three main stages. The first stage is a basic model which represents the Earth as a whole and uses the energy flows averaged over the entire surface of the planet. The boundaries are then restricted to produce a model which represents the part of the Earth's surface which is at a latitude of approximately 56 degrees north of the equator. Finally, this restricted model is tuned to simulate the climatic conditions peculiar to the three regions of Scotland, by introducing an exogenous flow of energy representing the contribution to the climate of Scotland of the North Atlantic drift. This flow of energy is exogenous to the model only when it has been restricted to Scotland, and represents energy absorbed by the atmosphere and oceans at low latitudes.

6.2.1. Theory

The solar energy flux just above the Earth's atmosphere is estimated as 1,372 W/m^2, where 1Watt = 1Joule /second. This energy flow varies because of solar activity (sun spots), the Earth's distance from the sun and other variables. Nevertheless, despite these changes it is convenient to represents this input of energy as the solar constant

$$W_s = 1372.\pi.R^2 \qquad \text{equation 1}$$

where W_s is the amount of energy per time period delivered from the sun and R is the radius of the Earth.

In 24 hours the energy is distributed over the entire spheroid of the earth (assumed to be a sphere) with an area of $4.\pi.R^2$. Hence, the average flux of solar energy reaching the Earth is

$$1372.\pi.R^2/4.\pi.R^2 = 343(W/m^2) \qquad \text{equation 2}$$

and this is the solar flux (Ω_s).This energy flux (E) covers a large portion of the electromagnetic spectrum.

Not all the energy reaches the Earth's surface as the Earth also reflects some of the energy back into space. This reflected heat is referred to as the albedo and accounts for approximately 31% of all incoming solar radiation. The remaining 69% of the energy is either absorbed by the Earth's atmosphere or passes through and is absorbed by the Earth's surface. This is usually is re-radiated from the Earth in the infra-red part of the electromagnetic spectrum.

Under steady-state conditions the Earth is in an energy balance: the amount of incoming solar flux is equal to the amount of energy reflected and re-radiated from the Earth

$$\Omega_s = \alpha .\Omega_s+(1-\alpha).\Omega_s \qquad \text{equation 3}$$

$$\Omega_e = \Omega_s-\alpha.\Omega_s = (1-\alpha).\Omega_s$$

Where Ω_e (W/m2) is the energy flux re-radiated from the Earth; Ω_s is the incoming solar flux (equation 2) of 343W/m^2 and α is the albedo of the earth (0.31).

Under steady state conditions we can apply the Stefan-Boltzmann Law of Black-Body radiation. This law states that the energy flux radiation for a black body is a function of the surface temperature of that body raised to the fourth power

$$\Omega = \lambda.T^4 \qquad \text{equation 4}$$

Where Ω_e = energy flux (W/m^2)

λ = Stefan-Boltzmann Constant (5.67 x10^{-8} W/m^2/K)

T = is the temperature in degrees Kelvin (NB to convert degrees Kelvin (K) to Celsius (C) use the formula K= C+273.15). By combining equations 3 and 4 the Earths' average surface temperature is given as

$$T = (\Omega_e/\lambda)^{1/4} = [(1-\alpha).\Omega_s/\lambda]^{1/4} \qquad \text{equation 5}$$

By substituting the values of α =0.31 and Ω_s =343 W/m^2 then equation 4 yields a value of

T = 255K (or –18 degrees Celsius)

Such an average temperature of the Earth would be too cold to support life as we know it. Fortunately, the real Earth surface temperature is not so low. It is approximately 33 degrees Celsius higher than the temperature calculated by equation 4, at 15 degrees Celsius. The discrepancy between the calculated and actual temperature is due, mainly, but not exclusively, to the presence of greenhouse gases.

The greenhouse gases expressed as CO_2 thermal equivalents can be included by including two sectors representing the Earth and its atmosphere. A proportion of the incoming solar energy is reflected from the Earth, represented by its albedo, $\alpha\Omega s$. The incoming radiation that is not reflected is then absorbed in the atmosphere by a fractional parameter ($fb < 1$). The energy which is absorbed by the Earth is given as $(1\text{-}fb)\,(1\text{-}\alpha)\Omega s$. Some of the energy absorbed by the Earth is then re-radiated into the atmosphere and contributes to global warming from greenhouse gases. This can be represented in the model as $fa\,(1\text{-}te)E$ where te is the thermal transfer coefficient

6.2.2. The Basic model

The basic model was constructed with three reservoirs which represent:

1. Energy stored in the atmosphere
2. Energy stored in the Earth
3. The level of carbon dioxide in the atmosphere

1. Taking the atmosphere as a store of energy there are five flows in and out.

Inflows

- Sun to atmosphere

- Earth to atmosphere (radiative)
- Earth to atmosphere (thermal)
-

Outflows

- Atmosphere to space
- Atmosphere to Earth

2. For the reservoir representing the store of energy within the Earth's surface there are five flows.

Inflows

- Sun to Earth
- Atmosphere to Earth

Outflows

- Earth to space
- Earth to Atmosphere (radiative)
- Earth to Atmosphere (thermal)

3. The reservoir representing the concentration of Carbon Dioxide in the atmosphere had one inflow, the rate of change of atmospheric CO_2.

These flows were controlled by a number of factors, the exact values of which can be seen on the listing of equations in Appendix A. These are described briefly below.

Solar flux

This represents the incoming solar radiation, and is set at the mean value reaching the upper atmosphere across the globe. This is set at 343 $Wm^{-2}s^{-1}$.

Albedo

The mean value for the Earth is used, allowing 31.3% of incoming radiation to be reflected back into space by either the atmosphere or surface features of the planet.

Short wave absorbed (fb)

This factor represents the proportion of incoming (short wave) radiation which is available to heat the atmosphere. A factor of (1-fb) reaches the earth's surface.

Latent and sensible heat transfer (te)

This represents the proportion of the energy stored in the Earth which is transferred to the atmosphere by thermal conductivity. The remaining energy (1-te) is available as long wave radiation in the flow "earthtoatmosphere".

Long wave re-radiated by atmosphere to Earth (ra)

This factor represents the proportion of the energy stored in the atmosphere which is radiated down to Earth as long wave radiation. The remainder (1-ra) is radiated out to space.

Long wave radiated from Earth to atmosphere (fa)

Is the factor controlling the proportion of the Earth's energy which is radiated as long wave radiation into the atmosphere, the remainder passing through to space.

The rate at which CO2 increases warms the Atmosphere (Sensitivity)

This factor acts as a multiplier for the logarithm of CO_2 concentrations, representing the sensitivity of the atmosphere to changes in levels of greenhouse gases.

sbconstant

This is the Stefan-Boltzmann constant, which allows for the energy which accumulates in the atmosphere to be converted to a temperature in degrees Celsius.

The model was run using an interval between calculations (dt) of one year, using Eulers method of integration and was initially run for 100 years of simulated time, to allow any initial oscillations to die down and stable temperatures to be achieved.

6.2.3. Calibration of basic model.

Theory predicts (Drake 2000) that an Earth without any atmosphere would stabilise with a mean surface temperature of approximately -18°C. An Earth which had it's atmosphere composed of nitrogen, oxygen and water vapour would stabilise with a mean surface temperature of around -6°C, due to the limited absorption of radiated long wave energy by these gases in the atmosphere. The addition of greenhouse gases raises this figure to produce a mean surface temperature of around 15°C.

Initially the model was run with a simulated carbon dioxide level (representing all greenhouse gases) of one part per million. The value of te was then altered slightly until a mean surface temperature of -6°C was achieved.

The level of atmospheric CO_2 was then increased to 270 ppm, representing a reasonable estimate of pre-industrial atmospheric concentrations. The value of the variable "sensitivity" was then adjusted to ensure that this increase in atmospheric CO_2 generated an increase in mean surface temperature to the desired level of 15°C. The graphical output representing the model output using these two different values of atmospheric CO_2 is shown in Figure 6.1 and the overall structure of the model is illustrated in Figure 6.2.

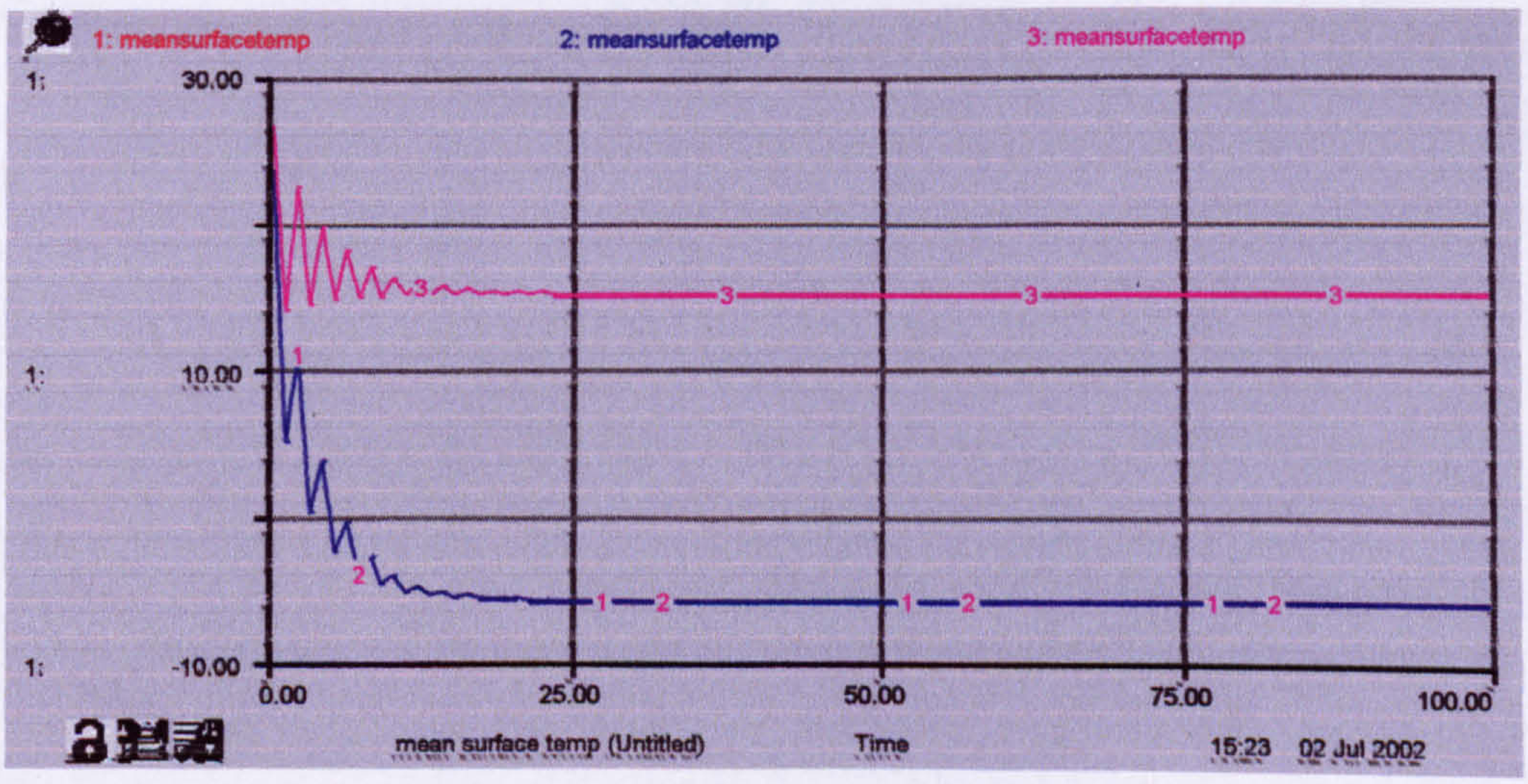


Figure 6.1 Output stabilising at –6 °C and 15 °C

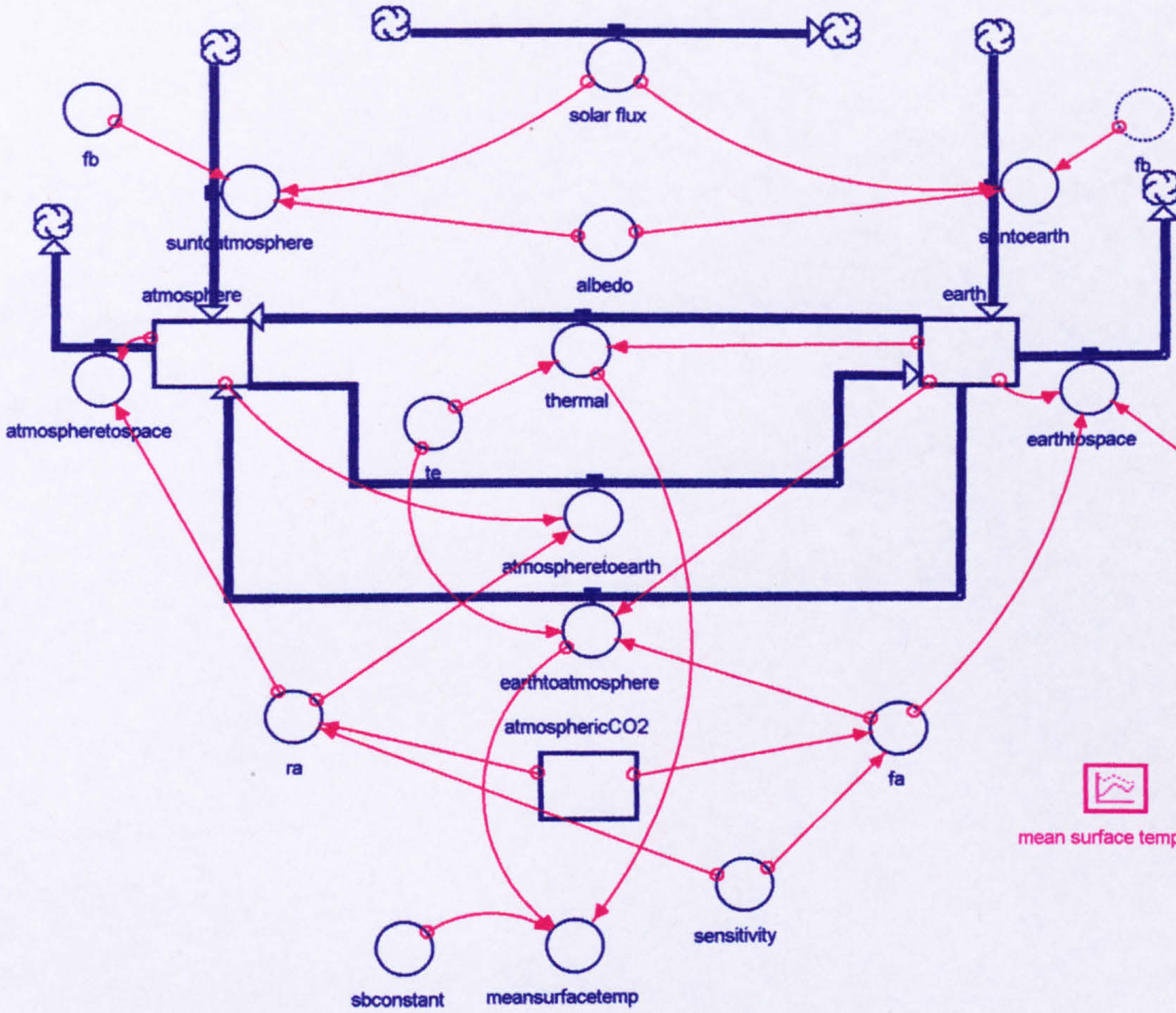


Figure 6.2 The structure of the basic climate model in Stella.

The basic model could now be modified to represent the three regions of Scotland chosen for the study as follows.

6.3. Developing a Regional climate model for Scotland.

The basic model represents a flat disc facing the sun and receiving the same amount of incoming radiation across the entire surface. This generates an even surface temperature of 15°C which is absolutely stable. In order to simulate more accurately the incoming radiation reaching Scotland, several adjustments were made to this flow.

Firstly, in recognition of the inter-decadal variability in solar output associated with the sunspot cycle, solar flux was multiplied by a factor involving a sine wave ("sun"), which varied solar output by 2% over an 11.6 year cycle. This does not affect total incoming radiation over the long term but introduces some periodic variability in the flow.

Secondly, in recognition of the seasonal cycle, the incoming radiation was adjusted to take into account the angle of incidence of solar radiation at a latitude of 56° North throughout the year. In this way the tilt of the Earth towards or away from the sun could be included, making solar radiation relatively strong in the summer and weak in the winter. This was included as "seasonal effect"

One value was calculated for each of the seasons, taking the day at the mid-point of each season and taking the sine of the angle of incidence for that particular date as being the a suitable estimate of the relative strength of solar radiation for that season. An approximate value was arrived at using the formula

Seasonal effect = 0.76 – 0.22*cos ((360/365)*d),

where "Seasonal effect" is the desired multiplier, d is the number of days following the winter solstice, 0.76 represents the sine of the angle of incidence at the equinoxes and the 0.22 is the amplitude of the cosine wave between winter and summer solstices. The mean value of this expression was then taken for each of the seasons. This was included as an array, providing a separate calculation throughout the model for each season.

Thirdly, a component was introduced to represent the varying duration of incoming solar radiation throughout the year ("daylength"). This approximates the difference in the length of time that incoming solar radiation actually falls on the Earth's surface during the different seasons. Again a similar calculation was carried out to give approximate mean lengths of day for each of the seasons. This used the formula

Daylength = 12 – 6*cos ((360/365)*d),

where d is the number of days after the winter solstice and the minimum length of day is assumed to be six hours and the maximum to be eighteen.

The final modification to solar flux is a factor which introduces an element of variability to the final seasonal temperatures. This does not directly affect the value for incoming solar radiation but represents an additional component which attempts to capture some of the variability associated with the influence of circulation patterns such as the North Atlantic Oscillation and the East Atlantic Jet Pattern.

This takes energy, for illustrative purposes a fraction of mean solar radiation, and multiplies this by the sum of two normally distributed variables, each with a mean value of zero and a standard deviation of one. This generates a random pattern of increased and decreased energy input to the system. This is then scaled in order to generate temperature variability which corresponds to that of the empirical record. Since each of the seasons is characterised by a different amount of variability this is further modified by "seasonal variability" which for example scales the temperature fluctuations for winter to approximately twice those of summer. Final values for this were achieved iteratively by comparison of the variability of the model output for the period 1970-2000 with the actual meteorological data.

At this stage the model produced separate outputs, in the form of an array, for each of the seasons of the year, for an area of land at 56° North of the equator.

The mean surface temperatures generated were far below those experienced across central Scotland, as, so far, only incoming solar radiation had been included in the process. The contribution of energy in the form of latent and sensible heat transfer from the oceans surrounding Scotland had still to be included, as it is the main factor which explains the mild conditions experienced here relative to other areas of the planet at a similar latitude.

The inclusion of a component representing "ocean warmth" was therefore necessary in order to generate simulated temperatures which agreed with the empirical records. This also allowed for regional differences to be created by including another arrayed variable based on "regions". The relatively mild winters of Argyll could then be simulated by including a larger value of transferred energy during winter for Argyll than in Stirling or Fife. Similarly the particular character of the different seasons in the three regions could be simulated, by adjusting the values for this added energy by season and by region. Final calibration however required the changes in carbon dioxide levels to be included and this is detailed in the following section. At this stage the model was capable of generating a matrix of values for each dt, giving seasonal mean surface temperatures for the three regions at every calculation interval.

6.3.1. CO_2 Emissions Scenarios

The purpose behind the development of this model was to generate simulated climate for the next century, as an input to a socio-economic model. Of central importance to any consideration of possible future climates is the projected increase in concentrations of greenhouse gases. The model at this stage was capable of running with any chosen single value of atmospheric concentrations of CO_2, but required the ability to simulate different future greenhouse gas emissions.

The IPCC Special Report on Emissions Scenarios, SRES, (IPCC 2000) examines a whole range of potential scenarios, taking into account possible future changes in demographics, socio-economic development and technological change around the globe. The very nature of the complex dynamic systems which generate such changes creates a high degree of uncertainty as to the path which might eventually be taken. As a result, the teams working on this problem have developed a "suite "of scenarios, grouped according to certain basic common features, such as predicted levels of growth in the world economy and the possible developments in energy technologies. In total 40 separate scenarios were developed, all being considered equally sound (IPCC 2000).

The team responsible for the UKCIP02 model chose just four of these emissions scenarios which would be used as the input for the development of future climate scenarios. Details of the predicted CO_2 concentrations in the atmosphere are given below in Table 6.1.

UKCIP02 Scenario	SRES Scenario	2020'sCO_2(ppm)	2050'sCO_2(ppm)	2080'sCO_2(ppm)
Low Emissions	B1	422	489	525
Medium-Low	B2	422	489	562
Medium-High	A2	435	551	715
High emissions	A1F1	437	593	810

Table 6.1 Scenarios from the UKCIP02 and SRES in parts per million CO_2

These figures as detailed in Table 6.1 were included in the regional climate model to provide four separate versions, each corresponding to a Low, Medium-Low, Medium-High or High scenario.

To achieve this, a flow named "CO_2 change" was attached to the reservoir representing atmospheric CO_2. The initial value of this reservoir was set at 270, representing pre-industrial levels of atmospheric CO_2. Known values from 1970 and 2000 were then used in conjunction with the values from the SRES scenarios to generate a set of points ranging from 1850 (pre-industrial levels) up to 2085, for each of the four scenarios.

The flow "CO_2 change" was then set as a graphical function, which allowed the rate of change of CO_2 to be altered with respect to the level of CO_2 in the atmosphere. By an iterative process it was possible to generate an output table of CO_2 concentrations which ran through all the known points up to the year 2000 in the simulation.

A similar process was then carried out for each of the four separate scenarios and a good fit to projected levels achieved. Each scenario produces a different graph representing future CO_2 concentrations, with the curve running through known points at historical dates, and the projected levels at future dates.

These graphs of the atmospheric concentrations of CO_2 projected by the four scenarios are presented below as Figure 6.3.

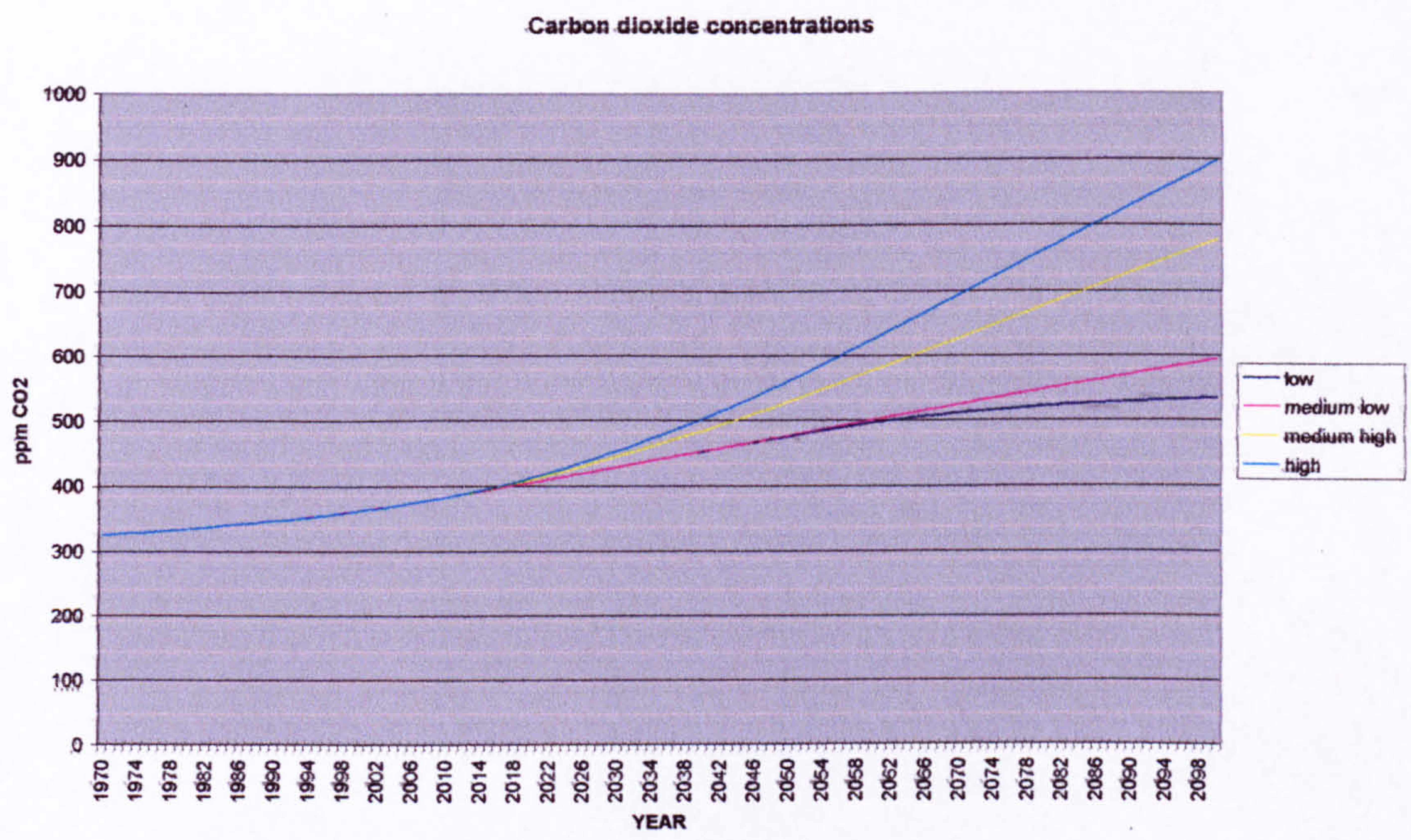


Figure 6.3 Carbon dioxide concentrations according to the four scenarios

Each separate version of the model was then ready to generate simulated temperatures under different conditions of increased CO_2 concentrations for a period of 250 years, representing the period from 1850 to 2100.

6.3.2. Calibration of the regional model

For each region and for each season the mean temperature and standard deviation was obtained from the empirical records for the period 1970-2000.

The model was then run and the section from a tabular output representing years 120-150 was extracted. Since the model has been designed to simulate temperatures for a 250 year period starting in 1850, this time slice represents 1970-2000 in the simulation.

All four versions of the model use the same initial values for "CO_2 change" and so have an identical structure up to the 150th simulated year.

Descriptive statistics were then obtained from the output, for each of the regions and each of the seasons. This was compared to those from the empirical record and any required adjustments to the model were made.

"Seasonal variability" controlled the spread of the data and was adjusted for each season until a reasonable fit with the temperature records was achieved.

"Oceanwarmth" controlled each regions seasonal temperature and fine tuning allowed the mean value to be adjusted again to fit with the temperature records.

The final values obtained can be seen in the relevant section of the listing of the program presented in appendix 1.

Table 6.2 illustrates how the simulated temperatures compare to the meteorological data for the period 1970-2000.

	Empirical records		Simulation	
Region/season	Mean temperature	Standard deviation	Mean temperature	Standard deviation
ARGYLL				
Spring	7.7	0.6	7.6	0.5
Summer	13.4	0.7	13.2	0.8
Autumn	9.6	0.6	9.7	0.7
Winter	4.9	0.9	4.9	0.9
STIRLING				
Spring	7.7	0.6	7.7	0.5
Summer	14.3	0.8	14.2	0.8
Autumn	9.2	0.7	9.4	0.7
Winter	3.9	1.1	3.9	1.0
FIFE				
Spring	7.0	0.6	6.9	0.5
Summer	13.7	0.7	13.6	0.8
Autumn	8.7	0.7	8.8	0.7
Winter	3.4	1.1	3.3	1.0

Table 6.2 Comparison of Stella model output and empirical records for period 1970-2000

It can be seen that the model matches well ($R^2 = 0.99$ sig <0.01) both the mean values and the spread of the data as measured by the standard deviation.

6.3.3. Introducing precipitation to the model

The generation of seasonal precipitation figures from first principles was considered beyond the scope of a simple model so the output from the UKCIP02 model (UKCIP 2002) was adapted for use with the existing model.

This is presented in the report in the form of maps with 50km grid squares, each of which is coloured according to a predicted percentage change in precipitation. These are given for each of the four scenarios, with one map representing the percentage change at points in time, representing the 2020's, the 2050's and the 2080's.

Each of the scenarios is developed according to a particular rate of growth in atmospheric carbon dioxide concentrations. It was decided to list the CO_2 concentrations in ascending order, regardless of scenario, and to examine how the precipitation changes corresponded to CO_2 concentrations. A data file was created in SPSS V10, which had as one variable, listing in ascending order the CO_2 concentrations listed in Table 6.1. Other variables were then created which listed the percentage precipitation increase for each region and for each season, corresponding to the scenario and date for the particular CO_2 concentration listed in the first variable.

It was then possible to perform regression analysis in order to determine the relationship between increases in CO_2 concentrations and percentage changes in precipitation.

A good fit was found using both linear and quadratic equations with the latter providing a slightly higher value for the adjusted R^2. This relationship, however, as CO_2 concentrations continued to rise beyond those used in the analysis, would eventually pass a maximum value and begin to descend. No such relationship is suggested in the literature so the linear relationship was chosen as the best method of describing the relationship between carbon dioxide concentrations and precipitation change.

The linear equations generated are listed in Table 6.3 below along with their respective values of R^2 and the significance of the regression.

ARGYLL	Regression Equation	R^2	Significance
Spring	%precipitation change = -7.2 + 0.026*CO_2	0.38	0.034
Summer	%precipitation change = 25.3 - 0.087*CO_2	0.9	<0.001
Autumn	Constant		
Winter	%precipitation change = -24.7 + 0.061*CO_2	0.83	<0.001
STIRLING			
Spring	Constant		
Summer	%precipitation change = 10.9 - 0.069*CO_2	0.83	<0.001
Autumn	Constant		
Winter	%precipitation change = -24.1+ 0.064*CO_2	0.82	<0.001
FIFE			
Spring	Constant		
Summer	%precipitation change = 16.5 - 0.077*CO_2	0.81	<0.001
Autumn	Constant		
Winter	%precipitation change = -13.0+ 0.059*CO_2	0.84	<0.001

Table 6.3 Regression equations relating precipitation change to atmospheric CO_2 concentration

It can be seen that only Argyll shows a slight increase in precipitation during spring. Other changes are restricted to increases in precipitation during winter, and decreases during summer.

These equations were then included in the model in the following way. The reservoir representing CO_2 concentrations was connected to a converter named "precipitation change". The level of CO_2 was taken and 270 subtracted to give the increase over pre-industrial levels. This was then multiplied by the coefficient from the relevant equation listed above to give the percentage change in precipitation for each region. Dividing this figure by 100 produced a multiplier for the seasonal mean figure to give the actual change in precipitation. Where the relationship was best modelled as a constant, then this multiplier was set at zero.

The seasonal precipitation could then be calculated by taking the mean figure from the empirical record and adding this CO_2 induced change. In order to model more accurately the variability of precipitation totals, an additional converter was included. This was based on the natural variability which could be observed in the seasonal figures for each region.

For each region and each season, descriptive statistics were obtained for the precipitation data. A figure was obtained for the standard deviation as a fraction of the mean and this was then used as the standard deviation for a normally distributed variable with mean one, and the standard deviation as above. Summer rainfall in Stirling showed the greatest variability and this was multiplied by a normally distributed variable with mean one, and a standard deviation of 0.35. The lowest variability was found to be in Argyll in Autumn, where the standard deviation of the variable was set to 0.218. All other seasons for the regions fell between these two values.

One unintended consequence of this was to allow for negative precipitation to occur, albeit infrequently. To prevent this an if/then statement was included which prevented the factor "variability" taking a value which then produced less than the recorded minimum value for each regions seasonal rainfall total.

The climate model could now be run and would generate at each dt a value for temperature and precipitation for each region and for each season. The built in functions of Stella "Arraysum" and "Arraymean" allow annual precipitation totals and annual mean surface temperatures to be calculated from the matrix of values generated at each calculation interval.

The final structure of the model is shown below in Figure 6.4 and all of the equations are presented in Appendix 1

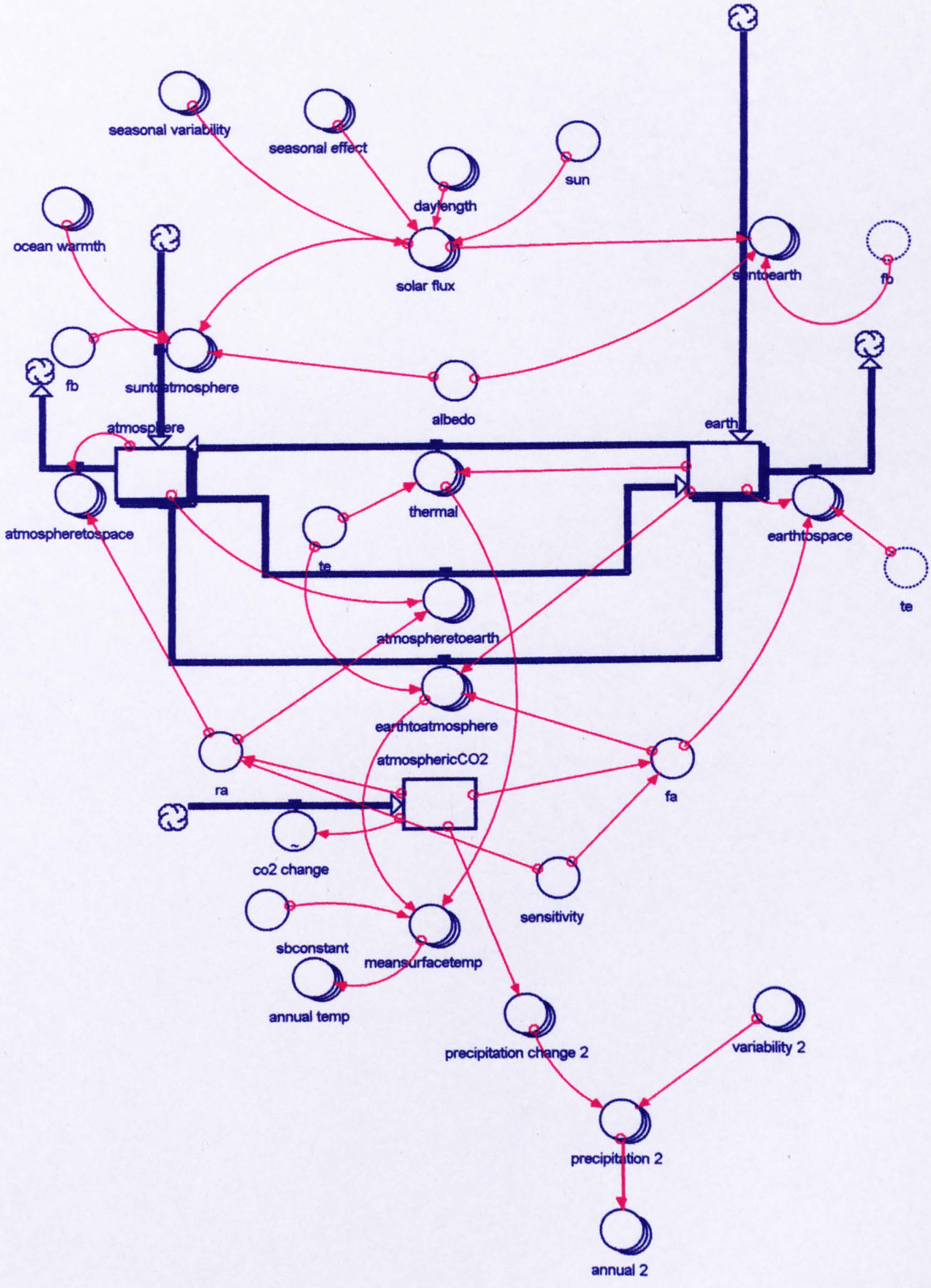


Figure 6.4 The final structure of the climate model.

Chapter 7 A comparison of empirical trends, the Stella model and the UKCIP02 output.

7.1. Temperature

In this chapter a comparison is drawn between the trends generated by linear regression on the empirical data, the temperature model developed in Stella and the forecasts from the UKCIP02 model constructed at the Hadley Centre.

The empirical trends are those described earlier (see Chapter 4) and relate to the mean values of temperature for each region produced by the amalgamation of data from the separate meteorological stations. For each region there is one future projection, in contrast to the Stella and Hadley Centre models which generate four separate possible future trends, one for each CO_2 scenario.

Results are generated for each region, for each season, as well as for the annual change in temperature. This allows for a comparison of the three methods, and an identification of where similarities and differences lie.

7.2. Preparing the output for comparison

7.2.1. Empirical trends

Linear regression was performed on the regional mean daily surface temperature data for the period 1970-1999. This was done using all the data to produce an equation relating to the annual trend, and using the split file option in SPSS 10.0 to generate regression equations for each of the seasons. In most cases this produced a regression equation which was significant at a level of either 0.05 or 0.01. Not all the regression equations were significant at this level and details of the equations are shown in table 11.1

In each case "T" represents the temperature in degrees Celsius (x 10^{-1}) and year is the date, e.g. 1970. As such this represents a simple trend through time.

SEASON	REGION	REGRESSION EQUATION	SIGNIFICANCE
Spring	Argyll	T = - 410.3 + 0.246 * year	<0.01
	Stirling	T = -326.7 + 0.203 * year	0.021
	Fife	T = -406.8 + 0.241 * year	<0.01
Summer	Argyll	T = -114.9 + 0.126 * year	<0.01
	Stirling	T = -66.8 + 0.105 * year	0.05
	Fife	T = -160.5 + 0.150 * year	0.05
Autumn	Argyll	T = -253.9 + 0.176 * year	0.11
	Stirling	T = -474.2 + 0.285 * year	<0.001
	Fife	T = -234.2 + 0.162 * year	0.056
Winter	Argyll	T = -239.0 + 0.145 * year	0.014
	Stirling	T = -229.2 + 0.135 * year	0.125
	Fife	T = -281.4 + 0.159 * year	0.018
Annual	Argyll	T = -211.9 + 0.167 * year	<0.01
	Stirling	T = -596.1 + 0.345 * year	<0.01
	Fife	T = -449.7 + 0.268 * year	<0.01

Table 7.1 Regression equations for temperature

It can be seen from Table 7.1 that only two sets of data, those for Argyll in Autumn and Stirling in Winter, fail to generate a regression equation which is significant at the 5% level of confidence. These two equations are nevertheless included in order to provide a comparison for the model outputs. In each case the trend line was extrapolated to the year 2100 and these trend lines have been included in the relevant graphs for comparative purposes. This allows a comparison of the extrapolation of current trends with the model outputs, effectively indicating how current trends, based on past increases in CO_2, compare to future trends with different rates of increase of atmospheric CO_2.

7.2.2. The Stella Model

Data for the comparative graphs was generated using six runs of the model. The Exception was winter where the in-built variability of the model was greatest. In the case of winter all data was produced using twelve runs of the model. This was exported to Excel and the mean value of these was then taken. This had the effect of dampening down the built in variability in temperature, which had been included to provide realistic inter-annual variations. Each simulation ran for 250 years and only the section of the output relating to 1970-2100 was used. The standard deviation associated with these runs of the model was used to provide error bars on the following graphs. Each graph is presented with error bars representing plus and minus one standard deviation.

7.2.3. UKCIP02

The report (UKCIP 2002) presents projected temperature changes in the form of increases over the mean value for the standard period of 1960-1990. This takes the form of maps on which the UK is split into 50x50 km boxes. Each box is coloured according to a key where different colours represent a rise in temperature between an upper and lower value. Thus an orange box might signify an increase in temperature of between 1 and 1.5 degrees Celsius. Maps are provided for time periods representing the 2020's, the 2050's and the 2080's with a set being presented for each of the four CO_2 scenarios. This means for each scenario it would be possible to take an average temperature increase for each of the time periods or to take an upper and lower boundary, effectively generating two separate trend lines between which the temperature increase should lie. The latter option was chosen in order to represent graphically the uncertainty of these future scenarios.

The empirical data was taken from the decades of the seventies to the nineties. As such it was not compatible with the standard three decade period used for the baseline of this model. In order to generate an annual mean surface temperature for each of the three regions for the period 1960-1990, the above regression equations were used.

Data for the 1970's and 1980's was available, so this was combined with a figure for the 1960's which was calculated by subtracting the temperature change per decade from the 1970's figure. This yielded mean annual temperatures which could be combined with those from the period of the study to generate a single mean surface temperature for the standard period.

The increases in temperature as an upper and lower value were obtained by inspection of the UKCIP report. This posed a problem in terms of the resolution of the map. Identifying the correct grid squares for each region was not straightforward. Fife proved to be the easiest and one single grid square was identified as being representative of this region. Two adjacent squares were then chosen to represent Stirling, giving it a reasonable correspondence with the actual location and dimensions. Argyll, however, is larger in extent but the map fails to give any representation of the islands and peninsulas of the west coast. Two grid squares were identified as representing Argyll, one adjacent to the more westerly grid for Stirling and one to the south of this.

For many of the maps, temperature change did not vary greatly between the grid squares relating to each region, so no problems arose. In the event that two adjacent grid boxes representing one region were different in colour, the lower boundary was taken as the lower value of the two and the higher boundary taken as the higher of the two.

In this way it was possible to generate for each region a set of figures which gave the upper and the lower boundaries of the projected temperature rise for periods taken as 2025, 2055, and 2085. These were included in an Excel spreadsheet and the complete time series generated by filling the missing data points, using a built in function of Excel which generates a linear trend between two points. Given that the rate of change was different for different time periods, it was decided to generate data between successive points rather than simply the first and last. This produced a graph which rose in stages, with the higher emissions scenarios being relatively flat initially but becoming steeper towards the end of this century.

7.3. Results for temperature.

The results of this exercise are presented as graphs from which it is possible to identify similarities and differences between the different methods. Each graph follows a similar pattern and the key is the same throughout.

7.3.1. Spring

The following graphs represent the Low, Medium Low, Medium High and High scenarios from the UKCIP02 and Stella Models for spring (March, April and May). Also included are the trends obtained by use of linear regression applied to the empirical data.

For each of the scenarios it is possible to generate a separate graph for each of the regions. For illustrative purposes only one graph from one region has been included in the text. Each graph shows the extrapolation of the empirical trend (pink), the lower and upper boundaries of the projected temperature increase from the UKCIP02 model (blue and green) and the output from the Stella model (red). In addition the output from the Stella model is presented with error bars. These represent plus and minus one standard deviation, calculated from multiple runs of the model. This gives an idea of the range of values produced by the Stella model as a result of the simulated variability. Winter temperatures show greater variability than do those of any other season. The model reproduces this by increasing the variability, and hence the size of the error bars, on the graphs for simulated winter temperatures.

Low Scenario

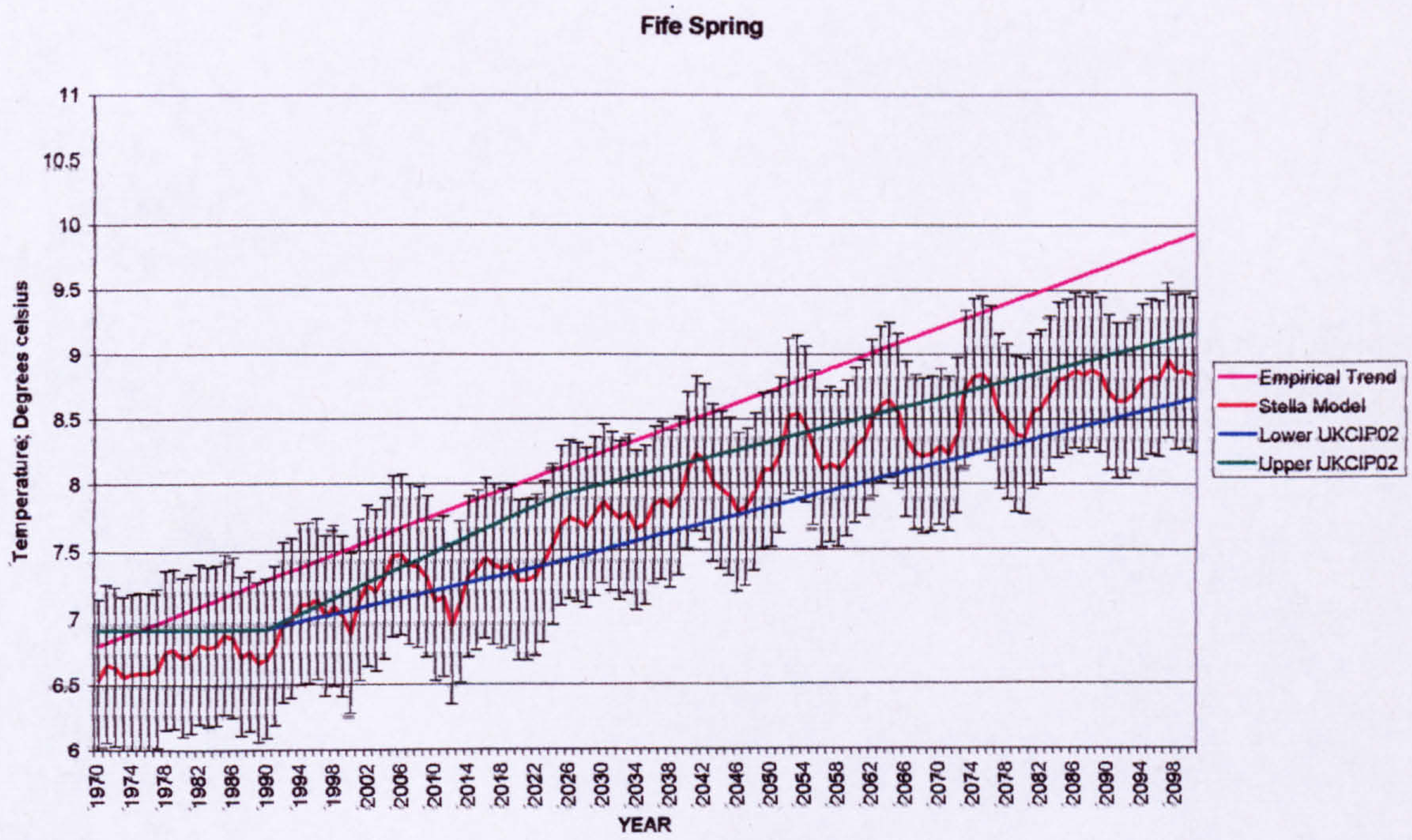


Figure 7.1 Low scenario Fife spring.

Inspection of Figure 7.1 reveals that in this case the empirical trend line lies above both the models projections. This is also true for Argyll. The empirical trend from Stirling is close to both sets of model outputs. For all the regions the Stella Model is very close to the upper boundary of the range predicted by the UKCIP02 model.

Both models do appear to generate a temperature increase of around 1.5-2 °C over the period of the simulation. In general, this is slightly less in the Low emissions scenario than an extension of empirical trends would suggest.

Medium Low Scenario

The graph for the Medium Low scenario, Figure 7.2, is very similar to that of the Low scenario, similar values of atmospheric CO_2 are predicted until the latter part of the century. Again there is a close match between the output of both models, the upper boundary of the UKCIP02 projections being very close to the output of the Stella Model.

Medium Low scenario

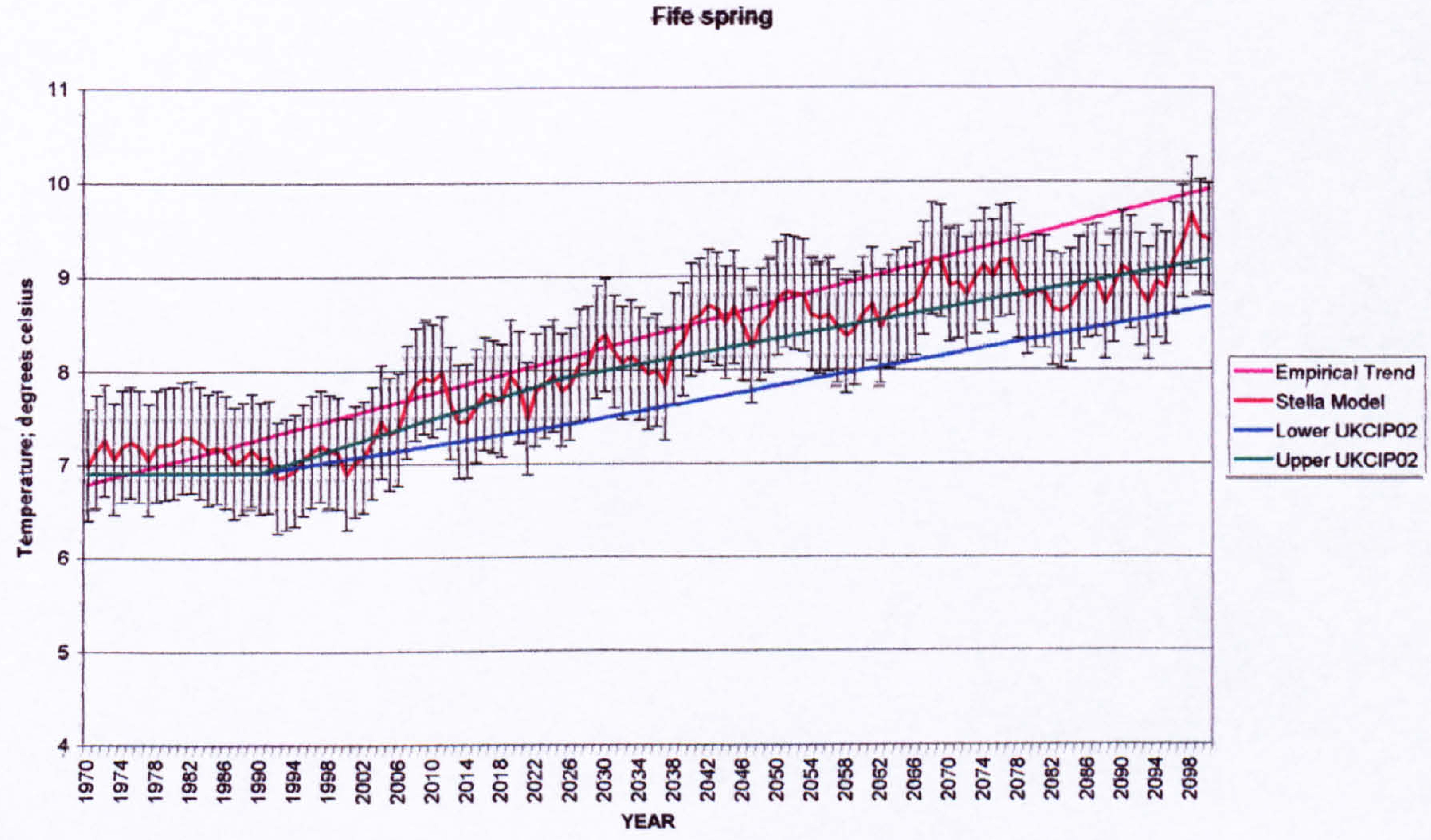


Figure 7.2 Medium Low scenario Fife spring

Again it can be seen that the empirical trends appear to be giving a somewhat larger increase in temperature than the two models suggest for the medium low scenario, especially for Argyll. Again the mean value of the Stella model is towards the upper boundary of the temperature increase generated by the UKCIP02 model.

Medium High Scenario

The Medium High scenario, Figure 7.3, has significant increases in atmospheric CO_2 towards the end of the century. This is reflected in the steeper gradient of the Hadley Centre model output, as well as the increase generated by the model in Stella. The empirical trends are very close to the models for most of the next century, being slightly lower towards the final decades.

Medium High Scenario

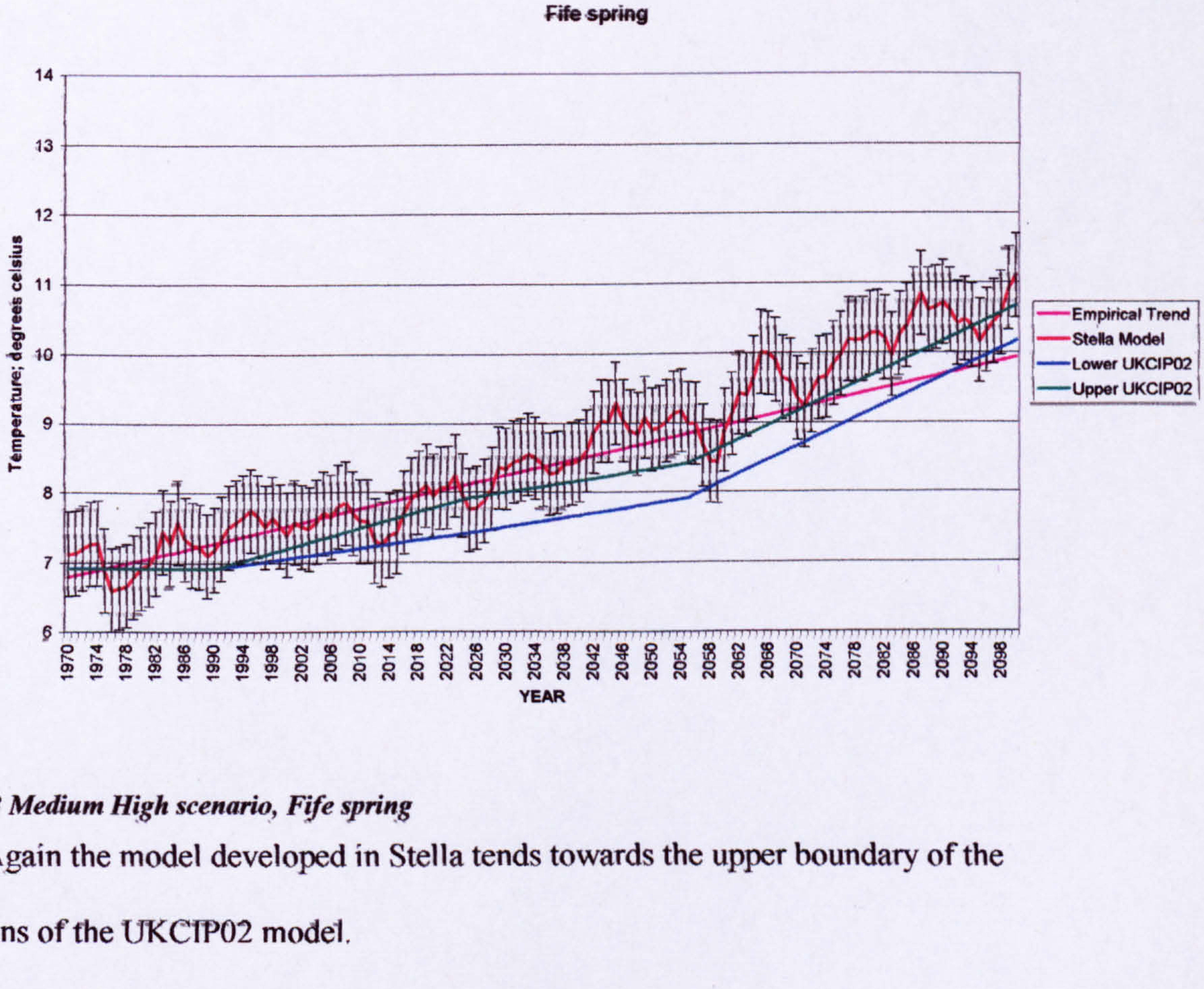


Figure 7.3 Medium High scenario, Fife spring

Again the model developed in Stella tends towards the upper boundary of the projections of the UKCIP02 model.

High Scenario

This scenario, illustrated by Figure 7.4, has by far the steepest increases in atmospheric CO_2 and the final temperatures achieved are a reflection of this. Again, the rate of increase itself grows towards the end of the century, and the boundaries of the UKCIP02 model projections increase their gradient as a reflection of this.

With the High scenario the empirical trends are below the final output of the two models. The model in Stella suggests a slightly higher spring temperature for Fife than is predicted by the UKCIP02 model and this result is repeated for Stirling and Argyll (not shown).

High Scenario

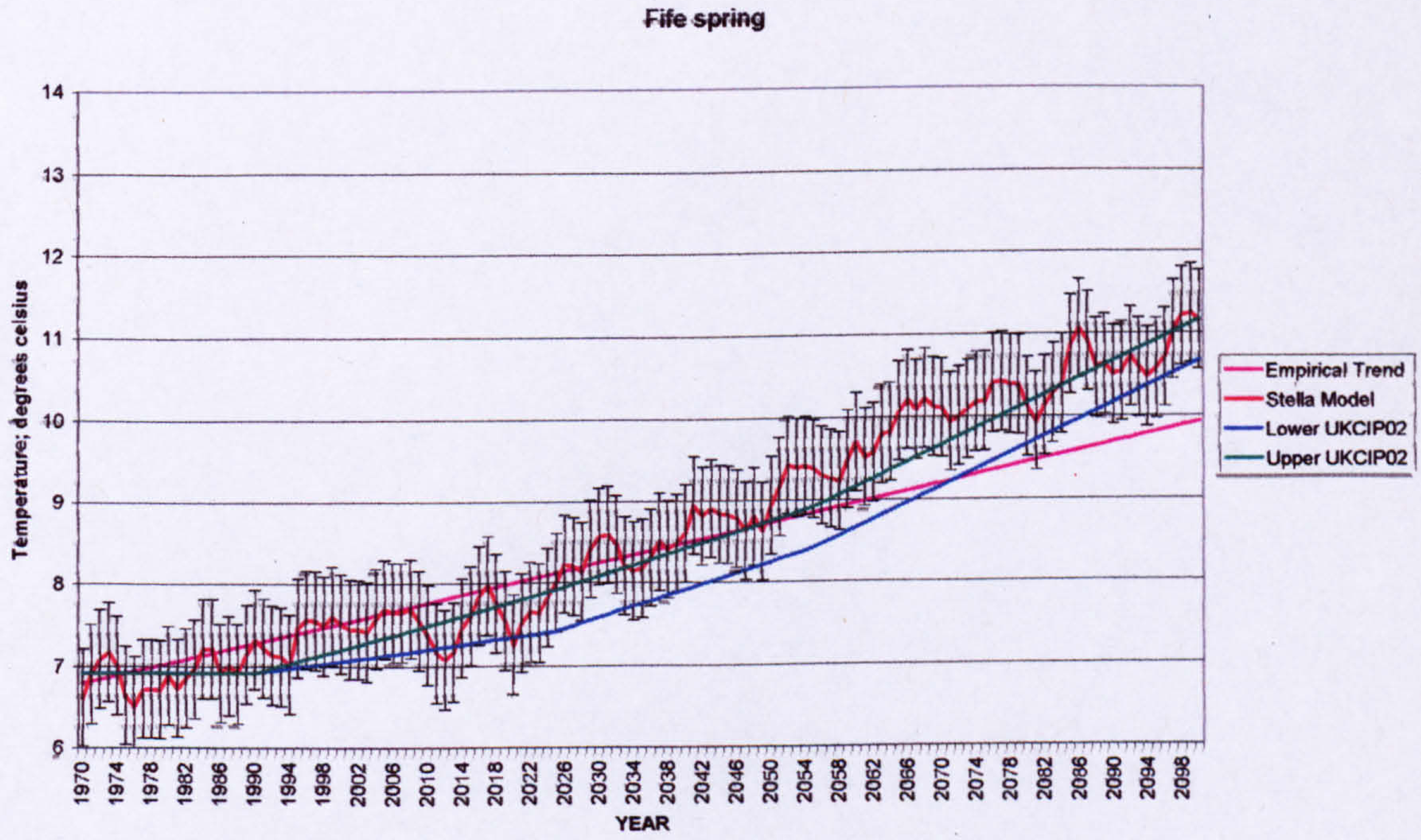


Figure 7.4 High scenario, Fife spring

Of the three regions the output for Fife shows the greatest amount of agreement between the models.

7.3.2. Summer

The following four graphs represent the Low, Medium Low, Medium High and High scenarios and illustrate the same sets of data as those for spring.

Low Scenario

Under the conditions of the Low scenario both models produce simulated temperatures which agree quite closely. The trends in the empirical data are not very strong and tend to be below the lines representing the models. For summer in the three regions the model in Stella generates slightly higher temperatures than does the UKCIP02 model. However the UKCIP02 output is largely within the boundaries of the error bars for the Stella model output. In Fife there is a good deal of agreement by the end of the century. Figure 7.5 illustrates the trends for the low scenario

Low Scenario

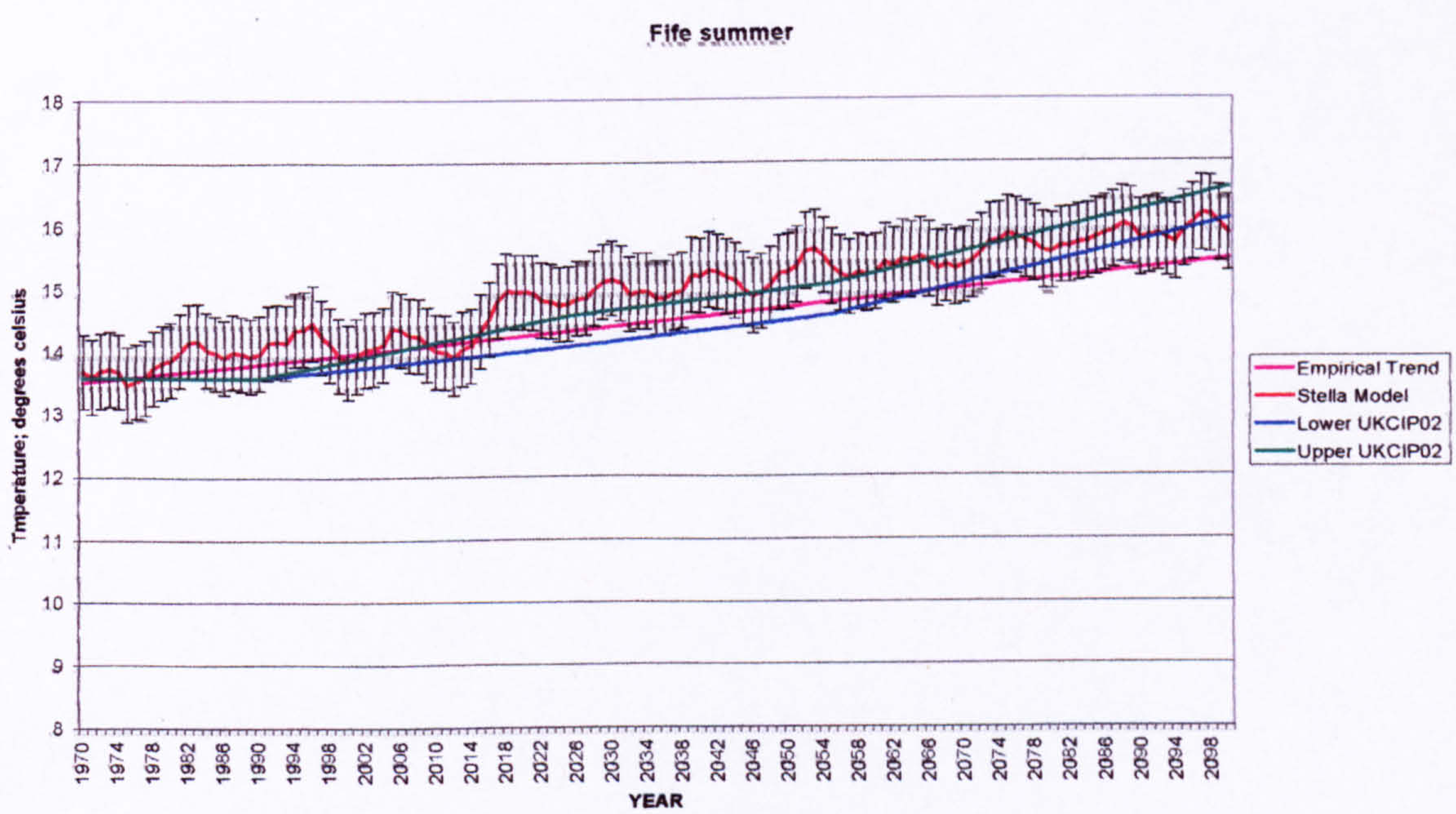


Figure 7.5 Low scenario, Fife summer

Medium Low Scenario

For the medium Low scenario there is close agreement between the two models. The trends are all below the models' output, though there is close agreement from all three methods until the middle of the century. Figure 7.6 shows the output for Argyll during the summer months.

Medium Low Scenario

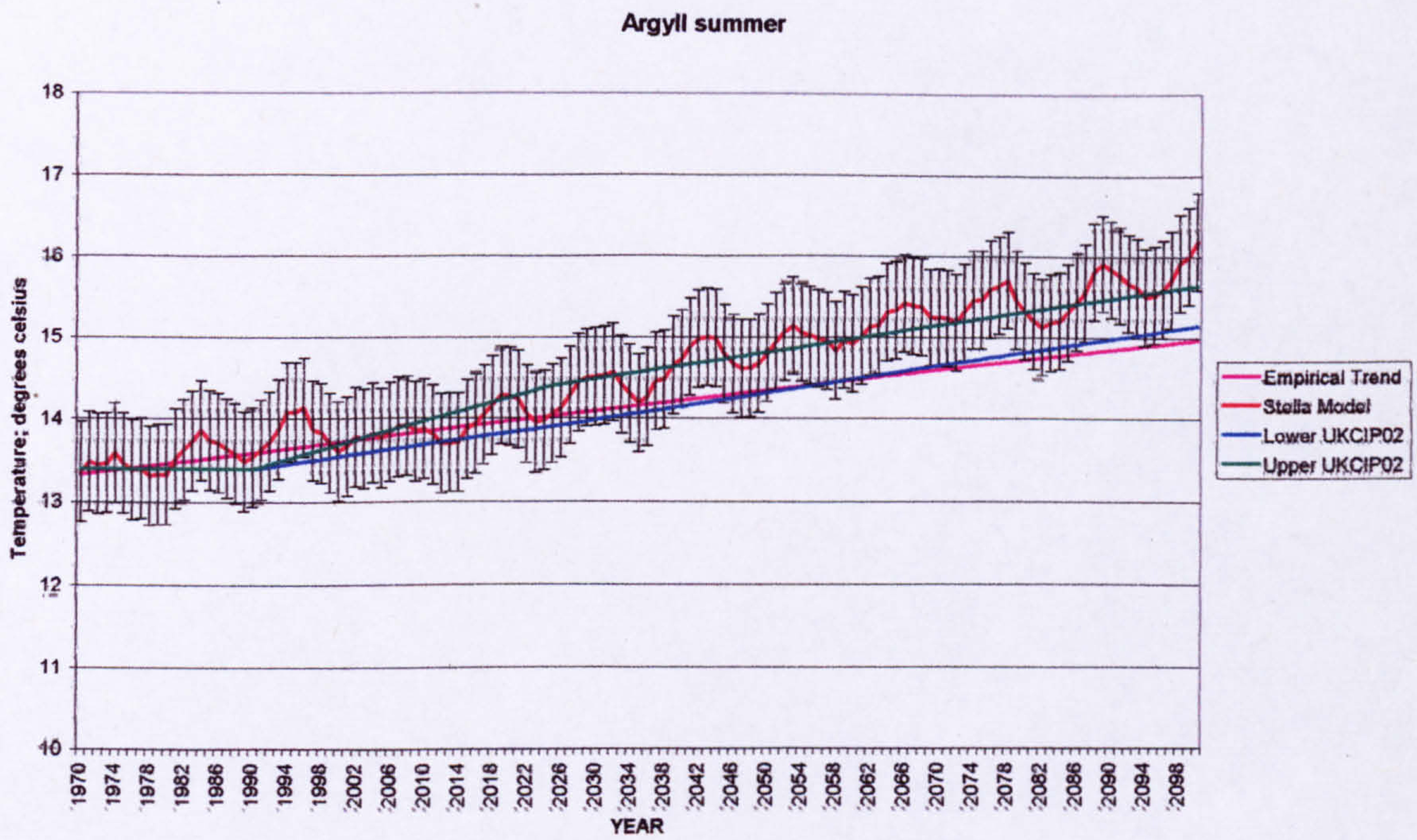


Figure 7.6 Medium Low scenario, Argyll summer

Again the Stella Model tends to be at the upper boundary of the output from the UKCIP02 model.

Medium High Scenario

The gap between the models and the empirical trends is increasing with greater CO_2 concentrations developing towards the end of the century, but there is still good agreement between the models. This is shown in Figure 7.7 which shows the results for Stirling.

Medium High Scenario

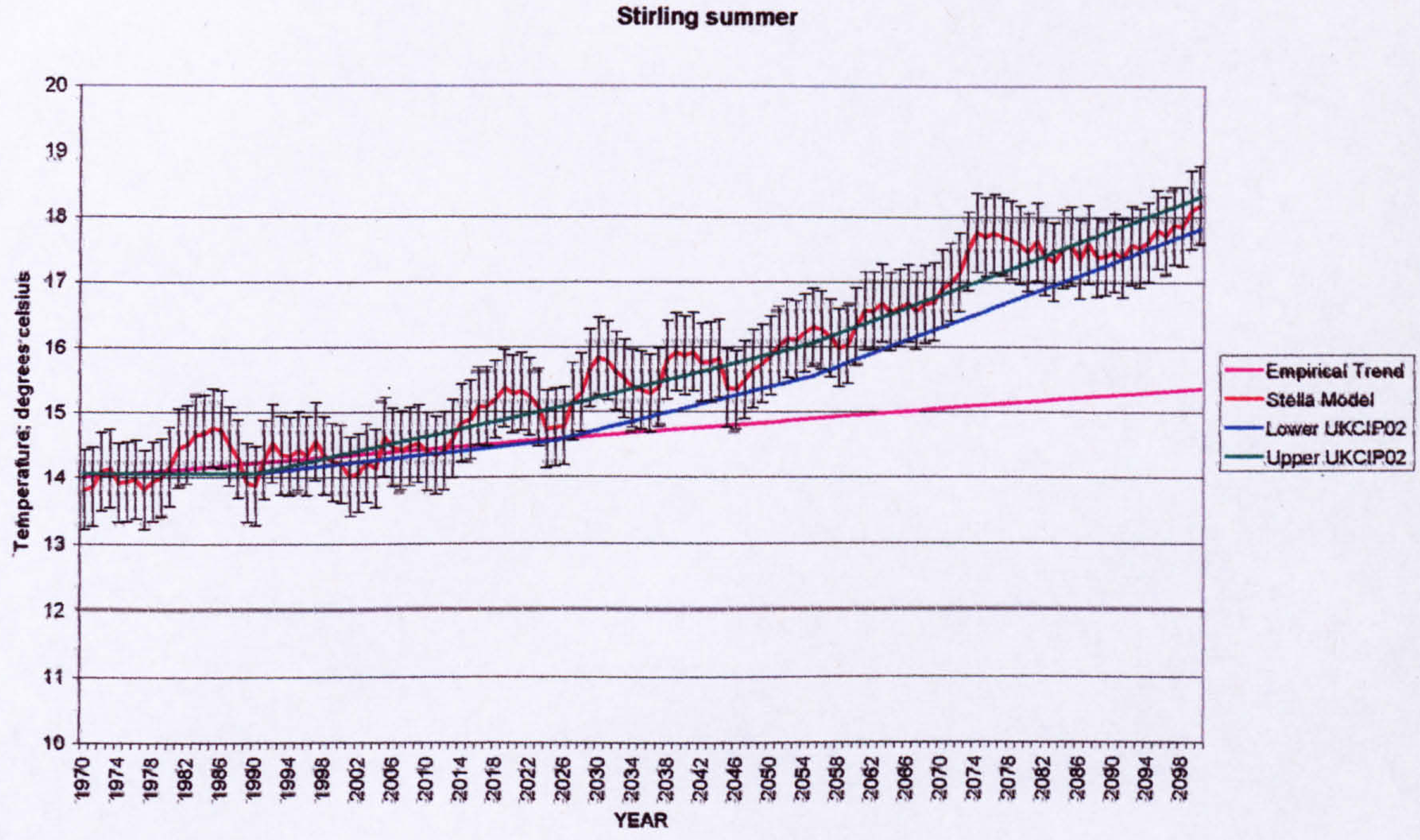


Figure 7.7 Medium high scenario, Stirling summer

Both Stirling and Fife are very close, whereas the Stella model generates temperatures which are slightly above those generated by the UKCIP02 model for Argyll.

High Scenario

Figure 7.8 shows the results for Argyll during the summer months.

High Scenario

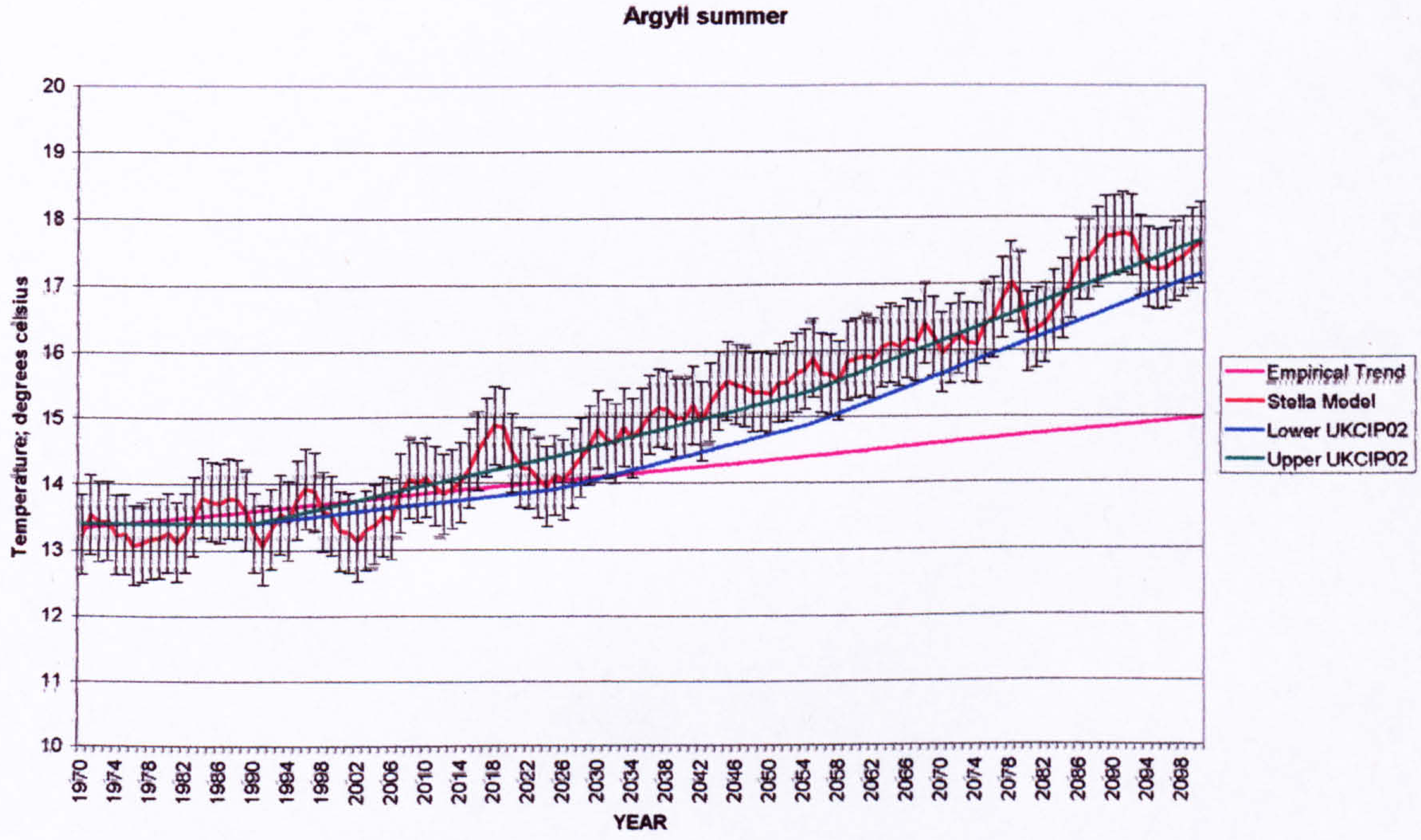


Figure 7.8 High scenario, Argyll summer

A similar good correspondence between the two model outputs is visible under conditions of the High scenario, with the mean value of the Stella model output being very largely situated between the upper and lower boundaries of the output from the UKCIP02 model.

7.3.3. Autumn

A similar set of graphs is presented below illustrating the comparison between the two models and the empirical trends for the autumn.

Low Scenario

Figure 7.9 illustrated the comparison for Fife in the Autumn. The UKCIP model tends to indicate a stronger warming trend towards the end of the century than the Stella model, particularly for the west coast. Both models show a lower temperature than that suggested by the empirical trends.

Low Scenario

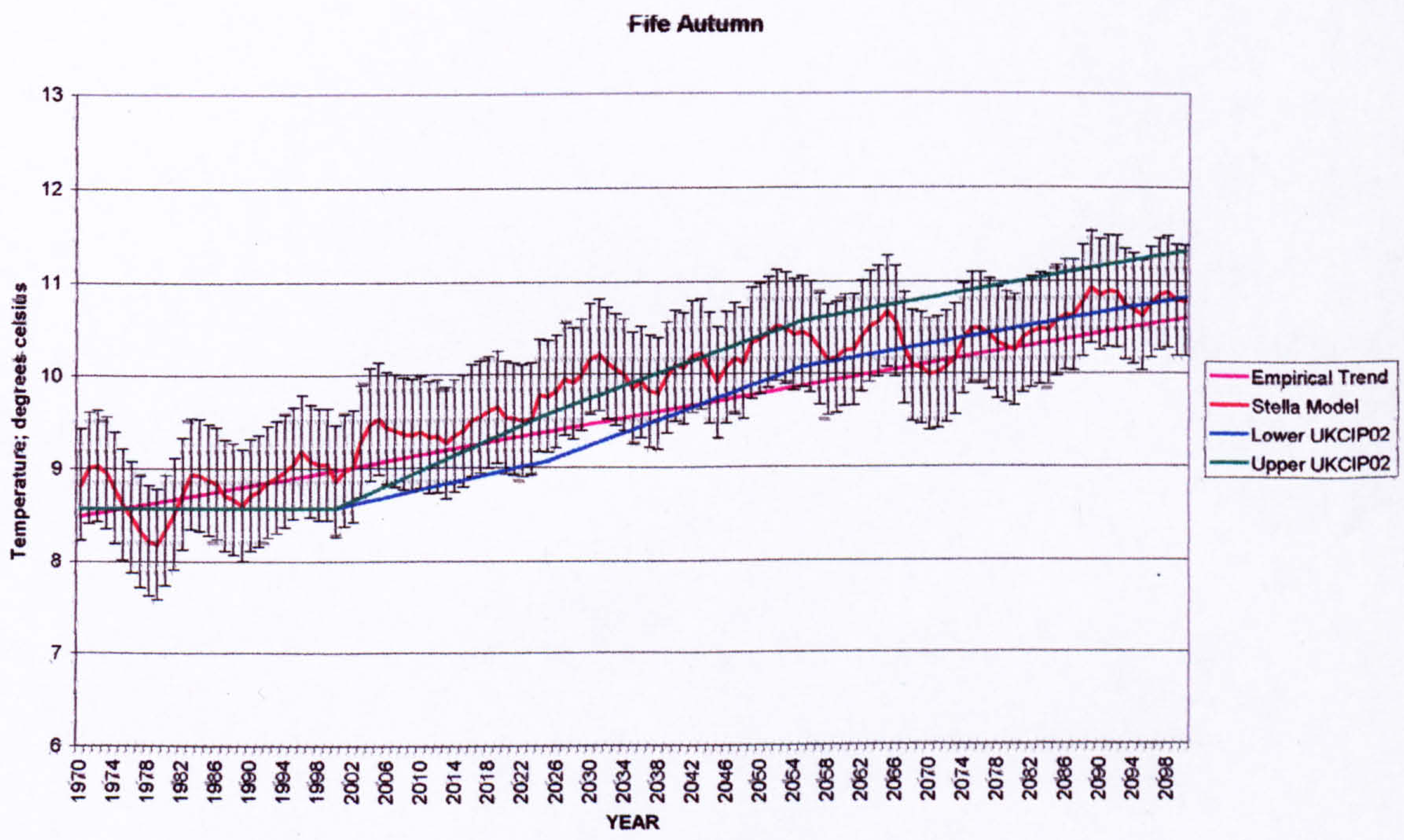


Figure 7.9 Low scenario, Fife autumn

Medium Low Scenario

With the medium low scenario there is close agreement between the two models and the empirical trends. For each region the Stella model is largely within the upper and lower boundaries generated by the UKCIP02 model. Figure 7.10 shows the results for Fife.

Medium Low Scenario

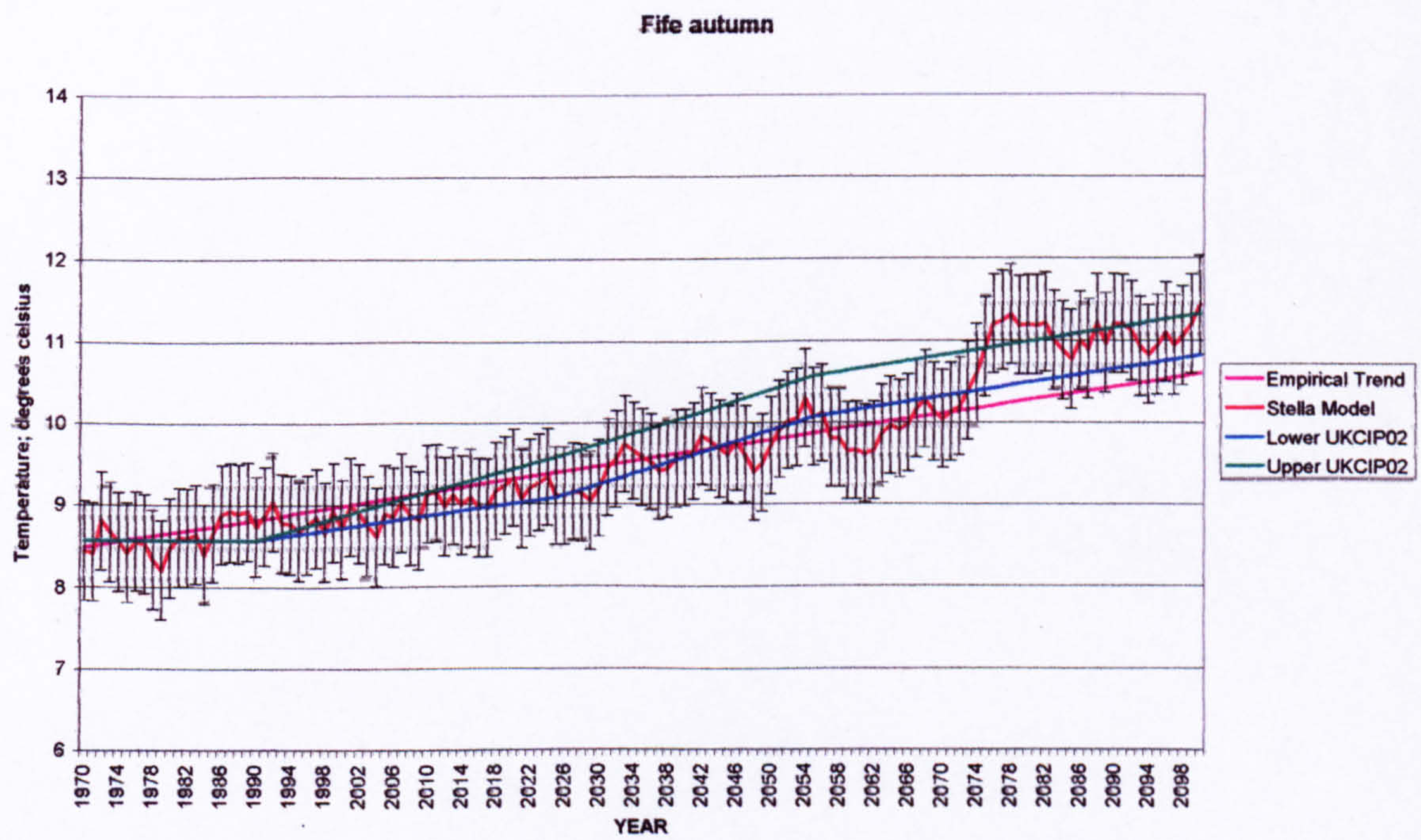


Figure 7.10 Medium Low scenario, Fife Autumn

Medium High Scenario

The empirical trends in Figure 7.11 appear below the model outputs, with the exception of Stirling which is very close to the output for the two models. Again the models appear to broadly agree with the Stella model output being largely within the upper and lower boundaries of the UKCIP02 model. Figure 7.11 shows the comparison for Argyll.

Medium High Scenario

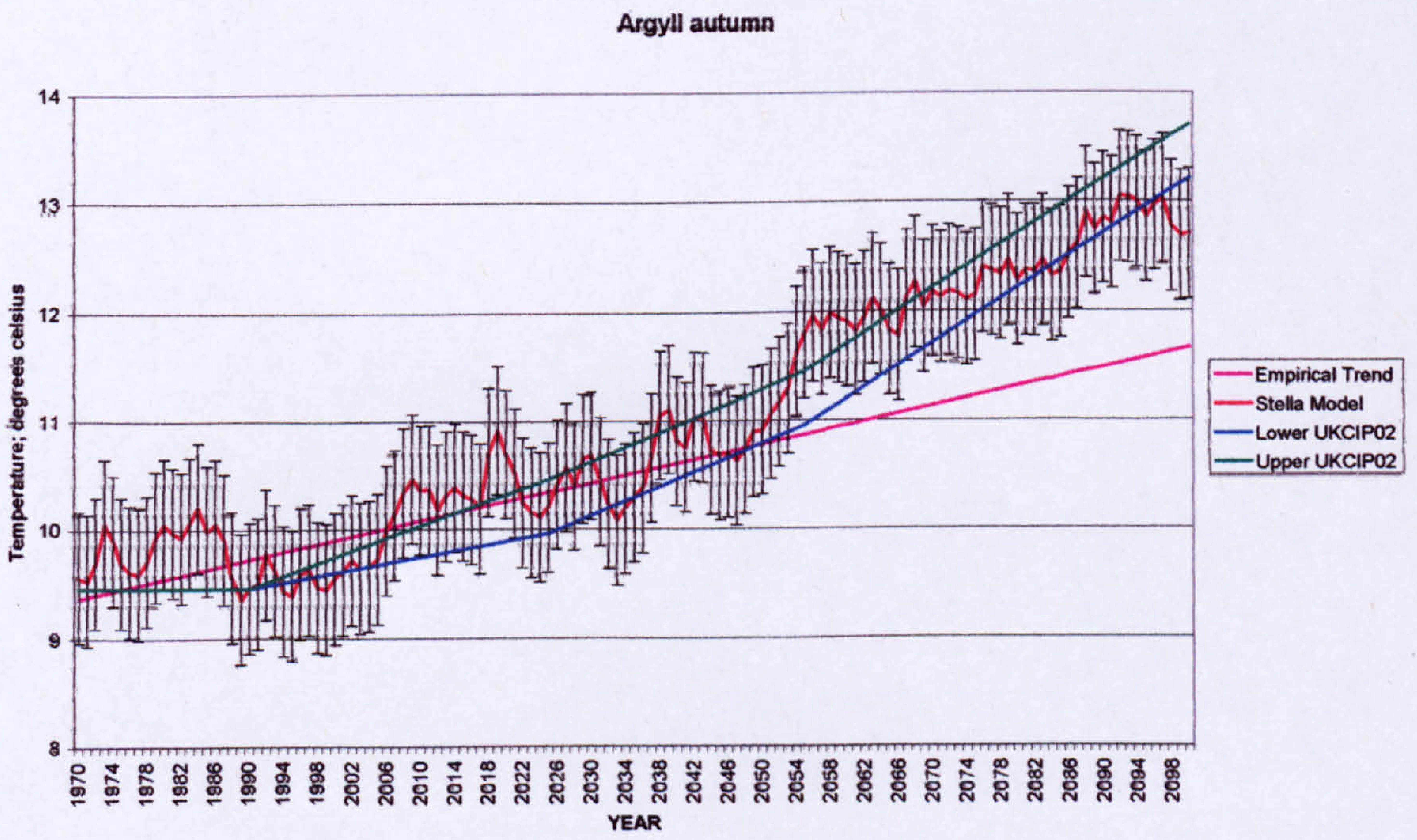


Figure 7.11 Medium High scenario, Argyll Autumn

High Scenario

The high scenario, illustrated by

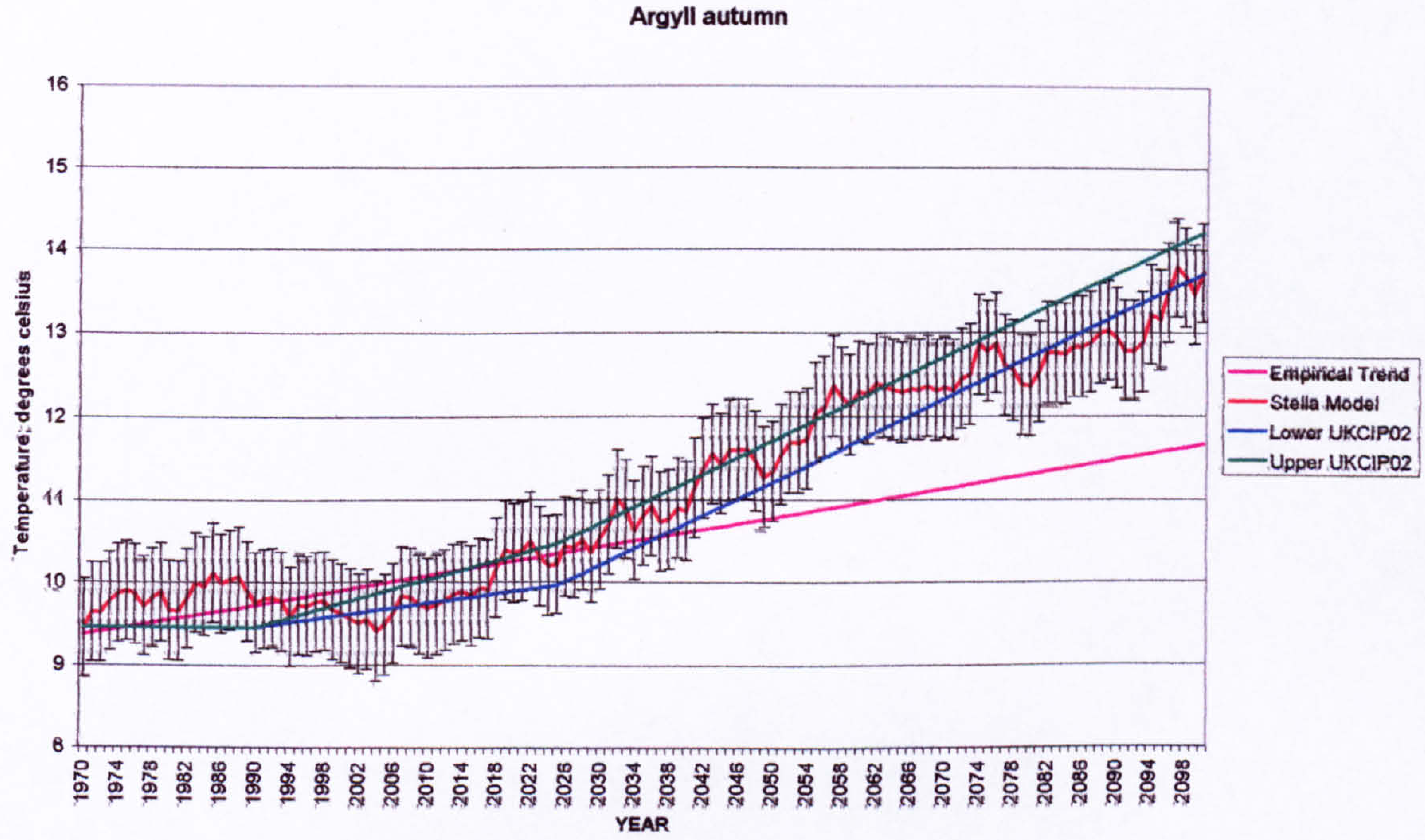


Figure 7.12, sees far higher temperature increases than is predicted by the empirical trend. The UKCIP02 model suggests a convergence of temperatures for Argyll, Stirling and Fife which is not a feature of the Stella model which retains the slight difference between the regions.

High Scenario

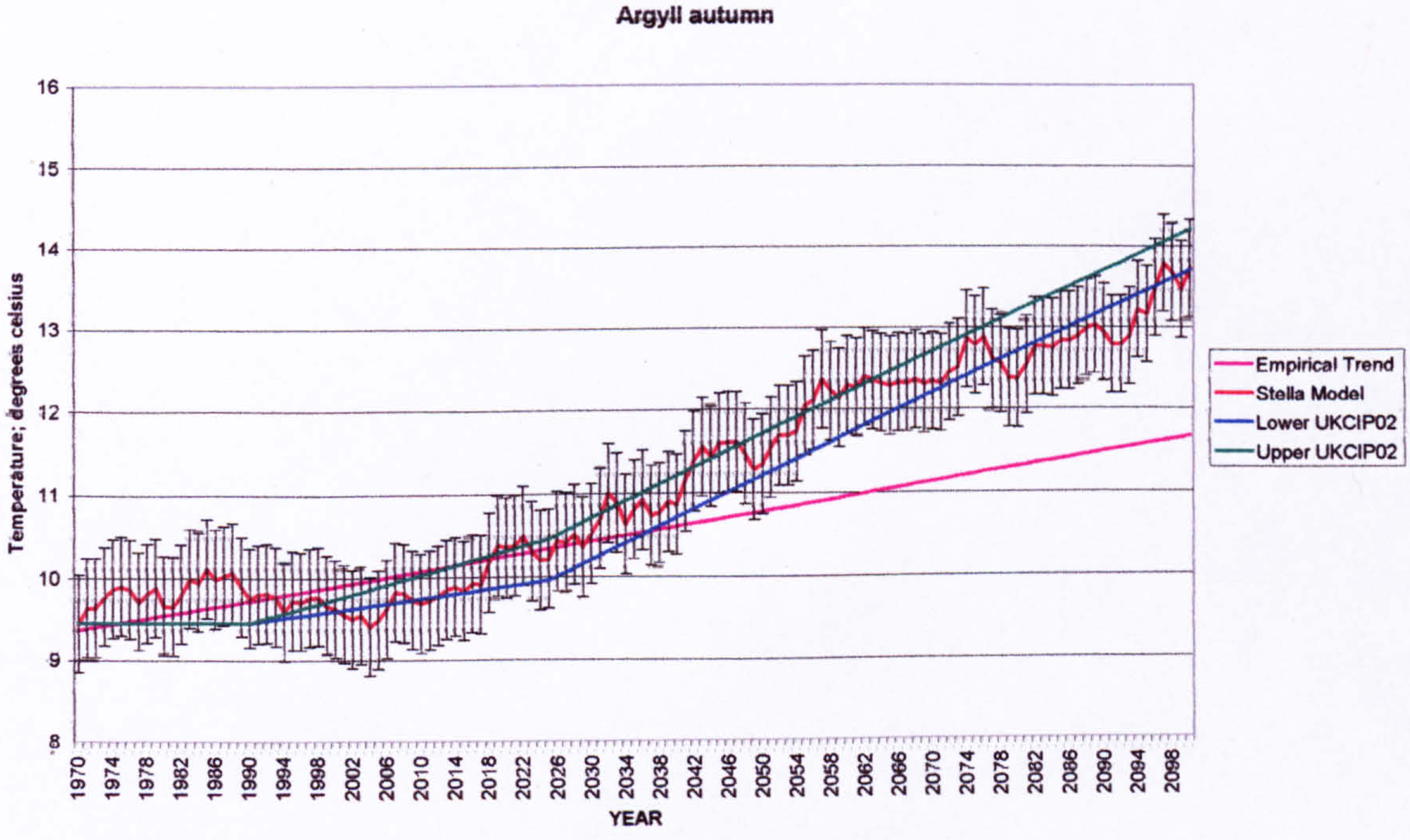


Figure 7.12 High scenario, Argyll Autumn

Thus the two models are in some agreement for Stirling and Fife but the Stella model generates lower temperatures for Fife. Towards the end of the century, than does the UKCIP02 model.

7.3.4. Winter

Because of the relatively high variability which exists in the empirical data and which is captured by the model in Stella, winter temperatures as generated by this model are far more variable. As a result, twelve runs of the model were used and the arithmetic mean calculated. This smoothes the graph but considerable variability is still present. However, the comparison with the UKCIP02 upper and lower boundaries is made easier by this method.

Low scenario

It is possible to see from Figure 7.13 that the lowest estimates of temperature are those of the UKCIP02 model, whereas the Stella model and empirical trends seem to concur.

Low Scenario

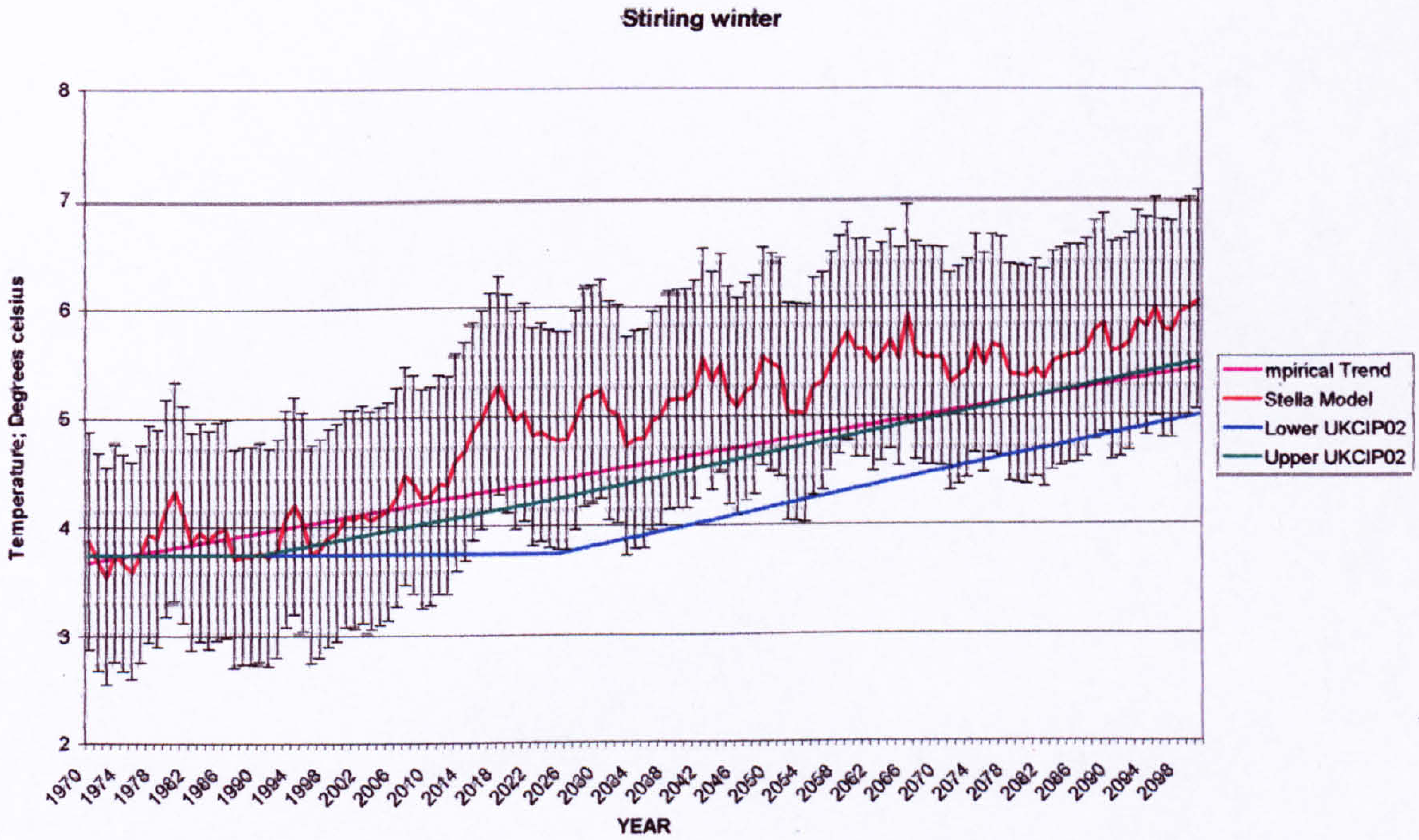


Figure 7.13 Low scenario, Stirling winter

The UKCIP02 model suggests very little change in winter temperatures before the middle of the century under the conditions of the Low scenario. The Stella model however has increases in temperature in the middle of the century, which then tail off towards the end of the century. In all cases there is a close match between empirical trends and the Stella model.

Medium Low

The projections for Fife and Stirling from the UKCIP02 model are lower than either the Stella model or the empirical trends. The projections for all three methods are broadly similar for Argyll. Figure 7.14 shows the results for Argyll.

Medium Low Scenario

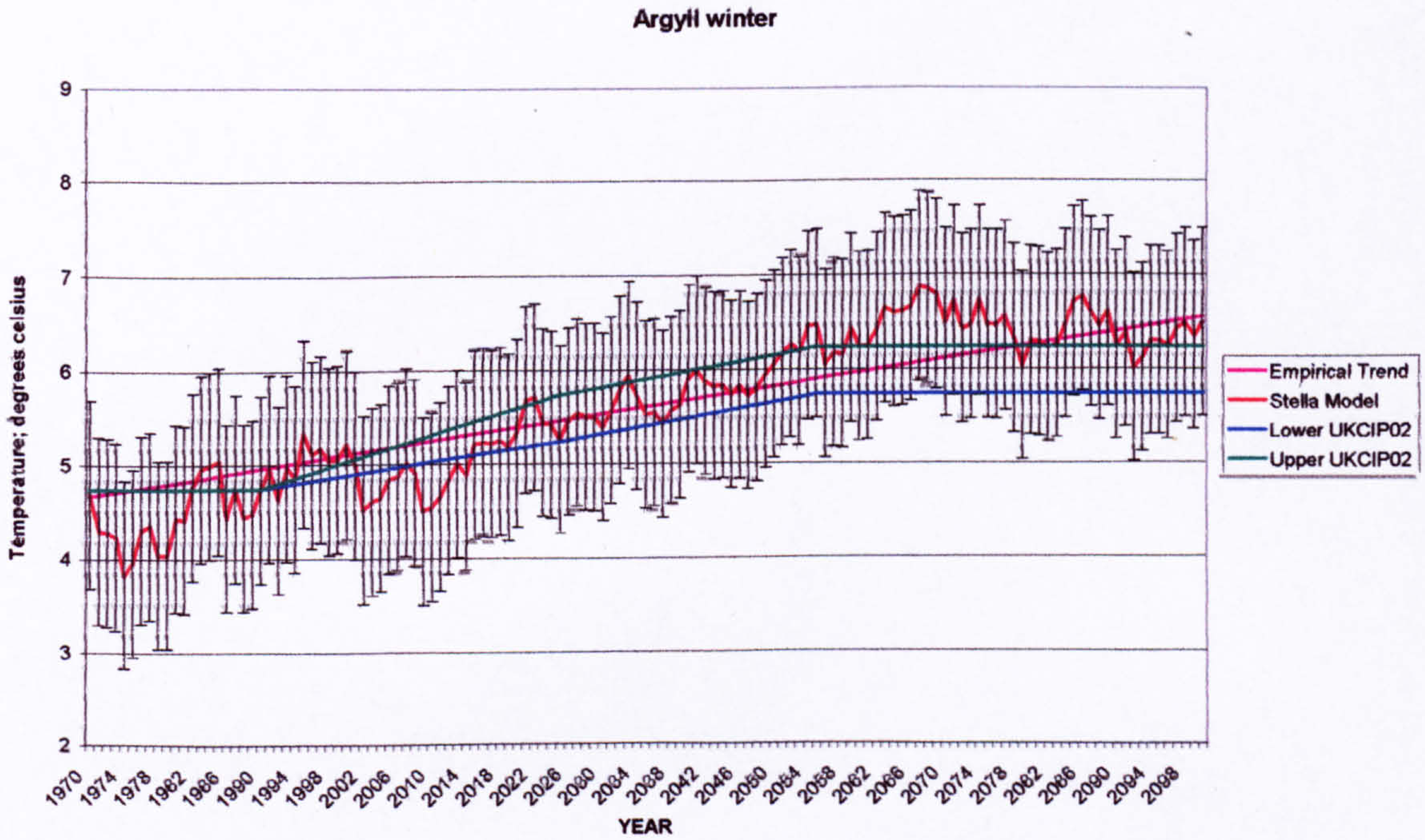


Figure 7.14 Medium low scenario, Argyll winter

Medium high

There is a great deal of similarity between the models for most of the simulation. However the UKCIP02 model does not generate temperatures quite as high as the Stella model towards the end of the century. The empirical trends are well below the output of the two models by the middle of the century. This is illustrated by Figure 7.15 which shows the results for Argyll.

Medium High Scenario

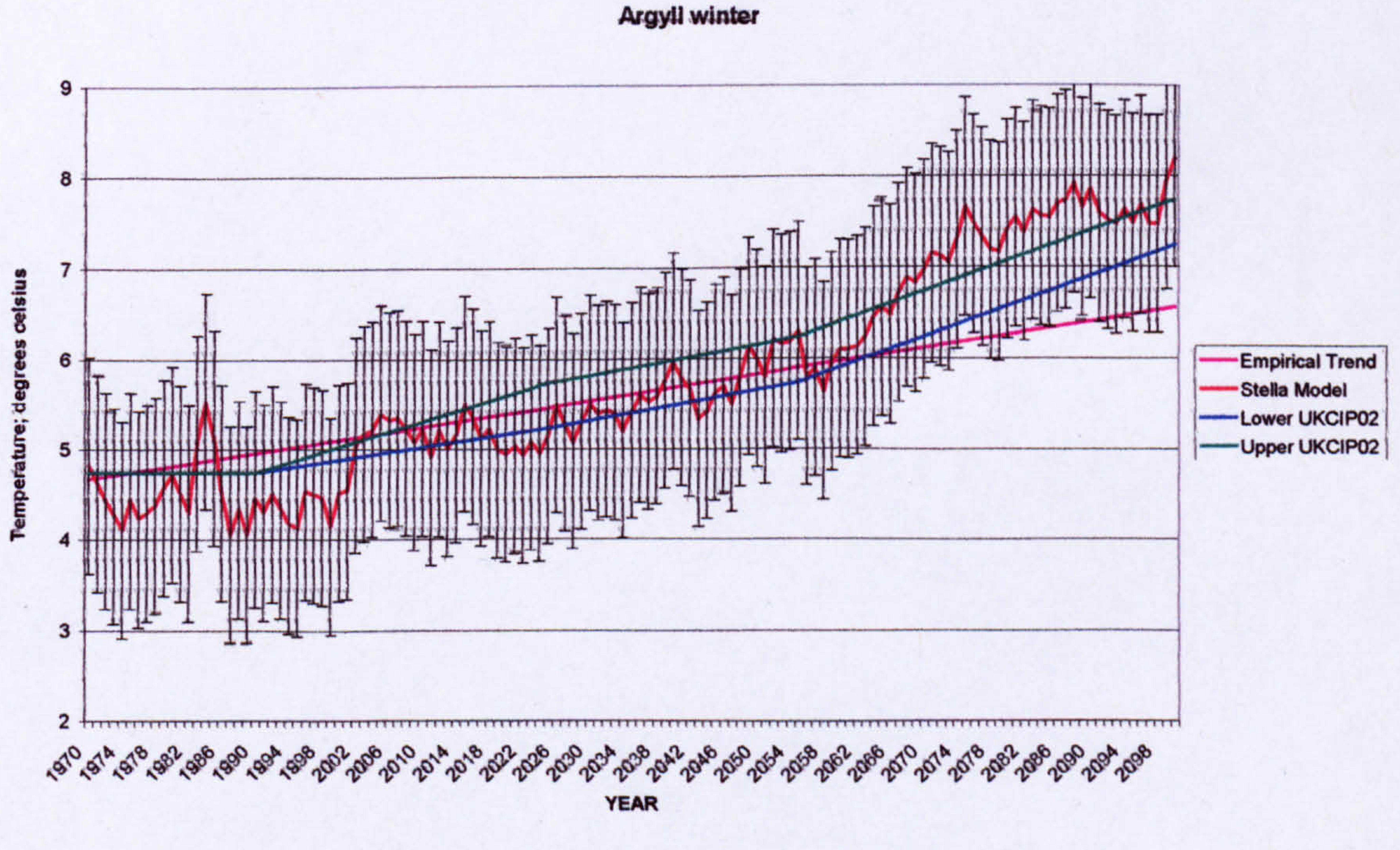


Figure 7.15 Medium high scenario, Argyll winter

High Scenario

Again, it is towards the last few decades of the 21st century that the two models tend to diverge. Up to this point there is a great deal of similarity in their outputs. Both suggest higher winter temperatures than does a simple extrapolation of current trends.

In all three regions the Stella model forecasts warmer winters than does the UKCIP02, particularly by the end of the century. Figure 7.16 shows the results for Argyll.

High Scenario

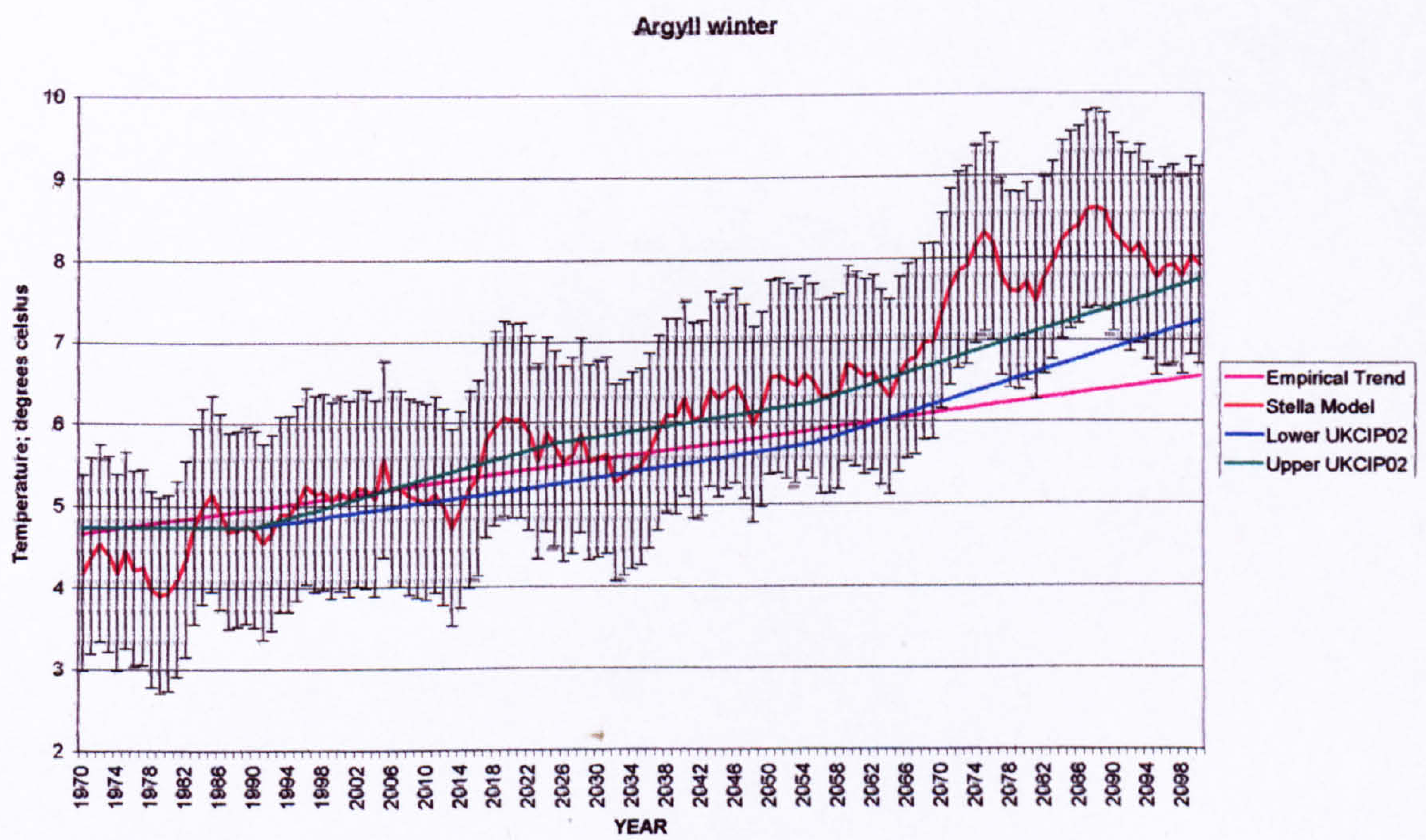


Figure 7.16 High scenario, Argyll winter

7.3.5. Annual

In this section the annual trends identified from the empirical data are compared with the two models' output. For the UKCIP02 model this comes from the 50km grids covering the UK. For the model from Stella it is simply the mean value of the seasonal temperatures generated for each interval of calculation. The colour scheme remains the same as for previous graphs.

In the low scenario there is remarkable agreement between the model outputs and in particular with Argyll, the empirical trend is very close to the models' projections. This is shown by Figure 7.17.

Low scenario

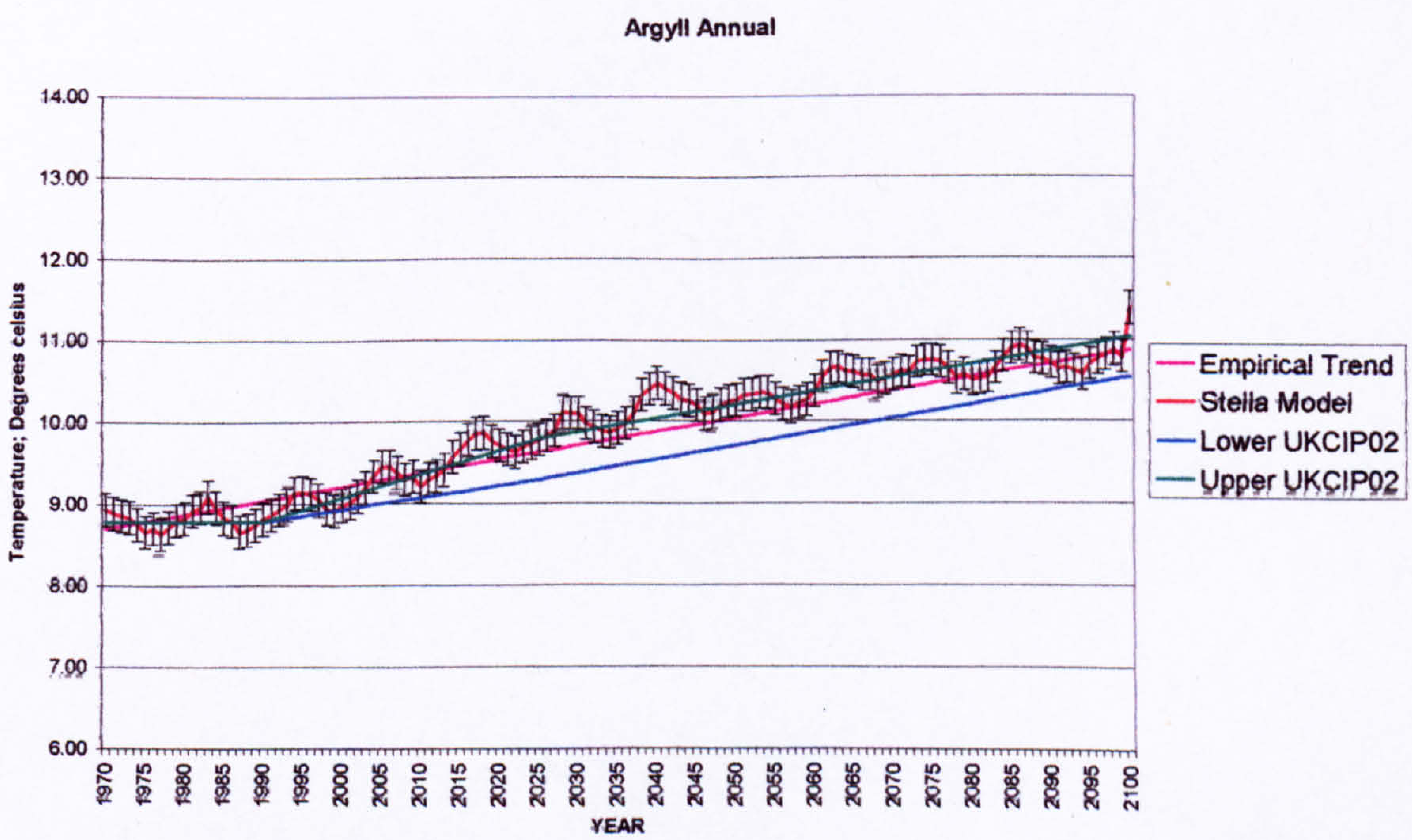


Figure 7.17 Low scenario, Argyll annual

Both models generate temperatures which are below those achieved by an extrapolation of current trends, with only Argyll having all three projections being very close. The trend identified for Stirling is well above that of the two models. In general there is good agreement between the three methods.

Medium Low Scenario

The two models generate similar temperature projections and it is only the empirical trend from Stirling which shows any disagreement with the other methods. Again all the projections are very close together. Figure 7.18 shows the results of the comparison for Fife.

Medium Low Scenario

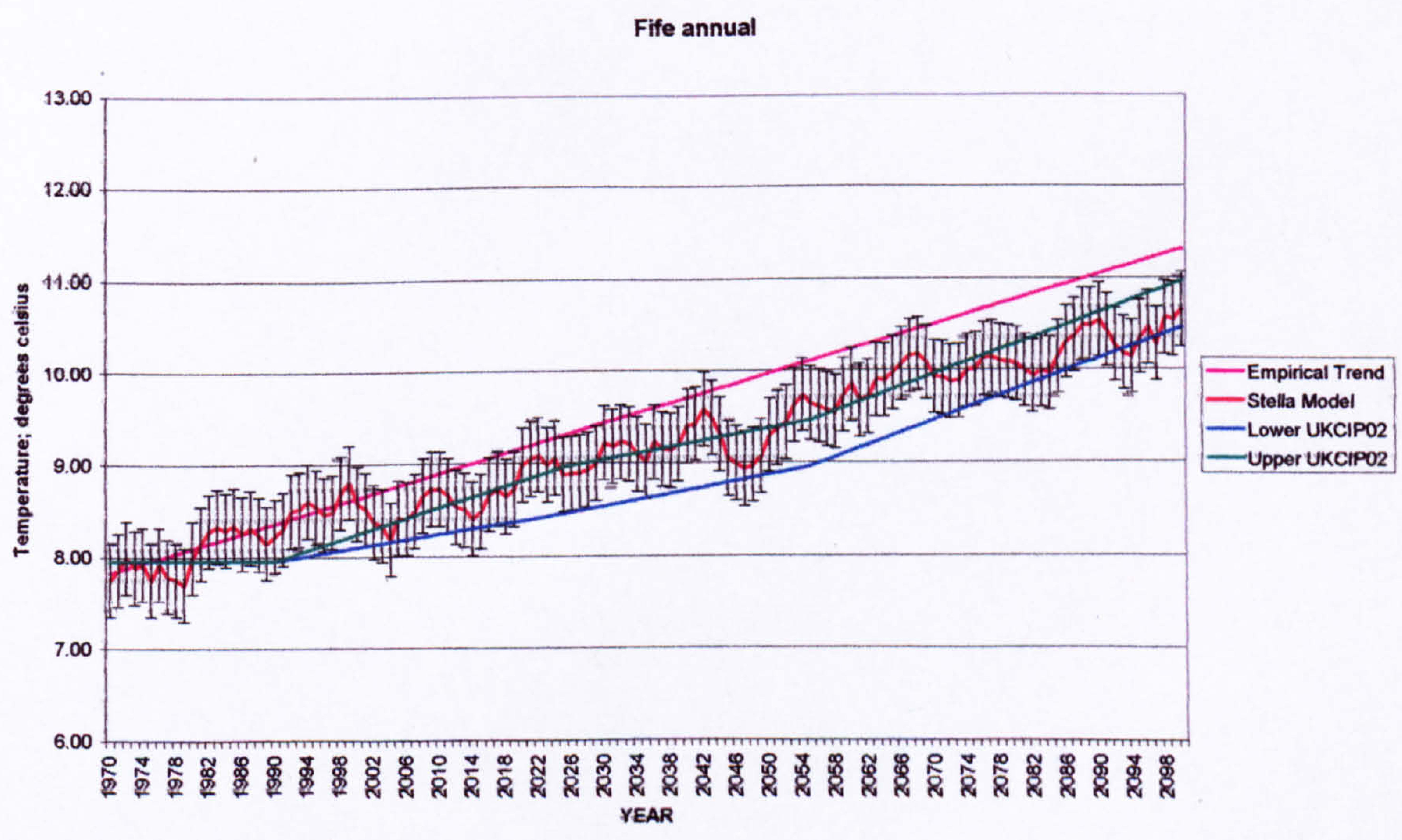


Figure 7.18 Medium low scenario, Fife annual

Medium High Scenario

Annual temperature increases are modelled in a similar way by all three methods, though the empirical trend lines for Argyll and Fife now have a gentler gradient towards the end of the century than the model outputs. The Stella model is generating temperatures towards the upper boundary of the output from the UKCIP02 model. Figure 7.19 shows the results for Fife.

Medium High Scenario

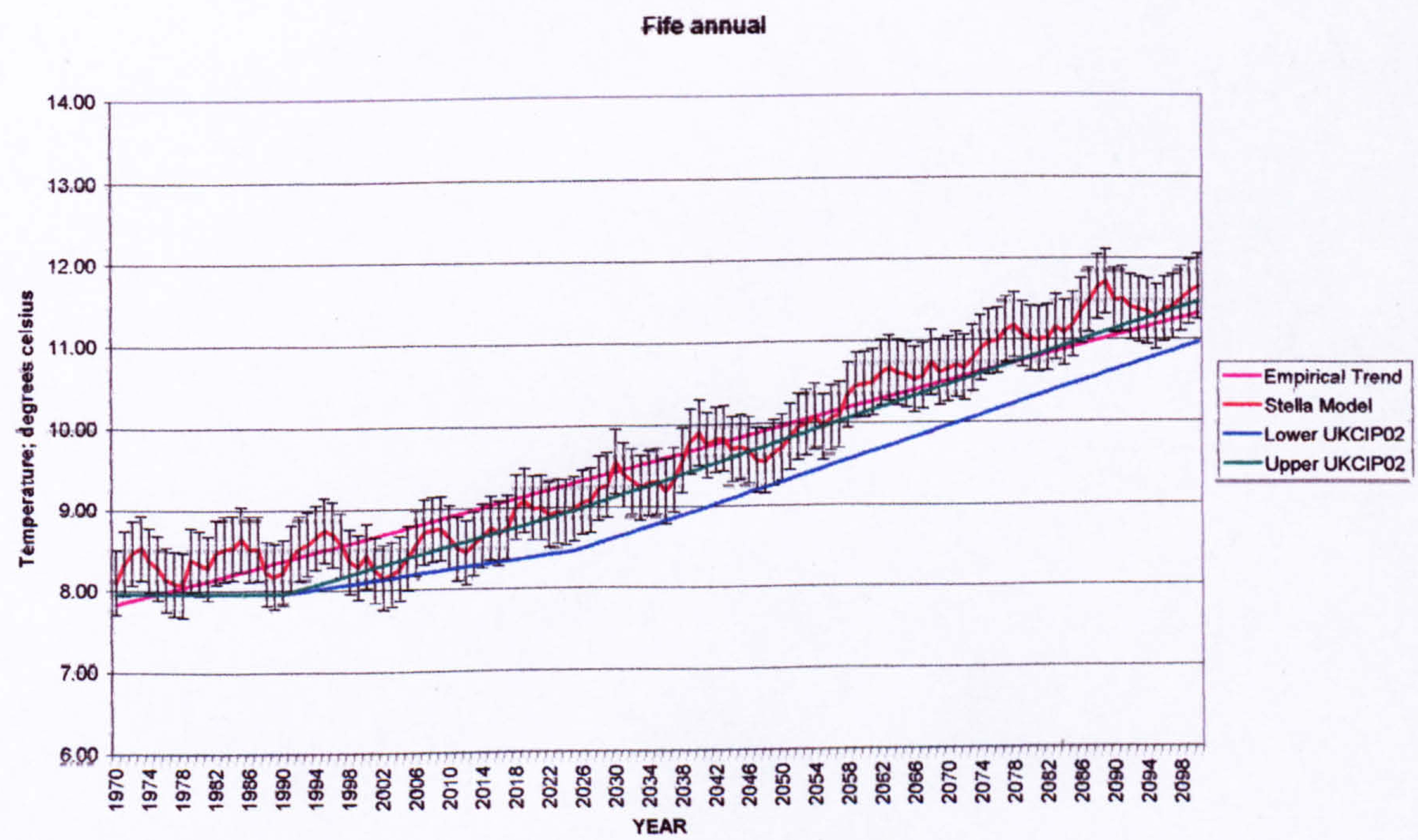


Figure 7.19 Medium high scenario, Fife annual

High Scenario

The high scenario sees a significant rise in annual mean surface temperature, especially towards the end of the century when this scenario predicts rapid accumulation of CO_2 in the atmosphere. This is captured by both models, and the gradients of the lines increase. There is again quite close agreement between the models with the Stella model tending towards the upper boundaries of the UKCIP02 model output. The results for Argyll are shown in Figure 7.20.

High Scenario

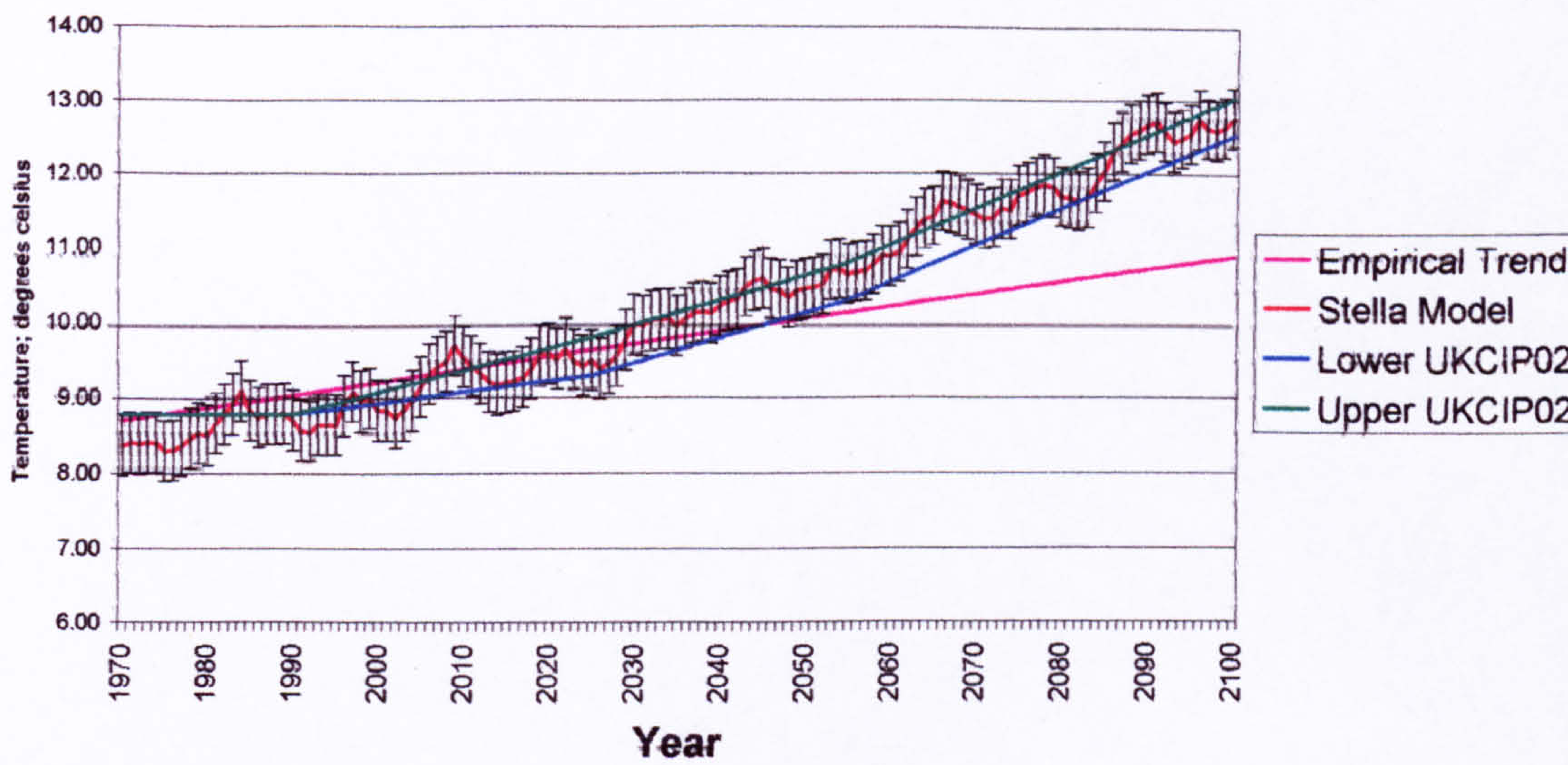


Figure 7.20 High scenario, Argyll annual

The agreement between the two models is most clear in the annual figures. Their relationship to the empirical trends is interesting as it suggests that with the Medium-high or High scenarios, the rate at which temperature change occurs is as great as, if not greater than, the temperature changes experienced during the past three decades.

7.4. Precipitation

The analysis of rainfall data from the three regions indicated a definite trend towards more intense precipitation events in the West. For the regions of Stirling and Fife there was no significant evidence of changes to levels of precipitation in any season.

The model developed in Stella was designed to simulate the temperature regime of the three regions under different CO_2 emissions scenarios, and was unable to generate rainfall patterns independently. The relationship between CO_2 and precipitation was taken from the UKCIP02 model output and therefore there should be a close correlation between the totals generated by the two models. The changes in precipitation are restricted to winter and summer seasons. The actual changes are only significantly out with natural variability under conditions of greatly increased CO_2.

As a result no comparison of the model outputs for precipitation was done.

7.5. Summary

The trends which were identified from the meteorological observations, and which have been extrapolated towards the end of this century are, in most cases within the upper and lower limits of the Low and High scenario projections.

In spring and autumn these lie close to the Medium Low and Medium High scenario outputs of both models, though for summer the trends from all three regions are closer to the Low scenario outputs.

There is good agreement between the two models, the Stella model generating higher temperatures during winter and spring than those predicted by the UKCIP02 model but being remarkably close during summer and autumn. The annual figures show very similar projections.

Given the similarities, there is good reason to feel that the inclusion of this climate model into a wider socio-economic model is justified and should generate changing climatic variables which can be used as drivers for change in social and economic aspects of the three Scottish regions.

Chapter 8 A Socio-economic Model

8.1. Introduction

Chapter 6 described the process of construction for the simple climate model. This generates simulated temperature and precipitation for each of the three regions of the study on a seasonal basis. For each of the four climate change scenarios there are distinct changes to temperature and precipitation. This chapter is concerned with the construction of a socio-economic model which draws on the current states of the three regions, and develops the relationship between different sectors of the regional economies. Of central importance to this model are the connections between the different sectors and the climate model, which is integrated into the overall model structure.

Some of the difficulties involved in the modelling of human systems were discussed in Chapter 2 and it is important to note that the output from such a model cannot be viewed as a definite prediction of what will happen in the future. What it represents is a simulation of what could happen if certain assumptions concerning human activities are accepted. Unlike natural systems where the outcome of events is determined by well established laws, human systems are subject to the actions and behaviour of individuals and groups, and as such, the relationships between variables can be changed. Factors which would be considered essential components in an economic model, such as wage differentials, interest rates, energy prices and investment patterns cannot be included in this system dynamic model. The long term behaviour of a whole range of economic variables cannot be predicted, and although they could have important impacts, the model is limited to assessing the impacts of climate change on socio-economic structures assuming that current relationships persist. The benefits of this approach are in the simplification of the model construction and the lack of interference from changes to other variables and relationships. The disadvantages are in the accuracy and predictive powers of the model, particularly in the longer term.

The following sections describe the construction of this socio-economic model which was calibrated using the data described in Chapter 3.

In order to allow the output from the climate model to be incorporated, this was built using Stella V5.1.1, running with the same dt of 1 year and with the same array dimensions used in the climate model. A regional dimension, treating each of the three regions separately, and a seasonal dimension were included.

This would facilitate the connection of the two models, allowing simulated temperature and precipitation for the coming century to act as a driver for changes in the socio-economic structures. This new model included the following sectors.

1. Population
2. Employment
3. Land use
4. Housing
5. Water resources
6. Emissions

In each case the relevant data was sourced and relationships between variables sought. Initially this was achieved by graphical means and the use of correlation. Of particular interest were instances where there appeared to be a link between climatic and socio-economic variables, as these might indicate that these would be areas sensitive to climate change. Where correlation was identified and causal links were established, regression analysis was used to provide equations which quantified the relationship. Correlation by itself throws up numerous cases where statistical links appear to exist. Most of these can be rejected, for example a correlation between birth rate and wind speed in Fife, as there exists no theoretical basis for such relationships. Relationships which are included are those for which there is evidence in the literature, for example the Scottish Scoping Study (Kerr et al. 1999), the socio-economic model developed by the University of Newcastle (Brookbanks et al. 1973), and the study of Weather Sensitivity in Scotland (Smith Keith 1989).

Other non-climate relationships were similarly established, allowing the model to develop a number of connections between the sectors. There follows a description each of these sectors, the relationships established and a description of the overall structure.

8.2. Population sector

8.2.1. Construction of the population sector

The population sector used the data as described in Chapter 3.

Three age cohorts were established and each one was represented by a reservoir in Stella. These were Young, representing individuals aged 0 to 20, Middle, from 20 to 65 and Older, representing those aged over 65. Flows were established between these age groups as follows.

A flow was created to represent the number of births, controlled by the variable "birthrate". Data from the General Registrar of Scotland (GROS) was used to calibrate this inflow for the three regions to achieve a reasonable fit with the data and allow the population from 1970 to change appropriately and generate the 2000 population.

The flow from "young" to "middle" represented those entering the workforce, simply set at 0.05 x the number of young people. The flow from "middle to "older" was set at a figure of 0.0222 x the number in the "middle" group (1 divided by 45). This was an approximate value for the number of individuals transferring between each of the groups but did not take into account the movement through the system of the smaller and larger groups of individuals associated with variations in the birth rate.

Figures for mortality for each of these groups and for each region were obtained (General Registrar of Scotland 1975-2000) and outflows (leakage) created to represent this annual loss from each population group. In the case of the "older" population this was the only (and final) outflow.

Migration was also allowed for in the construction of the model. Data for the numbers of migrants were obtained from the report of the General Registrar of Scotland and the age grouping and origins obtained from the Census data (UK Census Scotland 1971 1976), (UK Census Scotland 1981 1983), (UK Census Scotland 1991 1992). Those individuals classed as "internal" migrants, i.e. those who had moved within a region, were excluded, and only figures for migration from another region or country were included. Each region showed an individual pattern to migration, with the Argyll, and to a lesser extent Stirling, receiving a greater proportion of retired individuals than Fife.

The rate of migration was relatively small, with figures in the hundreds being the norm, compared to several thousand births every year. These figures do not appear to be strongly correlated with any other variables. However, a negative correlation with summer rainfall was detected in the Stirling region. This was significant at the 5% level but had an R value of only –0.568. It is plausible that wet weather may deter people from moving house but why this should only occur in the Stirling area is hard to explain, as such it can be considered to be an instance of statistical correlation without any causal mechanism. No such relationship was detected in either of the other two regions. In both Fife and Argyll the most significant events in terms of migration occurred with the opening and closure of Military establishments, both events generating movements of the population significantly larger than the typical annual figures.

For the purpose of the model it was therefore decided to introduce a graphical function to control the migration rates, allowing external control of this variable. Initially it was set at a figure representing the mean migration rate for each region, for the period 1975-2000.

Birth-rates showed a strong downwards trend through time. To include this trend in the model and control births according to the derived linear equations would lead to a zero birth-rate in Argyll within less than 1 century. The forecasts from the Registrar Generals Office (General Registrar of Scotland 2000) suggest that in Argyll and Fife these rates should stabilise at a level slightly higher than that of 2000 at around10.3 and 10.1 per thousand of population respectively. The decline of the birth-rate in Stirling was slower than in the other two regions and this is expected to stabilise at a slightly higher level than in either Argyll or Fife at around 11.7 per thousand of population.

Fife showed a relationship between the birth-rate and the local unemployment rate, lagged by one year, and was the only region to show this relationship. This was a correlation of 0.723 significant at the 1% level. This would suggest that within Fife there tends to be an increase in births in the year following a spell of higher unemployment.

One explanation for this may rest with an examination of the migration and unemployment statistics. All three regions have seen net in-migration over the past three decades, though the average rate for each has been quite different. The average rate of migration has been 3.5 per thousand of population in Stirling, 1.5 per thousand of population in Argyll and Bute but only 0.7 per thousand of population in Fife. This suggests that there is a more stable population in Fife, and this is backed up by examining the magnitude of migration figures, regardless of whether they are in-migration (positive) or out-migration (negative). This shows that as an annual rate per thousand of population, Argyll has the largest shifts in population, averaging a magnitude of 5.8 per thousand of population, whereas within Fife the average movement is 4 per thousand of population. For every two migrants in Fife there would be three in Argyll in communities of equal size. The size of movements within Stirling falls between these two figures at around 4.8 per thousand of population.

Unemployment rates in the three regions have shown quite marked differences also. Fife has consistently suffered higher unemployment rates, the average between 1985 and 2000 being 10.8% of the population. During this period the average rates in Argyll and Stirling have been 6.6% and 8.1% respectively.

Argyll has a relatively low unemployment rate, a population which sees relatively high levels of change due to migration and has the lowest birth rate of the three regions. Fife, on the other hand, has a relatively high unemployment rate, relatively low movements of population and a birth rate which appears to be influenced by the unemployment rate. Agriculture and tourism play a more important role in the economy of Argyll, both of which respond to seasonal demand for labour by employing temporary staff. The lack of security for workers may well influence their decision on whether to start a family or move to a new location where greater security is on offer.

Stirling would appear to be such a location, with the highest overall rate of in-migration and a birth-rate which has been, and is projected to remain, higher than either Argyll or Fife. Although unemployment rates are higher than in Argyll, the range of economic activities in Stirling is greater, as is the locus in which work can be sought, resulting from a more developed transport network.

For the purposes of the model the birth-rate in Fife has not been linked to the unemployment rate. This may have been a feature peculiar to the 1980's and the absence of any similar trend in other regions makes its inclusion seem unnecessary. All regions use a steady rate as projected by the GROS (2000).

Figure 8.1 shows the structure of the population sector, with the three reservoirs representing young, middle and older age groups. The birth-rate controls the flow into the "young " age group, and flows between this and the middle age group (enter workforce) and between middle and older age groups (retire) are as described above. Migration rates for older individuals are separate from the migrants of working age, but migration of children is controlled by the number of adults entering the region. According to the census data, the number of children classed as migrants, as a percentage of the number of adults similarly classed, is 43% in Argyll and Fife but slightly lower in Stirling at around 38%. This is reflected in the values which control the number of migrants entering the "young" age group.

In addition, there is a flow of migrants which is determined by the local balance of labour supply and labour demand. Labour supply is taken as a proportion of the population of working age and labour demand is the sum of the non-climatic sector and the simulated numbers employed in the climate sensitive sectors. No relationship was detected empirically between the rates of migration and factors such as local unemployment, national unemployment or the difference between these two rates of unemployment. The projections for births and deaths indicate an overall decline in the regional populations of Argyll and Fife. It was assumed that a growing demand for labour in agriculture (contrary to the recent trends, but stimulated by the increase in available land under the higher climate change scenarios), forestry and tourism might not be met by the native population alone. As a result, if there is a labour shortage in any region the model allows for in-migration to fill this gap. All inward migrants in this flow are assumed to be of working age.

The death rates for each of the age groups was calculated using the data from the Registrar Generals reports. For young and middle age groups this is a very low figure of

5 in ten thousand for the young group and 4.1 per thousand for the middle age group. Death rates for the older age group have been relatively stable, with only a slight decline and some small fluctuations being detected in the data. These were set at a constant level of 6.2% for Argyll, 6.3% for Stirling and 5.9% for Fife, representing the mean figure for the past decade.

The "labour supply" is the proportion of those of working age who are actually economically active, as defined by the GROS. This has been relatively stable through time, though the different regions have a different proportion of the adult population classified as being economically active. For Argyll this is set at 76%, for Stirling 91.6% and Fife it is 78.6%. The main difference between the regions is in the number of women who are classified as economically active.

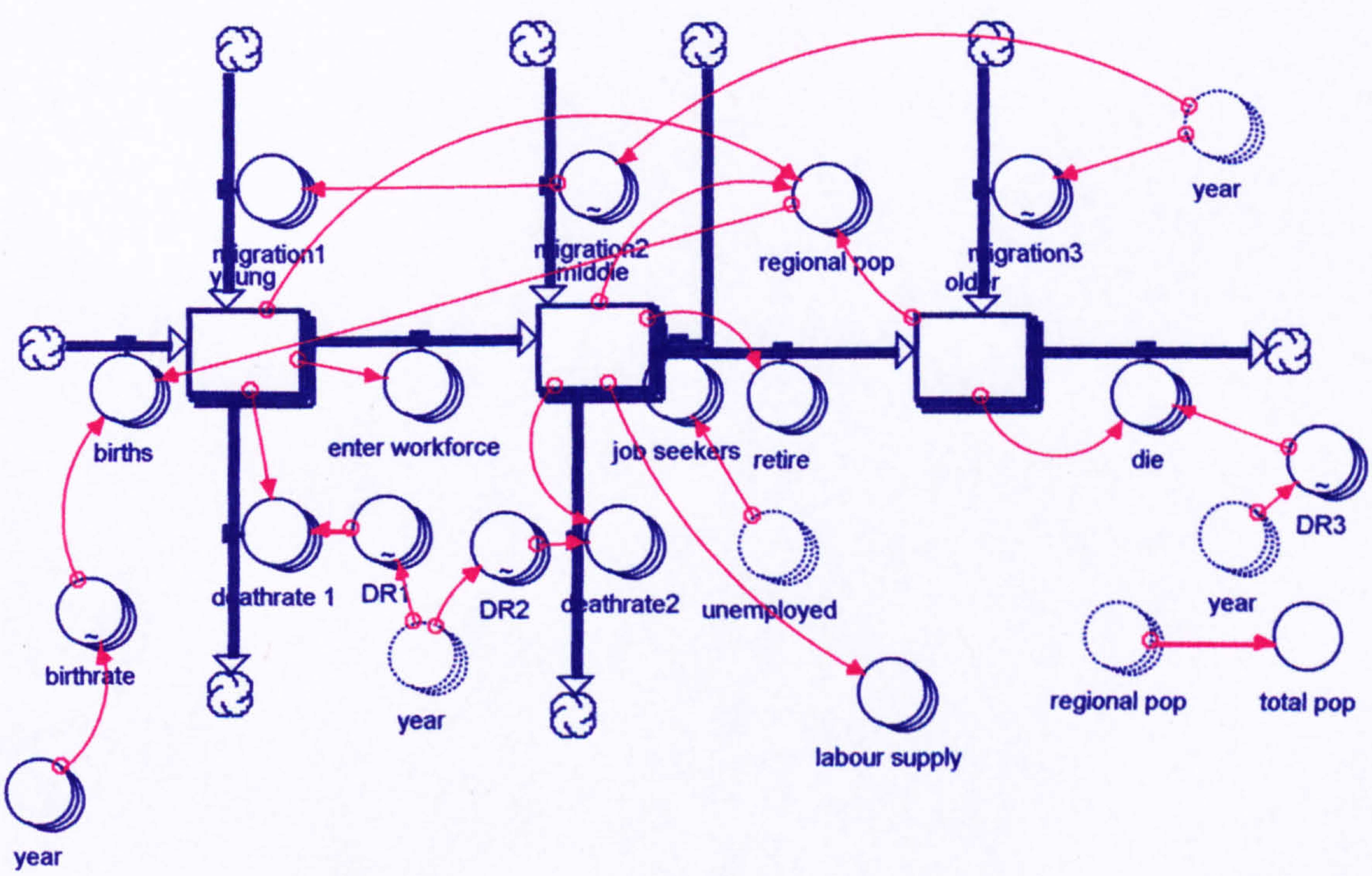


Figure 8.1 The structure of the population sector.

8.3. Employment sector

8.3.1. Construction of the Employment sector.

Total employment for each region was taken as the sum of climatically influenced and non-climatically influenced sectors. The climatically influenced sectors were farming and tourism, and forestry was treated separately from other economic activities because of its importance as a land use category and to enable carbon assimilation to be calculated. Forestry activities were separated into two main types, with plantation forestry as one aspect and a combination of farm planting and native woodlands being the other. Farming was similarly split into two separate activities, intensive farming and rough grazing. Figures were not available for the numbers of individuals employed in these precise activities, but general figures for employment in forestry and employment in agriculture were available.

8.3.2. Forestry

From the figures available on the forestry commission website (Forestry Commission Forestry Statistics 2001), it was possible to establish the total number of employees and the total area of forest in Scotland, and the value of approximately 8.3 workers per thousand hectares for forestry was established. Changes to the area of forestry could therefore be assumed to involve changes to the size of the workforce directly involved in the planting, maintenance and felling of trees, as well as the "downstream" activities of haulage, processing and manufacture of products.

Employment directly associated with forestry has an influence on the broader local economy. An increase in the demand for labour in one sector of the economy can have a knock on effect on other areas of the local economy. Increased forestry activity requires transport, catering, housing, education, and many other services to be provided, and the increase in income generated stimulates the leisure, retail and other sectors.

Input/output models can be used to assess this knock on effect, and are capable of generating "employment multipliers" for different economic activities. These multipliers quantify the effect that an increase in employment within one sector will have on employment in general. These can be either "type1" or "type 2" multipliers, depending on whether the direct changes in employment resulting from a change in one sector are calculated (type 1), or these changes are calculated along with the effects induced by the increased spending of the new employees added on (type 2). For the purposes of this model, where each region is treated as a separate entity as far as possible, the type two multipliers seem more appropriate.

An input/output analysis of Scottish forestry (Roberts et al. 1999) gave a detailed assessment of these multiplier effects, and by breaking the forestry sector down into sub-sectors was able to show that different types of forestry, and the different activities relating to forestry, produced different multiplier effects.

To take into account at least some of these differences, it was decided to include just two separate types of forestry activities: firstly those relating to commercial planting, maintenance and harvesting, predominantly of exotic species and secondly those relating to new native planting, including farm planting, and the maintenance and harvesting of these woodlands.

The extent of the areas devoted to these different activities was obtained, for each of the three regions, with the assistance of Ewan Purser at the organisation Highland Birchwoods (Ewan Purser, pers. Comm.). The areas of these activities in each of the three regions could then be used to generate the numbers of employees, which in turn would be increased by the appropriate factor found by taking the employment multiplier for that type of activity.

In order to maintain a simple structure, the employment multipliers for planting and maintenance were combined with those for harvesting to produce a single multiplier. In the case of farm and native woodland planting, as well as its maintenance and harvesting, the employment multipliers were very similar, resulting in both these categories being combined. This resulted in an overall employment multiplier for farm and native woodlands of 1.999 and an overall multiplier for the commercial forestry of 1.722. In real terms this implies that for every thousand jobs created in commercial forestry an additional 722 would be created in the wider economy, and for native and farm planting the figure would be higher at 999 for every thousand jobs directly linked to forestry. In real terms however the numbers are much lower than this. The creation of 1000 jobs in forestry would require an area of 120 thousand hectares to be planted, the actual figures are far lower than this with an average of less than 10 thousand hectares planted across the whole of Scotland per year. It is assumed that initially the extra demand for labour can be met by the unemployed and young people entering the workforce.

8.3.3. Agriculture

Data obtained from the Scottish Executive Environment and Rural Affairs Department (SEERAD) provided figures for the area of land under different forms of agricultural use. This included an amalgamation of a variety of activities to give the area under crops and grass as one distinct category. The area of rough grazing, both for land with one sole proprietor and land grazed in common, was also included. These two categories represent the contrasting activities of intensive farming, both arable and managed pasture, and extensive hill farming, mainly of sheep, over large areas of moorland and rough grassland.

Data was available on a regional basis relating to the number of individuals working in agriculture as either owner/occupiers or as full time employees. This did not specify the type of activity in which they were involved. By using data relating to areas of the two types of land use and the total number employed in each region, it was possible to calculate the average number of workers per thousand hectares by solving simultaneous equations. Solving these equations for Argyll and Fife gave the results of 1.03 workers per 1000 hectares of rough grazing and 16.29 workers per 1000 hectares of crops and grass. Taking these results and testing them against the data for Stirling produced an expected workforce of 719 against an actual workforce of 745. The calculated figure represents 95.5% of the actual figure, suggesting a reasonable fit using these figures.

Overall employment relating to forestry and agriculture could then be calculated on the basis of the area of land devoted to each of these activities. These areas were "ghosted" into the employment sector from the land use sector, a feature of which being the premise that changing climate is likely to alter the areas of land suitable for the different activities. Changing rates of grants and subsidies were not included, due to the complexity of the system and the fact that changes are frequent. What has been included is the consequence of different grants and subsidies in terms of the overall rate of growth or decline in the different sectors. It is clear from the records of forest planting that the change in forest grants, favouring broadleaved and native species over conifer plantations, had the effect of generating a shift in planting practices during the 1990's. The grants and subsidies have the intended effect of influencing individual decision makers as to the most beneficial course of action. However, there are a number of other factors affecting these decisions. Commercial conifer plantations have been affected by factors such as the strength of the pound, cheap imports from Baltic countries and a general decline in the world price of timber (Mainprize, pers comm.).

Similarly agriculture looks to the EU Common Agricultural Policy for grants and subsidies, where changes can be made to policy which have a significant effect on land management. The complexity of these policies makes them unsuitable for inclusion in this model. The value of particular grants, incentives and subsidies has therefore been excluded from the model, the assumption being that their values will remain similar to those of today for a considerable time. Reform of the CAP is being carried out at present, this is bound to influence future agricultural practices. This is an example of a variable which cannot be included in the model as future effects can not be known. By holding this constant it is just the effects of climate change which the model investigates.

In effect, this allows the impact of the climatic factors to be assessed independently of possible changes in policy during the simulation. Altering the rates at which changes to land use occur in the model is a method which could be used to test the effect of policy shifts, assuming that the consequences of policy change could be predicted in advance.

With climate change, and a consequent expansion of land suitable for agriculture, the projected values for agricultural employment were then increased by a factor according to the agricultural employment multiplier effect. As with the forestry employment, this allows for the knock on effects through the economy to be assessed. For agriculture this was set at 2.43 (Al-Ali and Burdekin 1978). More recent figures (Maxwell 2000) suggest that there is some variability with respect to the agricultural employment multiplier in Scotland. The figures quoted in this article refer to a change in the multiplier over a four year period, from 2.7 in 1995-96 to 2.36 in 1999-2000. The figure of 2.43 used in the construction of the model lies between these figures, and the sensitivity testing in Chapter 9 suggests that the difference caused by the choice of multiplier will not be great, either in terms of percentage change in employees or in the absolute numbers generated.

8.3.4. Tourism

Tourism plays an important part in the local economies of all three regions, with figures from the Scottish Tourist board suggesting that recently around 9% of employment in these areas has been directly related to the tourist industry. Exact figures are difficult to obtain, since businesses such as rural village shops may owe their survival to the influx of tourists but serve the local community as well. The line between what is strictly tourist oriented business and what is simply enhanced by tourism is difficult to define. As a result of this absence of exact data on employment it has been assumed that the scale of the impact on the local economy is directly proportional to the actual numbers of tourists visiting an area. Statistics relating to the number of "bed nights" sold to tourists and the actual number of visitors arriving at tourist attractions are available from Visit Scotland (Scottish Tourist Board 1989-2000). This is considered to be the most reliable method of assessing activity in this sector (Professor Page, pers comm., 2001), rather than income generated, as the latter is influenced by a range of external factors such as the currency markets, flight costs and special package deals.

Tourist numbers are collected on the basis of Area Tourist Boards (ATB) which are currently defined differently from Local Authority areas. Initially, the data did correspond to the local authority areas of Argyll, Fife and Stirling, and figures for "bed nights" were available for each of these areas from 1990 to 1994 inclusive. In 1995, the area of Argyll was added to that of Stirling and as such became a single Area Tourist Board known as Argyll, the Isles, Stirling, Loch Lomond and the Trossachs (AISLLT).

Rather that separating the combined figures by some arbitrary method, it was decided to combine the earlier data relating to Argyll and the Stirling area.

By using regression analysis with multiple climatic predictors, it was found that a strong relationship existed between tourist numbers and temperature (For AILLST n = 16, R^2 =0.7, sig = 0.027. For Fife n = 16, R^2 = 0.874, sig < 0.01). This relationship held for the two sets of data of Fife and AILLST area tourist boards. In both cases a strong relationship was established between tourist numbers and summer temperature, lagged by one year. In the case of AILLST, the model was further improved by the inclusion of the current years summer temperature. The differences are likely to be due in part to the different profile of visitors to each of the areas, and in part to the different climate of the two regions. Golf attracts a large number of visitors to Fife and the visitors tend to spend more on average per trip (Visit Scotland 2003). Given the higher precipitation in the west, current temperatures (negatively correlated with rainfall) are of greater significance in determining tourist numbers, given that much of the tourism associated with these areas can be described as "opportunistic". These tend not to represent tourists main holidays but a large proportion are short breaks taken by UK residents when the opportunity arises (Visit Scotland 2003).

The equations used were:

For Fife: (R^2 = 0.874, significance < 0.01)

Tourist numbers(millions) =-8.659+0.078*Summer temp(Fife) (lagged 1 year)

For AILLST: (R^2 = 0.7, significance = 0.027)

Tourist numbers(millions)= -18.356 +0.0911*summer temp(Argyll) + 0.088*summer temp(Argyll lagged 1year)

This treats the whole of the AILLST Area tourist board as being dependent on the temperatures in Argyll. However, the regional variability of temperature is far less marked than that of precipitation. A warm summer in Argyll will correspond to a warm summer in Stirling and the converse is also true. To test the Stirling area separately, it was decided to run a similar regression analysis but using the number of tourists visiting an attraction in the Stirling area. Data were available for visits to Stirling castle, the reliability of these figures being in no doubt as this is an attraction which charges an entry fee, and as such accurate records are kept.

A regression equation was obtained by the same method, $R^2 = 0.885$ with a significance of 0.002 ($n = 13$). This also combined prevailing summer temperature with the lagged summer temperature for the Stirling region.

It would seem that the previous summer temperature is the most significant factor affecting the number of visitors to these areas of Scotland, a cool summer having an effect on the number of individuals choosing to visit (or return) the following year. The importance of summer temperature can be seen by looking at the distribution of the timing of visits, with by far the majority occurring during the months of July and August.

Factors such as the strength of the pound, crises such as the foot and mouth outbreak, fears over travel as a result of terrorist activities, can all have a significant impact on tourism. By far the greatest source of numbers, and hence income, is from the domestic market. More than 90% of bed nights sold and 90% of visitors to either the AILLST or Fife areas were from UK residents (Visit Scotland 2003). While the impacts of factors affecting overseas visitor numbers can be significant, the bulk of tourist activity is home generated. Crises such as Foot and Mouth are not something that can be forecast or predicted, so their inclusion in a model would be difficult.

It is assumed that changes in tourist numbers alter the size of the workforce engaged in tourism related activities. Data from the Visit Scotland website provided an estimate, on an annual basis, for the numbers involved in tourism related work. Stirling and Argyll were again combined in data from the ATB's. By dividing the number of visitors by the number of employees, it was possible to determine on an annual basis how many visitors were required to generate one full time job. In the area covered by AILLST ATB, the mean figure for the years 1993-2001 was 406 visitors per employee. For Fife on the other hand, the figure was lower at 296 visitor per employee. This can be seen as a reflection of the differences in the tourist market for each of these regions and of the different types of activity undertaken by visitors.

Using these figures it was then possible to convert the calculation of tourist numbers for each of the three regions into employment figures.

As with employment in agriculture and forestry, tourism has a knock on effect which can be included in the model by use of an appropriate employment multiplier. In the case of tourism this was set at 1.37 (Al-Ali and Burdekin 1978). The figures for Tourist related employment, available from VisitScotland, are not just those directly involved, for example in the Hotel Business. These are "tourist related" jobs which could be considered to include the knock-on effects through related activities. It was considered more reasonable to use tourist employment figures without any multiplier as it was assumed that this was already included.

The final component in the calculation of labour demand in the regions is the "non climatic" sector. This represents the sum of all other employment and represents the majority of employment within the regions. The contribution from the climate linked employment varies from region to region, with Argyll having the largest proportion at approximately 24%, while Stirling and Fife have approximately 14% and 12%

respectively. The remaining employment was included in the model after analysis of employment data for the period and was set as a fixed proportion of the adult working population. The structure of the employment sector is shown in Figure 8.2.

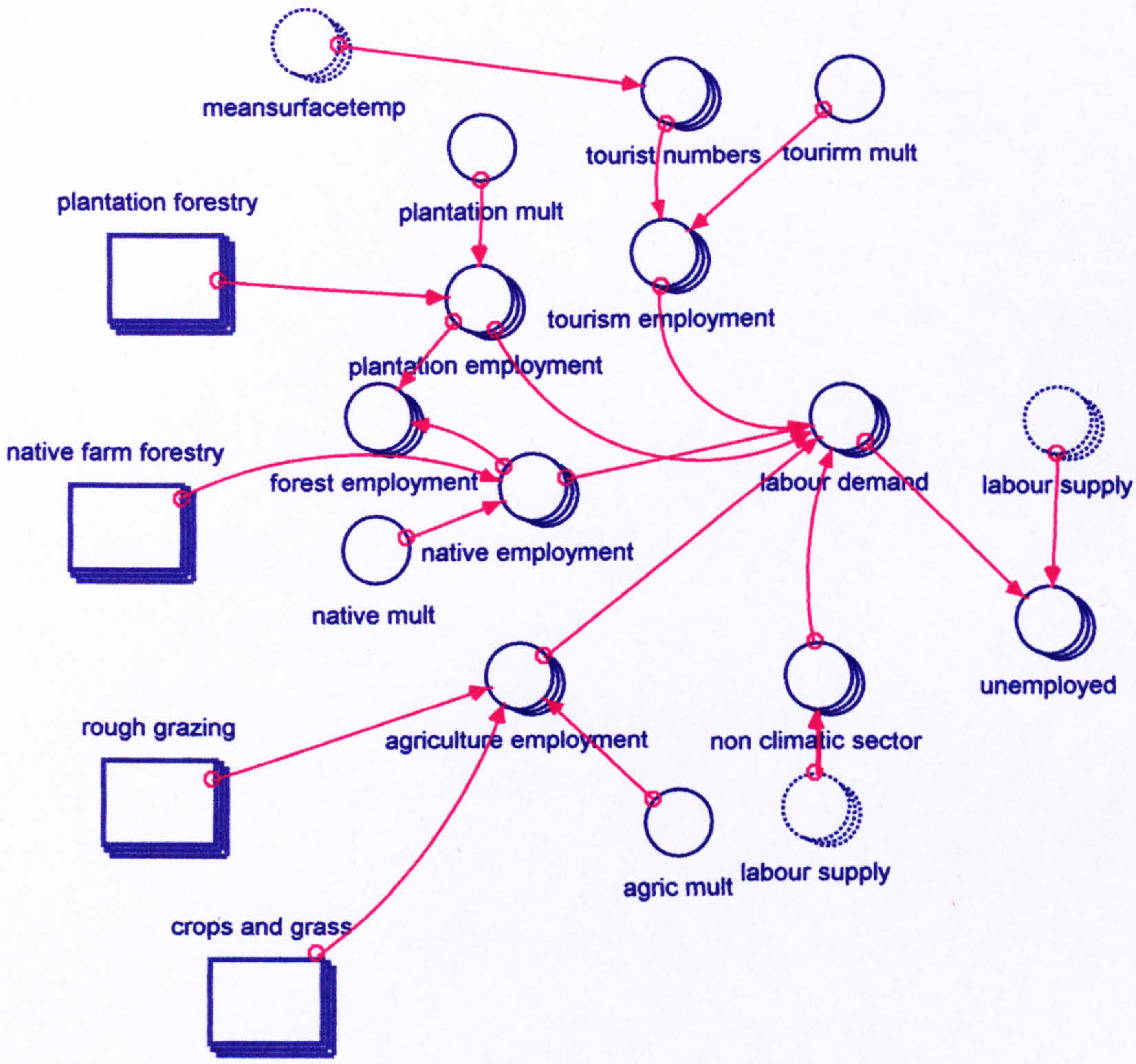


Figure 8.2 The structure of the employment sector.

8.4. Land Use

8.4.1. Construction of the Land Use sector

The Land Use sector comprised five reservoirs, representing urban, crops and grass, rough grazing, commercial plantation forestry and native or broadleaved forestry. The flows between these reservoirs allowed for the following changes to land use:

1. Crops and grass to urban.
2. Rough grazing to crops and grass.
3. Rough grazing to plantation forestry.
4. Rough grazing to native/broadleaved forestry.

Although this does not represent all possible land use changes, examination of the data led to the belief that these four flows can represent the *net* flows from one land use category to the other. Flows can go in the opposite direction, for example from forestry to rough grazing, however these are very small flows in comparison to the main trends in changing land use (Inskipp 1997).

8.4.2. Crops and grass to Urban

The settlement pattern for all three regions has by far the majority of urban areas and smaller rural populations situated in areas of relatively low lying agricultural land. Historically this would have reflected the needs of an agricultural based economy and subsequent development has followed this early pattern with growth of established communities being the norm. Where New Towns have been established this tends to be an accelerated and exaggerated form of this gradual urban encroachment. For the purposes of the model it is assumed therefore that new urban areas will be established at the expense of crops and grass.

The rate at which crops and grass is lost to housing depends on the number of new houses being built and the average area of land used for each new dwelling.

The number of new houses being built is taken from the Housing sector (section 8.5) which gives details of the methods used.

The area of land required for each new dwelling is calculated simply by taking the existing area of land classed as urban and dividing by the population of that region. This makes the assumption that new housing will follow the pattern of established housing in each area in terms of its general layout, structure and distribution. The figure used was 0.06 ha per house, or an average of roughly 16 houses per hectare of land.

8.4.3. Rough grazing to crops and grass.

By examining the data, it can be seen that in all three regions there has been a steady decline in the overall area of agricultural land. This decline is mainly due to a loss of rough grazing, the area of land classed as crops and grass (including improved grazing) having increased over the years for which data were available. A significant proportion of the loss of rough grazing has been due to afforestation, but here, too, a significant proportion can be explained by the ploughing, draining fertilisation and reseeding of rough grazing to create improved pasture.

The rates at which these changes have taken place could be established from the data and a relationship between the decline of rough grazing and the creation of improved pasture could be identified. In Argyll, where a large area of land has been forested over the previous few decades, it was found that on average for every fifteen hectares of rough grazing lost there was one hectare of crops and grass created. In Stirling and Fife however, around six hectares of rough grazing were lost for every hectare increase in the area of crops and grass. Over time this represents a considerable shift in the way land is managed, much of which can be explained in terms of the financial incentives which are available for different activities. A trend identified by researchers from the University of Aberdeen was for farmers in Argyll to sell off the least productive land to commercial forestry concerns, use the proceeds to improve the remaining areas of the farm, which were often those at lower altitude, and suffer no loss in productivity as a result (Mather and Thomson 1995).

The model reflects these trends by ensuring that as rough grazing is lost over time, the correct proportion of the loss is directed towards the creation of improved grassland.

In addition to this change in land use there is also the prospect of increased temperatures allowing for the expansion of agriculture to areas hitherto unsuitable for the more intensive agricultural activities. Examination of Ordnance Survey maps of the regions suggests that at present there is an upper limit to field boundaries, suggesting an upper limit to areas of improved grassland or cultivation. In Argyll these field boundaries are rarely above the 100m contour, and, indeed, much of the land below this is classed as rough grazing. In central regions there appears to be an upper limit of around 200m and again there is an absence of any such features at a higher altitude. In Fife almost all the land surface is partitioned by field boundaries, with only the few higher areas showing no sign of such activity. The boundary here appears to be around 250m in altitude, above which the symbol for rough grazing appears with great frequency.

Lapse rates, or the rate at which temperature drops as altitude increases, are generally accepted to be around 0.65°C for every 100m in altitude (Barry and Chorley 1992). It is reasoned that an increase in temperature of 0.65°C would therefore raise the upper limit of intensive agricultural activity by 100m. This would introduce the prospect of far more land, which is at present classed as rough grazing, becoming suitable for improvement to create new areas of crops and grass. Since this would require the use of farm machinery for ploughing, drainage, fertiliser application and seeding, it is assumed that only land with a slope of less than 15% could be utilised (Fenton and Gillmor 1994). At present in Argyll only 18.5% of the land below 100m is used for crops and grass. In Stirling 50.5% of land below 200m and in Fife, 67.6% of land below 250m is used. It is assumed that this disparity is due to features such as soil type, water-logging exposure and alternative land uses such as forestry, so a similar proportion of land made available due to increasing temperature will be considered suitable in each region.

Detailed maps of the regions were created using Digimap data download facility (Edina 2003) which were imported to Arcview GIS V 3.2. This used Meridion DTM tiles. Firstly, the area of land below the upper boundary of present day agriculture was calculated with the further constraint of having a gradient of less than 15%. Each 0.5°C increase in temperature was then converted to an increase in altitude of 77m. Subsequent calculations of area followed the pattern of increasing altitude by this amount. This allowed the change in area to be calculated for each 0.5°C rise in temperature for each of the study regions. In each case, only the appropriate percentage of this land was included.

Runs of the four climate scenarios were made and the average number of years required to reach successive 0.5°C step was calculated. Dividing the increase in area by the time taken for each scenario to increase temperature by 0.5°C gave a reasonable estimate of the rate of change of land use which could be incorporated into the model. The rates were quite different for each of the regions, with Argyll showing the greatest area of potentially improved land and Fife having relatively little. In general the rate of change slowed down as higher temperatures were achieved, but the logical structure of the model allows the initial rate of change to be continued until the appropriate area of land has been converted to crops and grass. To simulate the conversion of rough grazing to crops and grass without rapid temperature induced fluctuations, a ten year running mean of temperature was used. Only when this was above the initial temperature could land use change take place.

It is worth noting that the areas of land which the model defines as becoming suitable for more intensive agriculture must be seen as areas of "*potential*" land use change. Whether these changes actually occur may be determined by decisions related to the Common Agricultural Policy rather than the suitability of the land itself.

8.4.4. Rough grazing to plantation forestry.

Throughout the 1970's and 1980's a rapid expansion of plantation forestry took place across Scotland. Tax incentives and forestry grants made investment in forestry schemes an attractive proposition and this led to large scale planting mostly of exotic species, across large areas of the Scottish countryside. For example, between 1985 and 1990 there was a loss of approximately 74 000 ha of agricultural land to forestry (Scottish Office Agriculture and Fisheries 1984-2000). Other forestry schemes utilised land which was not classified as agricultural, such as heather moorland, so this figure represents only part of the forest expansion. The rates at which new areas were planted are available on a national level (Forestry Commission Forestry Statistics 2001). Firstly the ratio of each five-year period from 1970 to 2000 was calculated. This was an approximate ratio which showed how the overall planting rate dropped over this period. These comparative rates were assumed to apply to all regions, and were used to scale the level of planting within regions according to the actual figures for changes to forest cover which have actually occurred. The values used are shown in Table 8.1.

YEAR	70-74	75-79	80-84	85-89	90-94	95-99
Scaling	3	2	2	2	1	1

Table 8.1 Rates of forest planting 1970-2000

As well as changes in the overall rate of planting there was a definite shift in the type of planting carried out. Whereas in the 70's and 80's the majority of new forestry was commercial plantation of exotic species, changes in the grant scheme made in the early 1990's began a trend towards more planting of native pines and broadleaved species. In the period up to 1985 roughly 99% of new forestry was conifer plantation, by 1995-2000 this proportion had dropped to 45%.

Thus the rate of new planting of exotic conifers has dropped more rapidly than the figures in Table 8.1 suggest, though this still accounts for a significant annual change in land use. The projection into the 21st century assumes that the rate established by the end of the 20th century continues and that the trend towards more native and broadleaved forest rather than plantation forestry is also set to continue. Factors such as world timber prices may have a profound effect on this (Mainprize, pers comm) but cannot be included in the model.

8.4.5. Rough grazing to native and farm forestry.

As mentioned in the previous section there was a distinct shift in emphasis away from plantations of exotic species towards native species and broadleaved trees during the 1990's. This was largely driven by changes to the forest grants scheme which now favours native species over exotics, with a premium rate per hectare. The effect of this is to produce a situation where in the last few years of the 20th century a greater area was devoted to the planting of broadleaved and native pines than exotic conifers. Future changes to grants and incentives cannot be known, so cannot be included in the model. The assumption is made that the future relationship between these grants will remain, favouring broadleaved and native planting, and therefore the planting patterns established more recently will continue. Plantation forestry is set at 45% of new forestry, with the remaining 55% devoted to native pine and broadleaved species. These proportions are controlled by the auxiliaries "prop pl" and "prop bl" in the model.

There continues to be a loss of agricultural land due to new planting of forests and this is not exclusively the loss of rough grazing. The strongest discernible trend is towards less rough grazing, more forestry and more crops and grass, features which the model attempts to capture.

The structure of the Land use sector is illustrated in Figure 8.3.

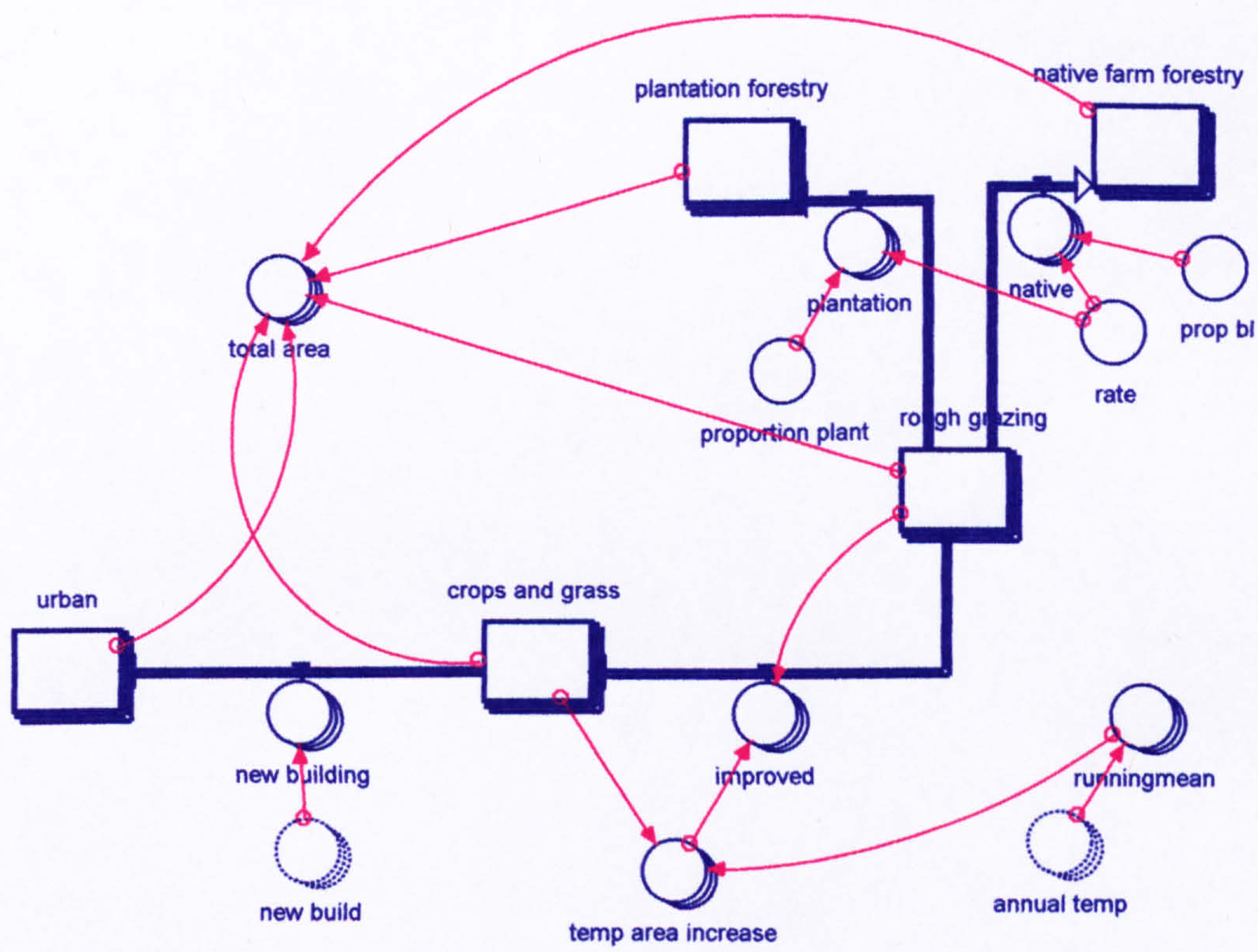


Figure 8.3 The structure of the Land Use sector

8.5. Housing

8.5.1. Construction of the Housing sector

Provision of housing in Stirling and Fife was closely correlated with population of these regions for the period for which data was available. New housing matched the increase in population for these two regions, allowing the rate of growth to be linked to the output of the Population Sector. It is assumed here that demand from population increase or changes to the average household size stimulates house building. Argyll showed a different pattern, with new housing being built at a similar rate to that of Stirling but with the population showing a simultaneous decline. The rate of increase for Argyll was approximately a 1% increase in housing stock every year. Two features of the housing stock in Argyll might explain this. Firstly, Argyll has by far the highest proportion of its housing stock classified as Below Tolerable Standard (BTS). Roughly 30% of homes in Argyll fall into this category and this figure has remained virtually unchanged over the past three decades. In contrast, both Stirling and Fife have seen the proportion of BTS housing fall from roughly 5% in the 1970's to around 1% in the late 1990's. The same grants are available to householders and landlords in all areas, so different rates of improvements must be the result of differences in the housing stock. The classification BTS covers a range of criteria, among them the connection of the house to a mains water supply. Given the dispersed nature of much of the housing in the rural and Island communities, no mains water can be accessed, so extraction from surface waters is common. No data was available on why these houses were classed as BTS, but this single factor could reasonably be expected to explain a significant proportion of the difference between the housing stock of Argyll compared to the other two regions.

Secondly there has been a growth in the number of second homes or holiday homes in Argyll, and some of the new housing may well be purpose built cottages designed for letting. The shortage of affordable housing in rural areas can be attributed in part to the sale of local authority housing which then becomes available to the tourist market as holiday homes. 20% of the housing on Mull is classed as holiday lets (Scottish Executive Central Research Unit 2001). In addition, the attraction of rural settings as retirement destinations distorts further the housing market in these areas.

For Argyll the rate of new house building continues in the model as a constant 1% increase in housing stock per year. In Stirling and Fife the rate of new buildings is linked to the population with increases in population generating new housing. New housing caters for both the needs of the present population and the needs of a changing housing market. Since the average household size has been decreasing steadily over the past few decades, and is projected to continue to do so for the foreseeable future, the number of new houses has been greater than the number of new people in both Stirling and Fife. For Stirling this has resulted in 1.56 new houses for every unit increase in population and for Fife the figure is 2.45. These figures were included in the model to allow current trends to continue. Should population begin to fall, the model does not react by reducing the housing stock. If the increase in population is less than, or equal to, zero then no change ensues.

In addition to the projected change in the stock of housing, this sector also calculates whether future provision will result in a surplus or shortage of housing in each of the regions. Data on population and housing stock were combined to produce figures for average household size over the past two decades. This is shown in Table 8.2.

Date/Region	Argyll	Stirling	Fife
1980	2.77	2.97	2.82
1985	2.71	2.8	2.66
1990	2.64	2.67	2.63
1995	2.34	2.53	2.43
2000	2.24	2.5	2.34
Long term projection	1.8	1.86	1.8

Table 8.2 Mean persons per dwelling

These data were included along with future projections from the Scottish Office Statistical Bulletin (Scottish Office Statistical Bulletin 2002) to generate future housing demand, by dividing the simulated population of each region by the figures for average household size. This was then subtracted from the projected housing stock. If the result is negative, then this indicates a housing shortage, if positive then a housing surplus.

The structure of the Housing sector is shown in Figure 8.4.

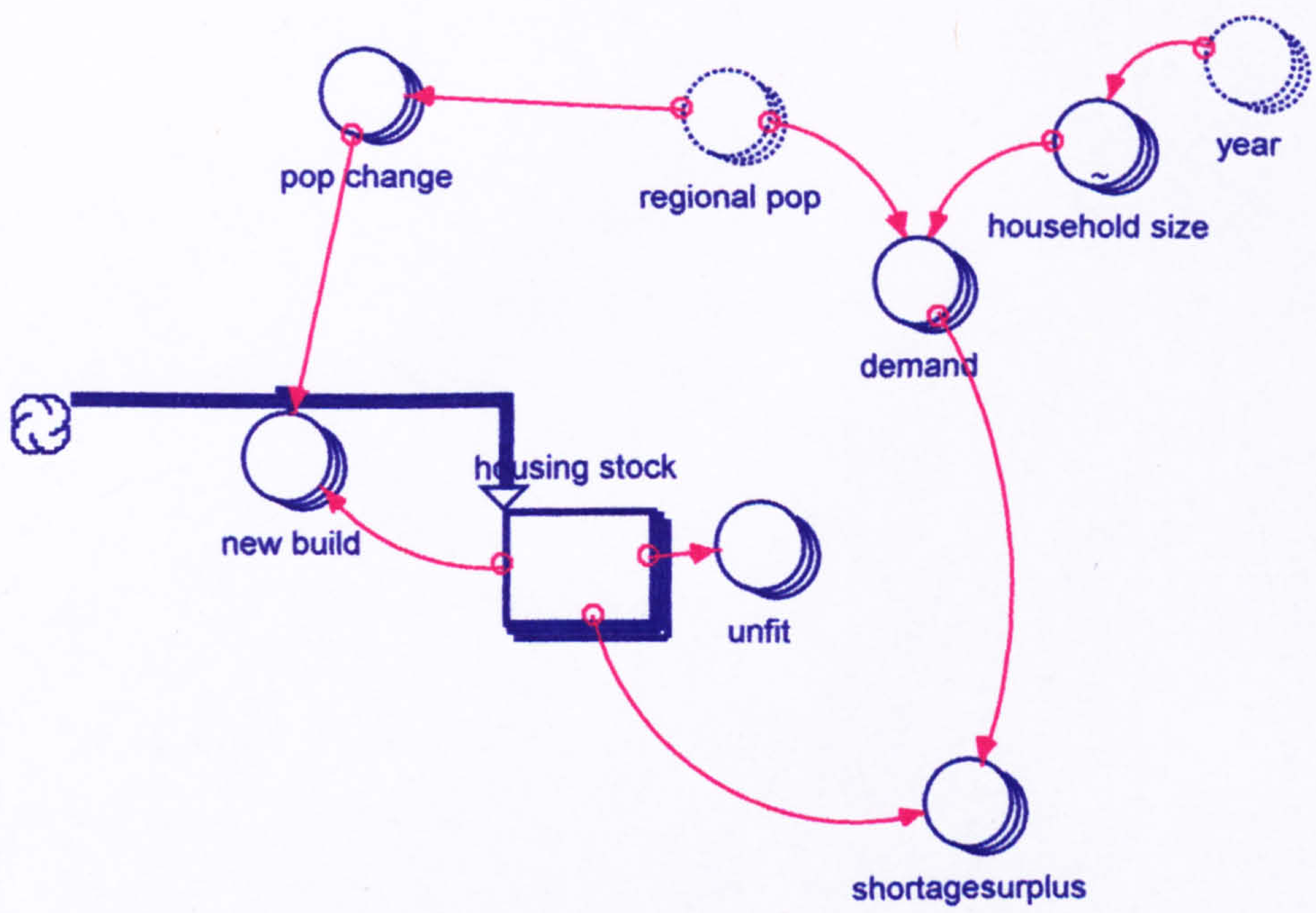


Figure 8.4 The structure of the Housing Sector.

8.6. Water Resources

8.6.1. Construction of the Water Resources sector

The water resource sector takes one reservoir, that of incoming precipitation, as its basis. Measured in millimetres per season, the total amount of water falling on a region can be calculated by multiplying the precipitation by the area of the region, measured in hectares. In this way the total volume of water arriving on the surface of each region can be calculated.

The losses are calculated by taking into account three main routes, evapotranspiration by the vegetation of the regions, extraction for use by humans, including industry, and the runoff through river systems.

The method of calculating each of these is briefly described below.

8.6.2. Evapotranspiration.

Rates of evapo-transpiration vary according to a number of factors. Firstly there is the nature of the vegetation itself, with different plants and plant communities behaving differently. The availability of moisture in the soil has a big impact on rates of evapo-transpiration, as do prevailing weather conditions, including sunshine and wind speed. Temperature plays an important role, with rates of evapo-transpiration increasing by roughly 4% for every 1C rise in temperature (Budyko 1982).

Building into the model a variable which shows such a great deal of spatial and temporal variability involved the use of average rates for each season for a whole range of bioclimatic zones, as described in the Monarch Report (Harrison, Berry, and Dawson 2001). This study uses statistical methods to classify the different areas of the country according to a wide range of prevailing climatic factors. Twenty-one of these bioclimatic classes were generated along with expected rates of evapo-transpiration for each class.

Close examination of the maps allowed for an estimate of the extent of each class falling within the boundaries of each of the Local Authority areas. Figures in the Monarch Report provided only summer and winter rates of evapo-transpiration, so some method of deriving suitable figures for Autumn and Spring was required. For this a study of grassland evapo-transpiration from both the West and East of Scotland was used (Institute of Hydrology 1991a). This paper gave monthly evapo-transpiration rates for grassland. From this a mean seasonal rate was created and the relationship between the different seasons used in the calibration of the data (winter and summer) from the Monarch Report. In this way a reasonable estimate of spring and autumn evapo-transpiration rates was obtained.

8.6.3. Human Use

Regional disaggregation of water use statistics were not found. Figures for Scotland as a whole were available from the Scottish Executive website (Scottish Executive b 2001), which deals with the public water supplies in Scotland. This stated that little regional variation in consumption rates was evident and a mean figure of 479 litres/head/day was used. This figure was then multiplied by the population of each region and by the number of days in each of the four seasons to give water consumption on a seasonal basis. Added to this was the consumption due to visitors, who were assumed to use the same amount per head per day. Thus a figure for total human use was derived for each of the regions for each season.

8.6.4. Runoff

In order to quantify the amount of incoming precipitation which is lost as runoff, data were extracted from the Hydrological Yearbook (Institute of Hydrology 1991a). This gives figures for runoff as a percentage of precipitation for catchments across the United Kingdom. Two rivers were selected for each region, where possible with their entire catchment within the region's boundaries. The rivers used for Argyll were the River Leven at Linbane and the River Nevis at Claggan, for Stirling the River Teith at Bridge of Teith and the River Allan at Bridge of Allan, and for Fife the River Carron at Headwood and the River Leven at Leven. The small number of sites in Argyll where discharges were measured meant that the choice of catchments was limited. The River Nevis is actually situated outside of Argyll and is fed from some of the highest mountains on the west coast of Scotland. The River Leven at Linbane flows from the south end of Loch Lomond and has a proportion of its catchment within the western parts of Stirling. Both of these rivers have catchments which contain very high ground, and as such are not representative of the islands or the lower lying areas around the coast of

Argyll. In order to get a more realistic figure for runoff as a percentage of precipitation, the figures for these two rivers were combined with data from four other rivers outside the boundaries of Argyll. Two rivers from Northern Ireland were included, the Falloch and Derg, and two from Ayrshire, the Irvine and Doon. The close geographical proximity of these catchments and the similarities in land form and land use to the inhabited parts of Argyll were the main justifications for this choice. The rainfall totals for these catchments takes into account the presence of extensive mountain areas, where precipitation totals are higher than at sea level where the meteorological stations used to generate the simulated precipitation regimes are situated. A comparison of the mean rainfall across the catchments used, and the simulated precipitation generated by the model for these regions, showed that there was a significant difference between them. Thus the very high percentage loss due to runoff is applicable to an area with, for example, 3219mm of rainfall as at the River Nevis, but this may be too high an estimate for a low altitude coastal setting. As a result the calibration of the model allowed for a reduction in the percentage runoff to take into account this discrepancy.

A similar situation arose in the other two regions but to a lesser extent, and the calibration required adjustments to the percentage runoff figures for these two regions also, to prevent unrealistic drought conditions from appearing too frequently. The calibration of this sector relied on the figures for soil moisture deficit published in the Hydrological data year book (Institute of Hydrology 1991a). This showed soil moisture deficit for two decades, the 1970's and 1980's, measured as the equivalent of a number of millimetres of precipitation. The available resource generated by the model for these years was then compared to the actual values for mean soil moisture deficit as well as the extreme values described in the data. A reasonable fit with the data was then obtained by adjusting the level of runoff as a percentage of precipitation, for each of the seasons in each of the regions. For winter, where no soil moisture deficit was evident in the data, the available resource was adjusted to ensure that no deficits occurred.

The overall structure of the water resource sector is shown in Figure 8.5

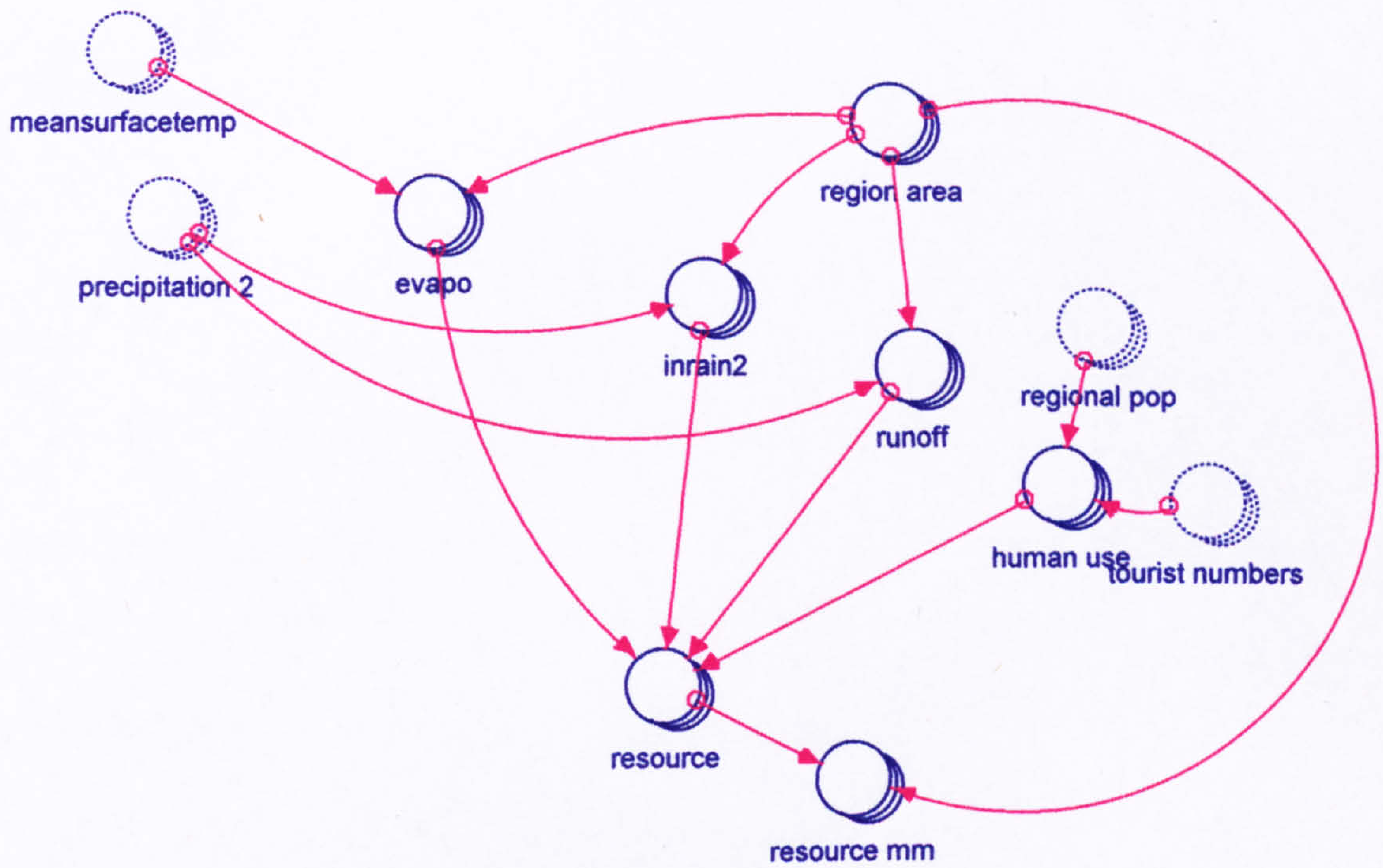


Figure 8.5 The structure of the water resource sector.

8.7. Emissions Sector

8.7.1. Construction of the Emissions sector

Estimates for the annual per capita consumption of fossil fuels for the United Kingdom were obtained from the Dobris Assessment (Officer for official publications of the European Communities 1995) based on 1995 figures. This gave energy use excluding renewables but including Nuclear power. There was no regional breakdown in these figures so it is assumed that little variation occurs between regions of Scotland. These figures relate to energy use in terms of oil equivalent, and this was converted to carbon by assuming that 90 percent of the fuel was carbon. This is at the higher end of the estimates from the DOE website, and is more in keeping with the use of heavy fuel oil and coal, both of which are still used to generate power. It is reasonable to assume that the increased use of natural gas reduces this figure. A per capita consumption of 3.9 tons of fuel oil equivalent, multiplied by 0.9 to convert this to 3.33 tons of carbon per person per year, was used. Rising oil prices, carbon taxes and other factors could well influence this figure, and the model is run with different values to examine the effect of possible changes on overall emissions totals.

Over 90% of tourists arrive by car and to reflect this, tourist numbers were added to the regional populations, thus increasing the total emissions.

This figure, however, was balanced against the assimilation of carbon by the planting of forests, which has been quite extensive over the past few decades. The figure of 6.2 tons of carbon per hectare of forest per year was used, this figure including above and below ground biomass as well as the increase in soil carbon below the canopy. This figure was obtained from the Ecocraft Framework 4 report (Jarvis 1999), which gave details of carbon assimilation from sites across Europe. One such site was in central

Scotland, near Pitlochry, and this produced the figure of 6.2 tons/ha/y, averaged over the life of a forest.

Forestry does not provide a permanent removal of carbon from the atmosphere, but in the short to medium term it could provide a means by which some of the current emissions can be absorbed. The crucial question concerns the longer term future of the wood produced by these forests, as this could represent a significant way of reducing CO_2 concentrations in the short to medium term, assuming the wood which is harvested is used in relatively long lived products.

The balance of CO_2 emissions from human sources, regional population and seasonal tourist numbers, minus the sequestration by existing and projected forest cover, represents the net emissions for each region.

The structure of the emissions sector is shown in Figure 8.6.

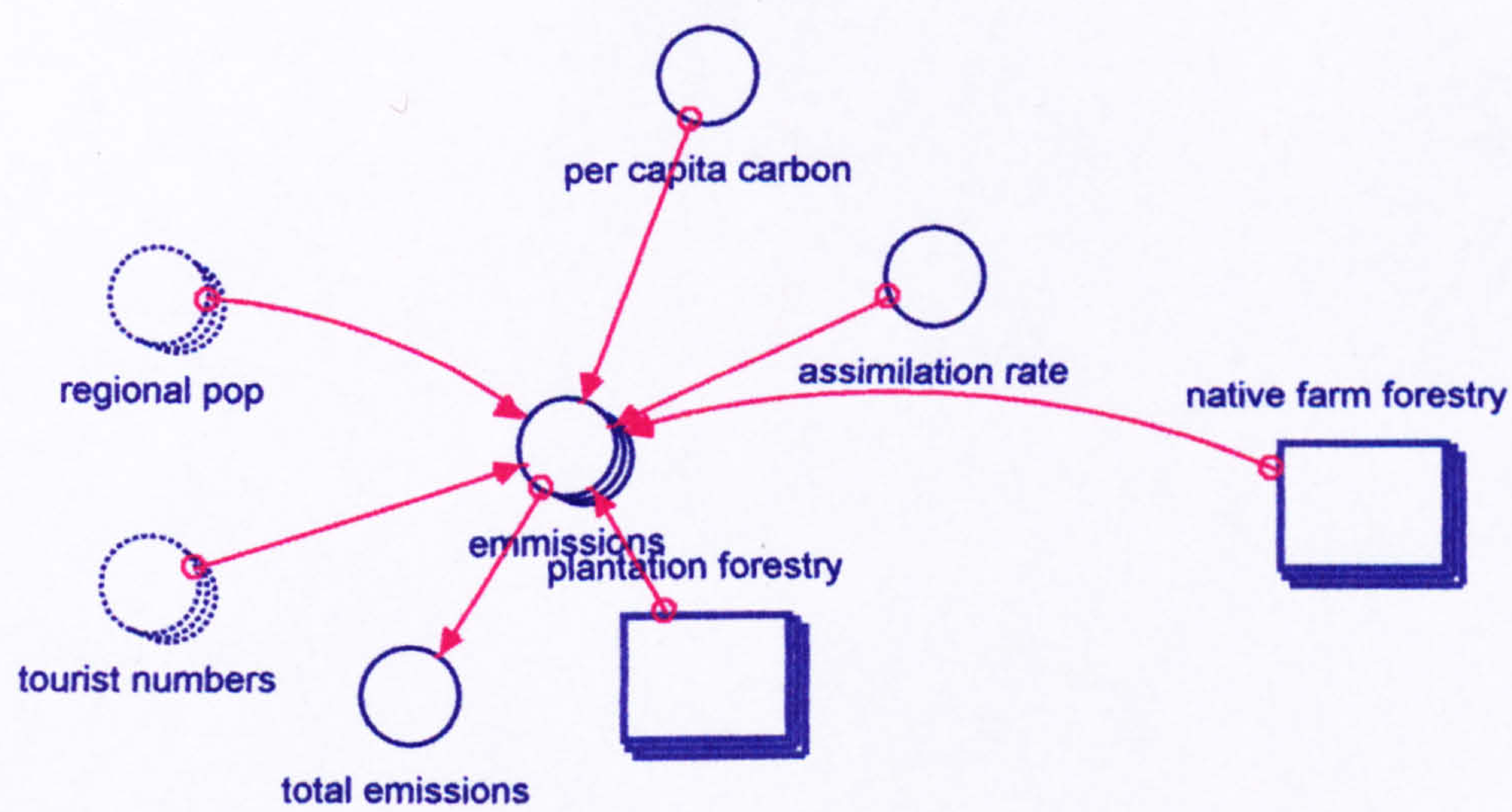


Figure 8.6 The structure of the emissions sector

Chapter 9 Sensitivity Testing

9.1. The Structure of the Combined Model

Of central importance to the functioning of the combined climate/socio-economic model is the structure of the feedback loops which have been created. Several of the sectors contain no feedback loops, for example the emissions and water resource sectors, and simply represent calculations based on the accumulations and processes from the other sectors.

Below in Table 9.1 are listed all the main reservoirs or stocks within the model, along with the number of loops which can be identified for each and whether they are positive (reinforcing), or negative (counteracting) in their effect. Each loop is described in some detail in the Appendix.

9.2. The feedback loops

Stock	Feedback loops	+ve or -ve	Elements contained in each loop Loop Number
Atmosphere (climate sector)	4	-ve +ve +ve -ve	1. Atmosphere > Atmospheretoearth > Atmosphere 2. Atmosphere > Atmospheretoearth > Earth > Earthtoatmosphere > Atmosphere 3.Atmosphere > Atmospheretoearth > Earth > Thermal > Atmosphere 4. Atmosphere > atmospheretospace > Atmosphere
Atmospheric CO_2 (climate sector)	1	+ve	5. AtmosphericCO2 > CO2change > AtmosphericCO2
Earth (climate sector)	5	-ve -ve -ve +ve +ve	6. Earth > earthtoatmosphere > Earth 7. Earth > thermal > Earth 8. Earth > earthtospace > Earth 9. Earth > earthtoatmosphere > atmosphere > atmospheretoearth > Earth 10. Earth > thermal > atmosphere > atmospheretoearth > Earth

Crops and Grass (land use sector)	2	-ve -ve	11. Crops and grass > agriculture employment > Labour demand > Unemployed > Job seekers > Middle > regional pop > popchange > newbuild > newbuilding > Crops and grass 12. Crops and grass > agriculture employment > Labour demand > Unemployed > Job seekers > Middle > retire > older > regional pop > popchange > newbuild > newbuilding > Crops and grass
Rough Grazing (Land use)	1	-ve	13. Rough grazing > improved > Rough grazing
Housing Stock (Housing sector)	1	+ve	14. Housing stock > newbuild > Housing stock
Young (population sector)	5	-ve -ve +ve +ve +ve	15. Young > deathrate 1 > Young 16. Young > enter workforce > Young 17. Young > regional pop > births > Young 18. Young > enter workforce > middle > regional pop > births > Young 19. Young > enter workforce > middle > retire > older > regional pop > births > Young
Middle (Population sector)	9	–ve -ve +ve -ve -ve +ve -ve +ve -ve	20. Middle > deathrate2 > Middle 21. Middle > retire > Middle 22. Middle > regional pop > births > young > enterworkforce > Middle 23. Middle > retire > older > regional pop > births > young > enterworkforce > Middle 24. Middle > regional pop > laboursupply > unemployed > jobseekers > Middle 25. Middle > retire > older > regional pop > laboursupply > unemployed > jobseekers > Middle 26. Middle > regionalpop > laboursupply > nonclimaticsector > labour demand > unemployed jobseekers > Middle 27. Middle > regionalpop > popchange > newbuild > newbuilding > crops and grass > agricultural employment> labourdemand > unemployed > jobseekers > Middle 28. Middle > older > crops and grass > Middle
Older (population sector)	5	-ve +ve -ve -ve -ve	29. Older > die > Older 30. Older > regional pop > births > young > enter workforce > middle > retire > Older 31. Older > regional pop > labour supply > unemployed > jobseekers > middle > retire > Older 32. Older > regional pop > labour supply > non climatic sector > labour demand > enemployed > job seekers > middle > retire > Older 33. Older > crops and grass > middle > Older

Table 9.1 The components of the feedback loops.

In total, the climate sector contains 10 feedback loops, 5 of which are negative and 5 positive. The land use sector contains 3 negative feedback loops. The housing sector contains one positive loop and the population sector has in total 19 feedback loops, 12 of which are negative and the remaining 7 positive. Each of these 33 loops is considered in some detail and the results presented in the Appendix, with the variables which are of importance listed.

9.3. Sensitivity

Testing the sensitivity of the model to variations in values for the different parameters is an important aspect of the model construction. In a more complex model there are considerably more variables which might have an impact on the output. In some cases this may be proportional to changes to the variable. Others may have little or no impact, while others may have an impact which is far greater than the scale of the change to the variable itself. If a 10% increase in a variable has an impact of 10% or less on the final output, then this is not a variable to which the model is sensitive. If the 10% change generates a 100% change to the output then this variable has to be treated with great care. Sensitivity could also generate a different pattern of output, rather than just different values with a similar overall configuration.

In particular, if there is little empirical evidence upon which to base the value of a variable, then it is important to test the sensitivity of the model to changes in that variable. In this way the implications of any errors or lack of exactitude will be understood, as will the implications of the boundaries of uncertainty. Where sound empirical evidence is used to produce the values this is not such a problem. Any parameter which has been set as the result of assumptions must be investigated fully and the sensitivity of the model to the assumptions tested thoroughly.

The structure of the model is the same for all three regions. In view of this, the sensitivity tests will be run on only one region at a time.

9.4. Climate sector

Variables to be tested

The climate sector is designed to generate simulated temperature and precipitation, but the latter used the output of the Hadley centre model to determine rainfall totals derived from CO_2 levels in the atmosphere. As a result the sensitivity testing will concentrate on the simulated temperatures and the variables included in their production.

The variables, which are defined in Chapter 6, and which will be tested within the climate sector are:

1. Latent and sensible heat transfer “te”
2. The sensitivity of the atmosphere to changes in CO_2 levels “sensitivity”
3. The proportion of incoming radiation heating the atmosphere “fb”
4. daylength
5. The reflectance of the planet “albedo”
6. Energy from the surrounding oceans “ocean warmth”
7. The proportion of the energy radiated by the Earth which heats the atmosphere “fa”

In each experiment the variable will be altered by approximately 10% or within reasonable limits, with four runs being made with incremental changes to the variable in question being made.

In each case a graphical output will be generated to examine the scale of the changes to temperature as well as the pattern of temperature change.

Sensitivity to changes in te

This has a value of 0.34, so the sensitivity test will take values between 0.31 and 0.37. Four runs spanning this range give values of 0.31, 0.33, .035 and 0.37. Figure 9.1 shows the resultant effect on the annual temperature of Stirling. It is clear that a greater thermal transfer of energy into the atmosphere has a warming effect, but does not alter significantly the pattern of the output.

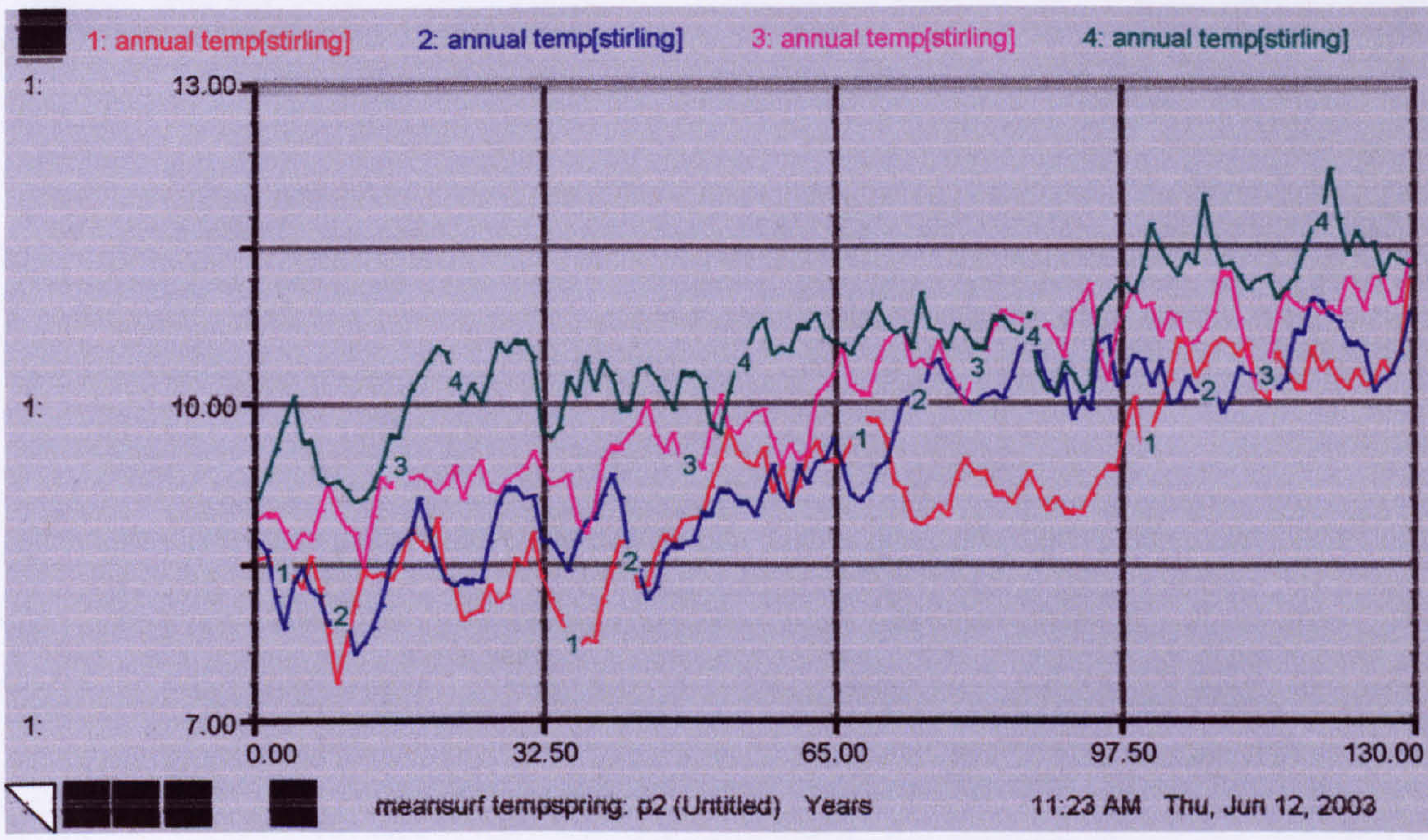


Figure 9.1 Sensitivity to changes in "te".

Sensitivity to changes in "sensitivity".

This variable controls the effect that CO_2 levels have on the absorption of long wave energy in the atmosphere. It has been set with a value of 0.0103, the value required to raise the temperature in the basic model from –6 degrees Celsius to 15 degrees Celsius as CO_2 was added to pre-industrial levels. Again four runs are made with values between 0.0098 and 0.0108 being used. The results are shown in Figure 9.2. This shows that increasing the sensitivity of the atmosphere to CO_2 does have the effect of increasing surface temperatures, but in a stepped manner, generating a similar pattern of results in each case.

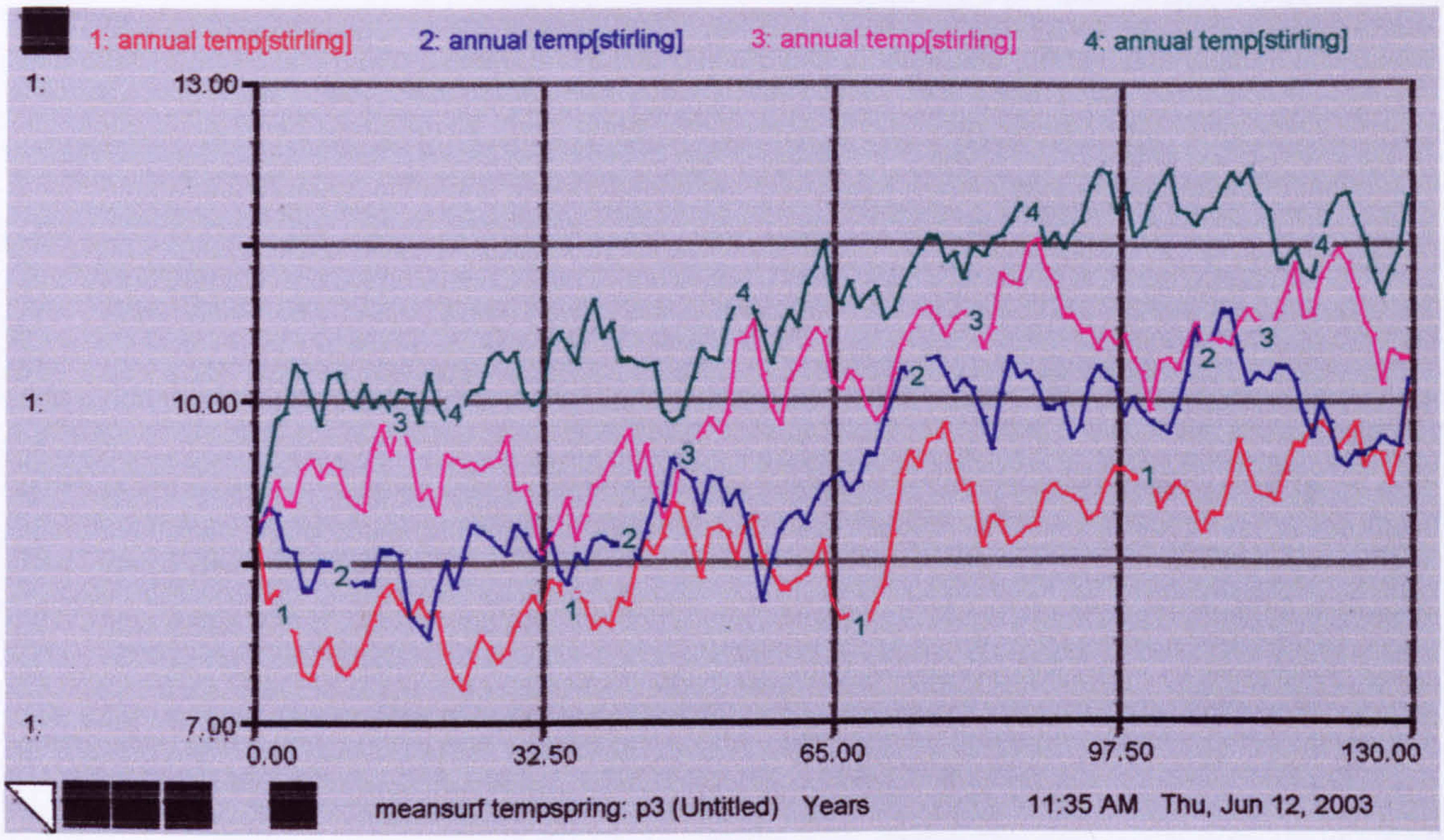


Figure 9.2 Sensitivity to changes in sensitivity, Low scenario.

The above graph, Figure 9.2, is based on a run of the Low scenario. A similar run using the High scenario, in which levels of atmospheric CO_2 are considerably higher, yields the results illustrated in Figure 9.3. This shows a similar pattern to the Low scenario suggesting that the model under different scenarios behaves in the same manner as changes to this variable are made.

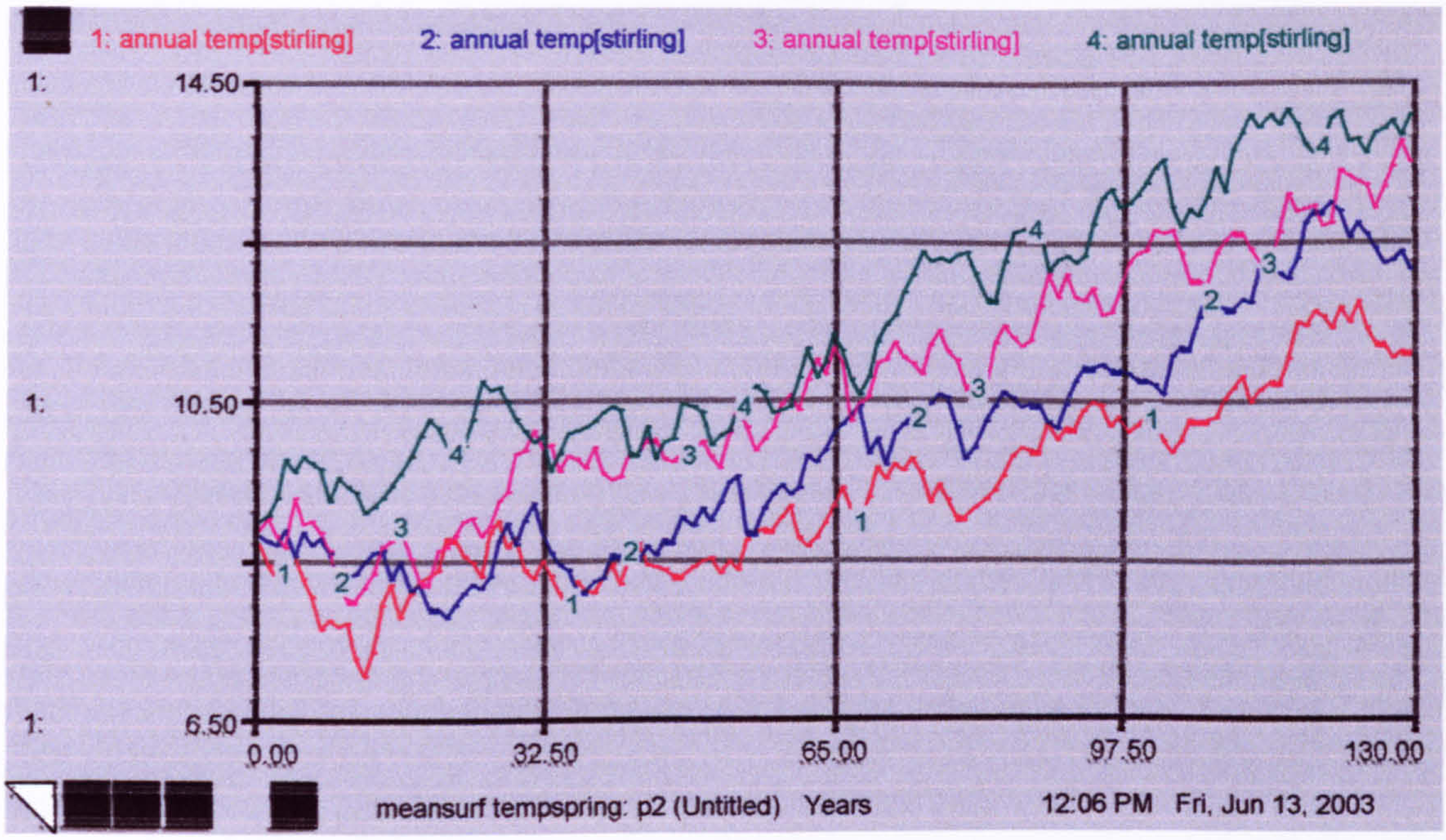


Figure 9.3 sensitivity to changes in "sensitivity; High scenario

Sensitivity to changes in "fb".

The variable fb is used to control the amount of solar short wave energy which is either absorbed by the atmosphere or passes through to the earth's surface. This has been set at 0.9285 so sensitivity runs will use values between 0.88 and 0.97. The results can be seen in Figure 9.4 and show that higher values of fb have the effect of lowering the surface temperature. The effect is less pronounced than with the previous examples, and results from a greater loss of energy to space from the atmosphere, energy which is lost to the system.

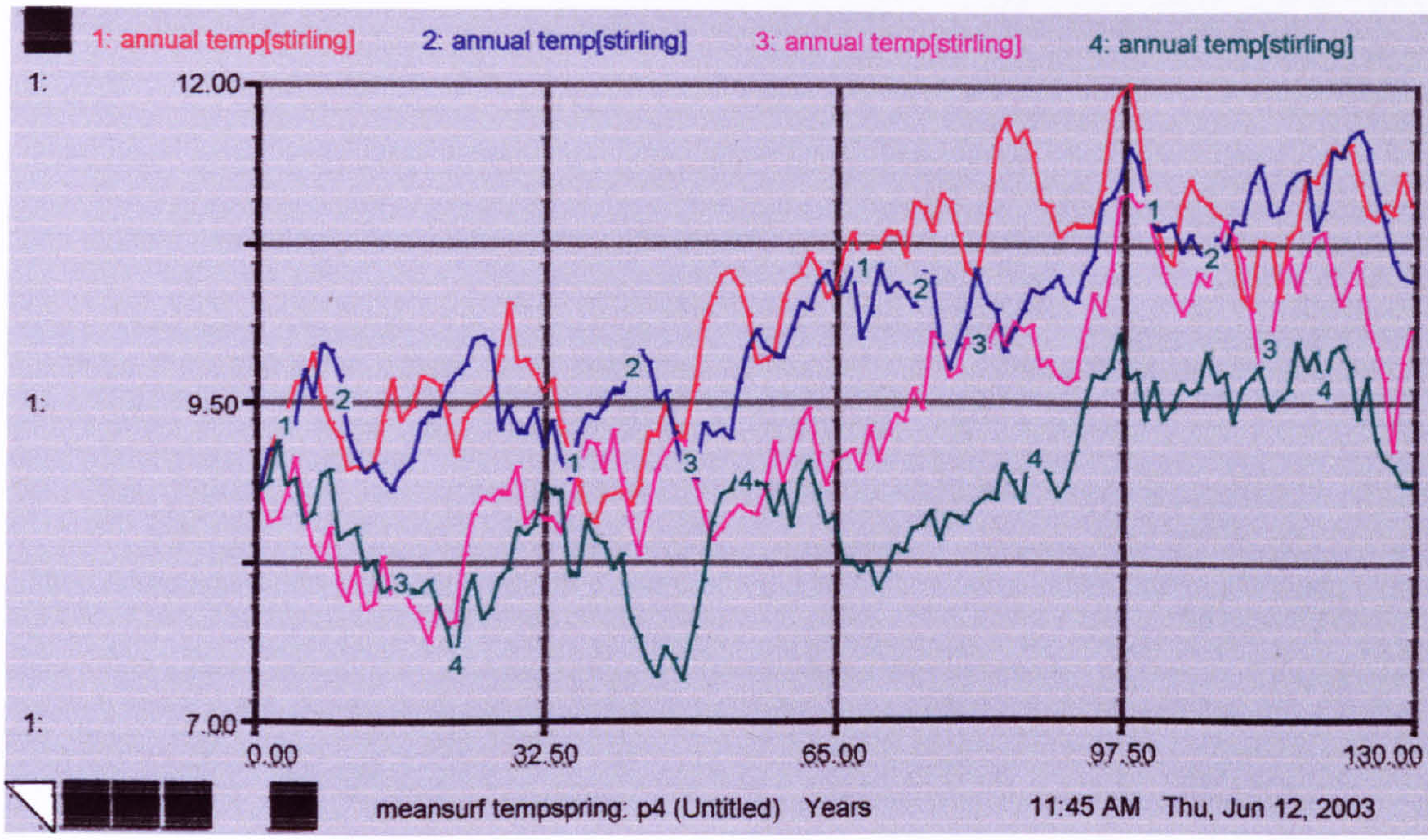


Figure 9.4 Sensitivity to changes in fb.

Sensitivity to changes in daylength.

Daylength has been set in the model as an approximate mean value for the days of each season. Testing the sensitivity of the output to changes in this variable has to be done on a seasonal basis, with summer and winter being the two seasons where this takes it's maximum and minimum values. One set of tests is performed for each of these two seasons using the regional output from Stirling again. The values used for mean daylength are winter 7 hours and summer 16.8 hours. The runs are made with winter values ranging from 6.6 to 7.4, and summer values ranging from 16 to 17. 6.

Changes to the length of day should have the effect of increasing the energy reaching the system and as a result should increase the surface temperature. This will have, as illustrated in Figure 9.5 and Figure 9.6, a greater effect on summer temperatures which depend more heavily on solar input rather than input from the oceans in the form of heat transfer.

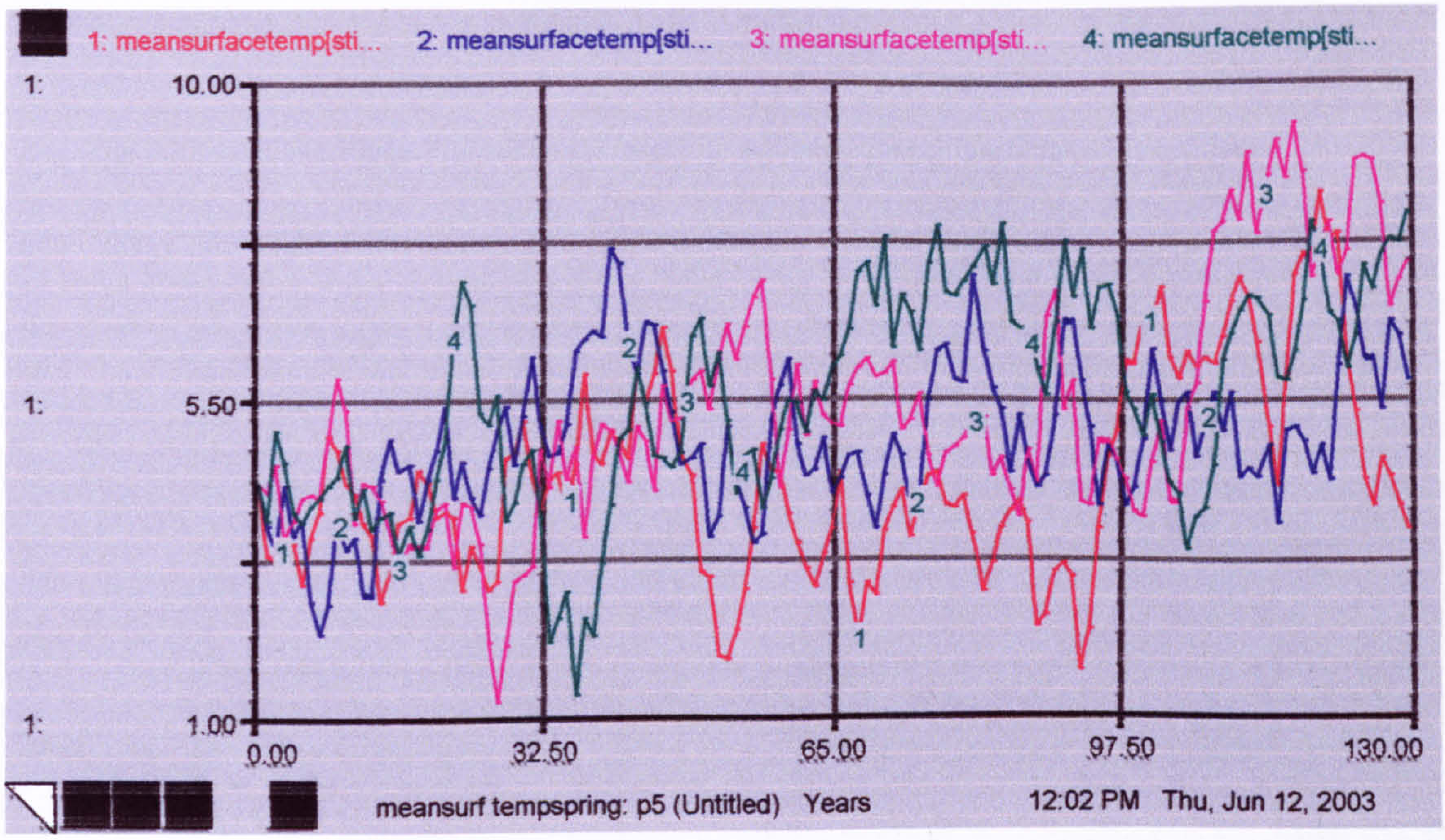


Figure 9.5 winter Sensitivity to changes in daylength

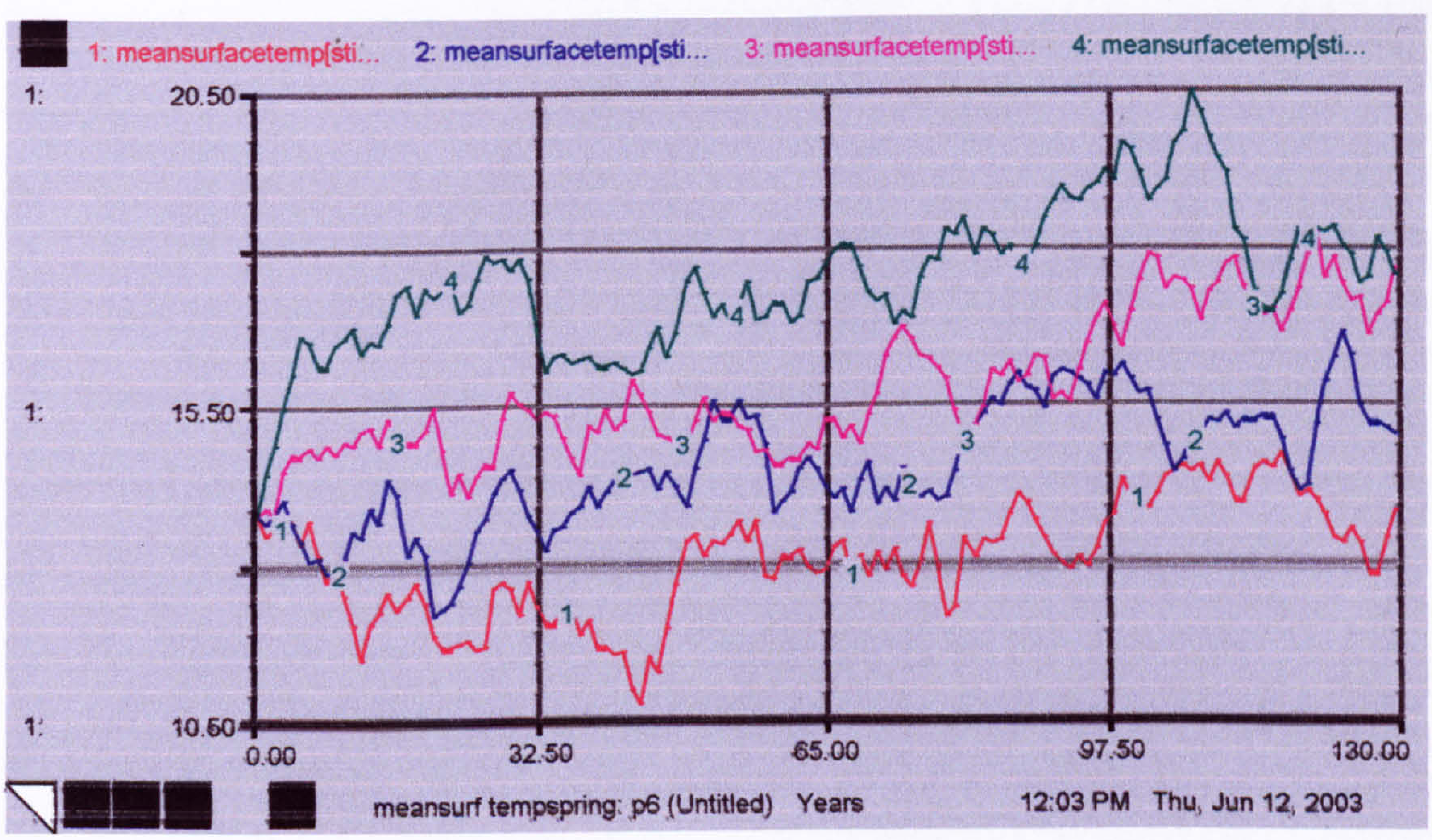


Figure 9.6 summer Sensitivity to changes in daylength.

In neither of the above graphs does the pattern of output change. The effect of longer days is to make winter temperatures increasingly resemble those of spring and autumn, and to increase the summer temperatures. The error in calculating the mean length of day is likely to be far less than 10% so any resultant effect will be of a far lesser scale than illustrated in the above graphs.

Sensitivity to changes in albedo.

Albedo, or the reflectivity of the planet surface, controls the amount of solar energy entering the system. The actual reflectivity of the Earth's surface is not a fixed constant. Factors such as ice and snow cover and areas of deserts or the amount of cloud cover all have an effect on the amount of energy from the sun which is reflected and hence lost to the system. The value used in the model is 0.313 and the sensitivity runs will cover the range from 0.3 to 0.33. The results are shown in Figure 9.7 and represent the effect on the annual temperature of Stirling.

It can be seen that the effect of increasing albedo is to lower the surface temperature, and within the range described above, the effect is a steady drop in temperature. Events such as massive volcanic eruptions can have a short term effect on the planet's albedo and a lowering of temperature is an expected consequence. A change of 10% would be quite drastic and can be seen to lower temperatures in the model by about 1.5 degrees Celsius.

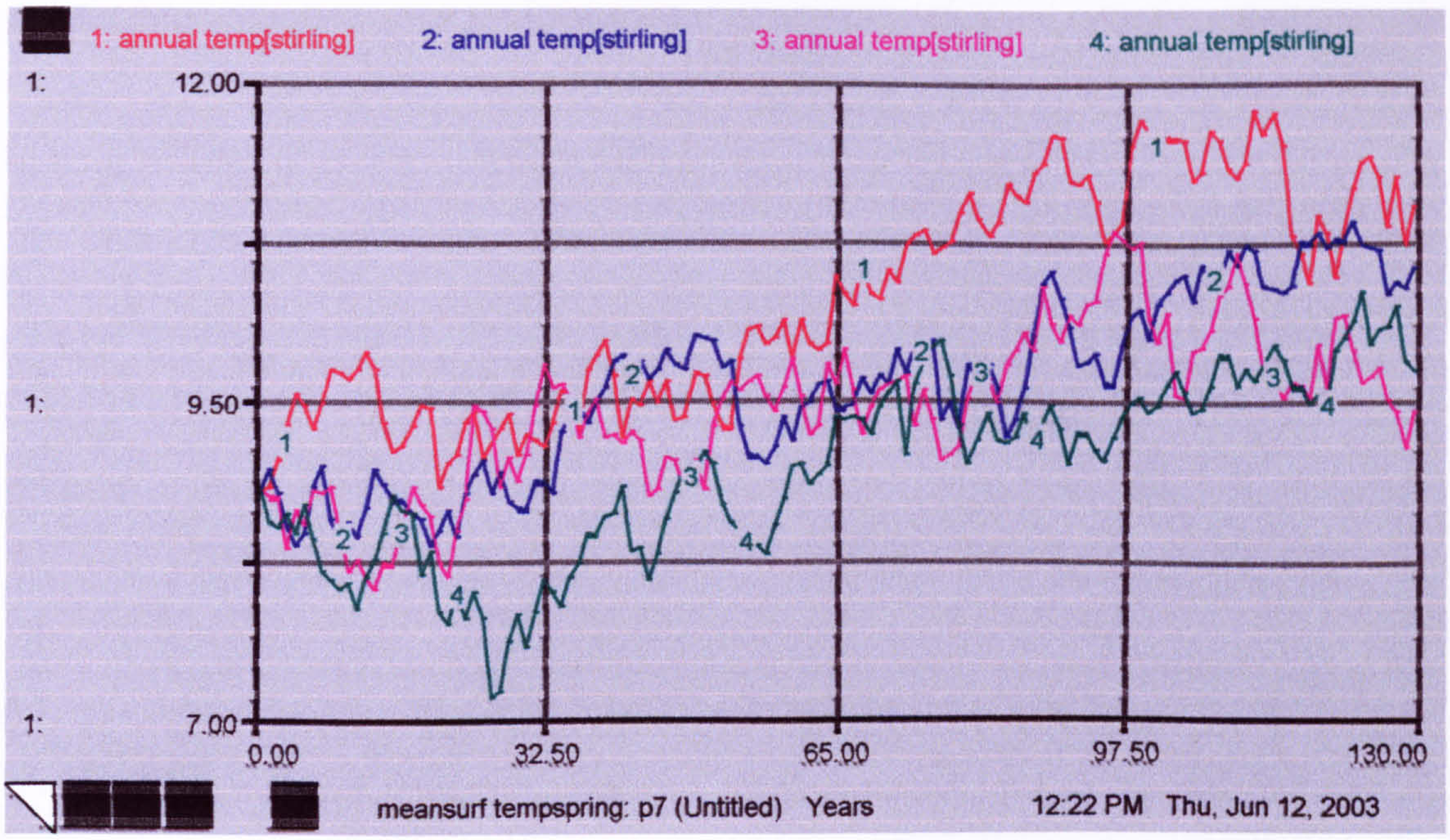


Figure 9.7 Sensitivity to changes in albedo

Sensitivity to changes in "ocean warmth".

Ocean warmth has been set at values unique to each region in each season. The largest effect is likely to be in winter, where proportionally more of the energy generating the surface temperature comes from the surrounding oceans. The values used were chosen in order to create a match between the model output and the empirical records over the period for which data was available. The test for sensitivity will focus on the region, Argyll, which has the greatest contribution from ocean warmth in the winter, when this transfer of energy is most significant. The values range in incremental steps from $1.2x\ 10^9$ to $1.4x\ 10^9$. This represents a considerable input of energy and, as such, the changes to mean surface temperature are more extreme than in any of the previous examples. However, the value of $1.3x\ 10^9$ which was used, generated the necessary increase in temperature to create a good fit between model output and the empirical data, and is therefore not a value which is subject to change.

The results are shown in Figure 9.8.

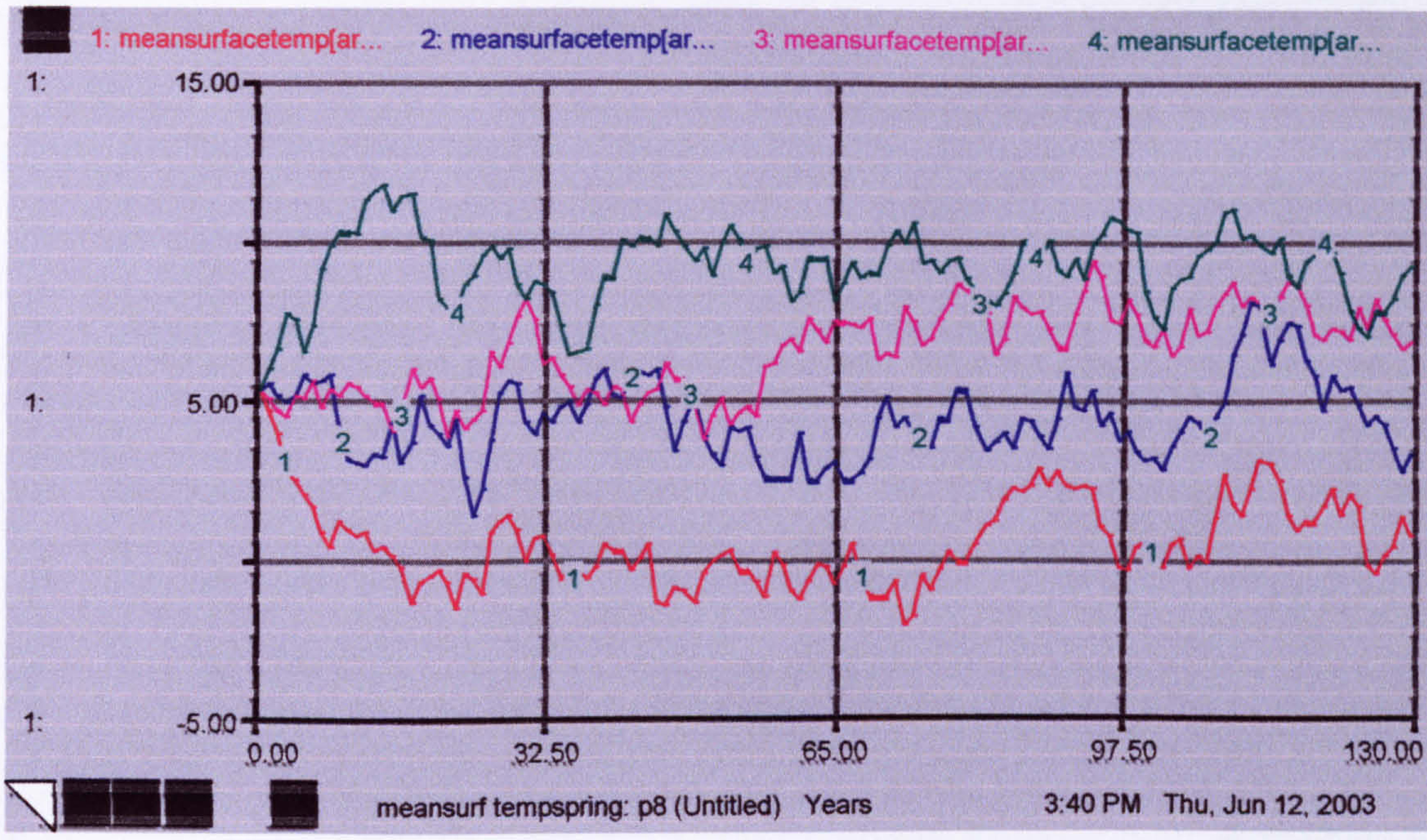


Figure 9.8 Sensitivity to changes in ocean warmth

None of the above variables generate significant changes to the pattern of output from the climate sector. All produce changes which are explicable in terms of the theoretical basis of the model.

Sensitivity to changes in "fa"

The variable "fa" controls the rate at which long wave radiation from the Earth is transmitted to the atmosphere (and is lost to space). It has been set at 0.815 in the model, and to test the sensitivity of the model to changes in this value the range between 0.75 and 0.85 will be investigated. The graph below (Figure 9.9) shows runs of the model with values of 0.75, 0.78, 0.82 and 0.85. The impact on annual mean daily temperature in Stirling is illustrated. It can be seen that the value of this variable is quite important. The changes described above have a significant impact on the temperature.

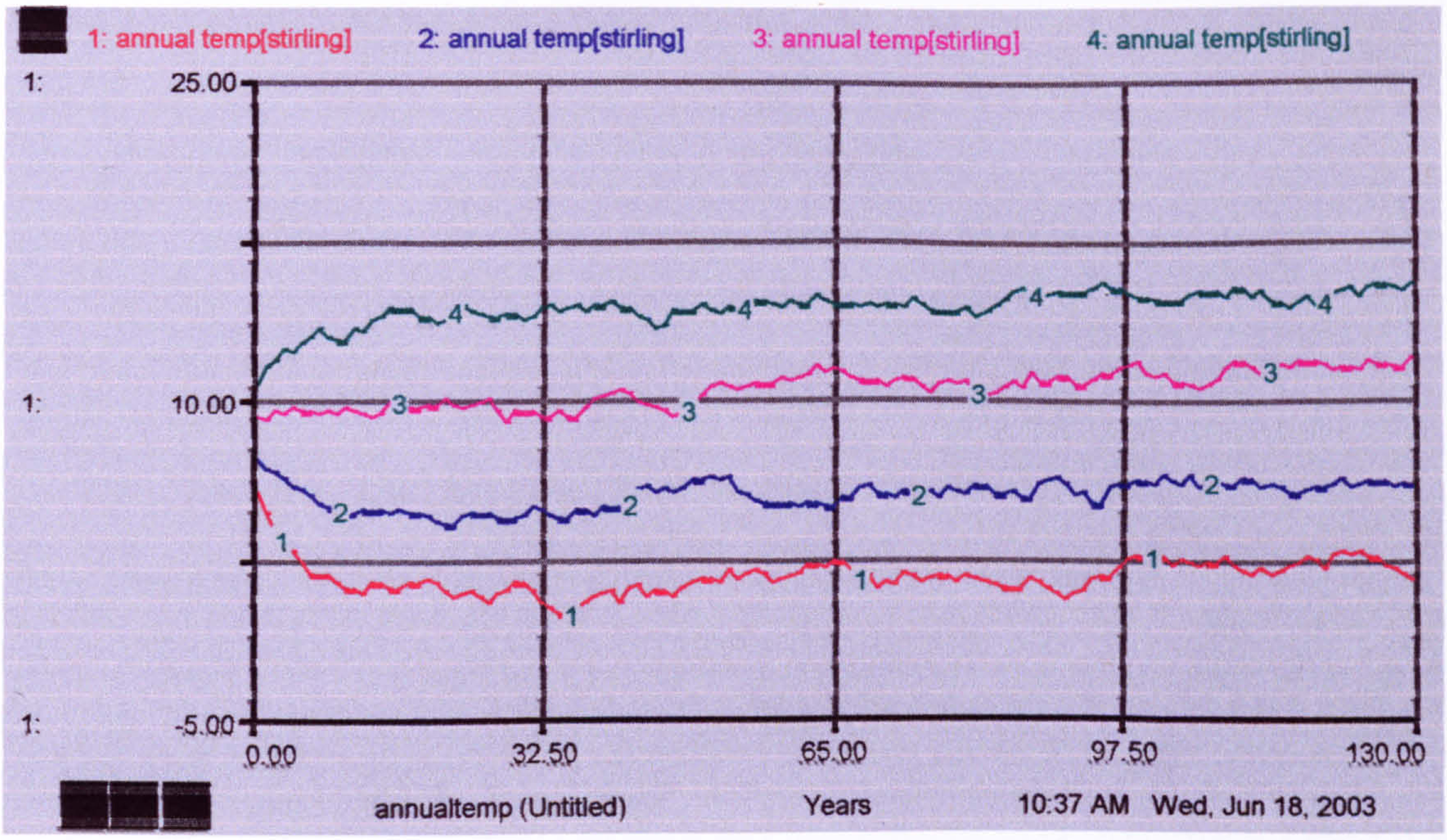


Figure 9.9 Sensitivity to changes in fa

Higher values represent more long-wave energy from the Earth trapped in the atmosphere and proportionally less escaping to space. There is therefore no surprise in the output represented in Figure 9.9.

9.5. Population sector

Variables to be tested

Within the population sector all variables, with the exception of the in-migration due to labour shortages, are based on accurate data from the General Register of Scotland (General Registrar of Scotland 1975-2000). The only allowable values for sensitivity tests are the initial values for young, middle and older age cohorts. In each case a similar pattern is generated. Changes to the initial values of each of these stocks generates a slight change in the total regional population, but certainly no change to the pattern of population change. The results for changes to the Young, Middle and Older age groups of Stirling are shown in Figure 9.10, Figure 9.11 and Figure 9.12, respectively.

The young age group was set at 23934, runs between 22800 and 25200 being used for the sensitivity test. The middle age group was set at 41756 with sensitivity to values between 40000 and 44000 being carried out.

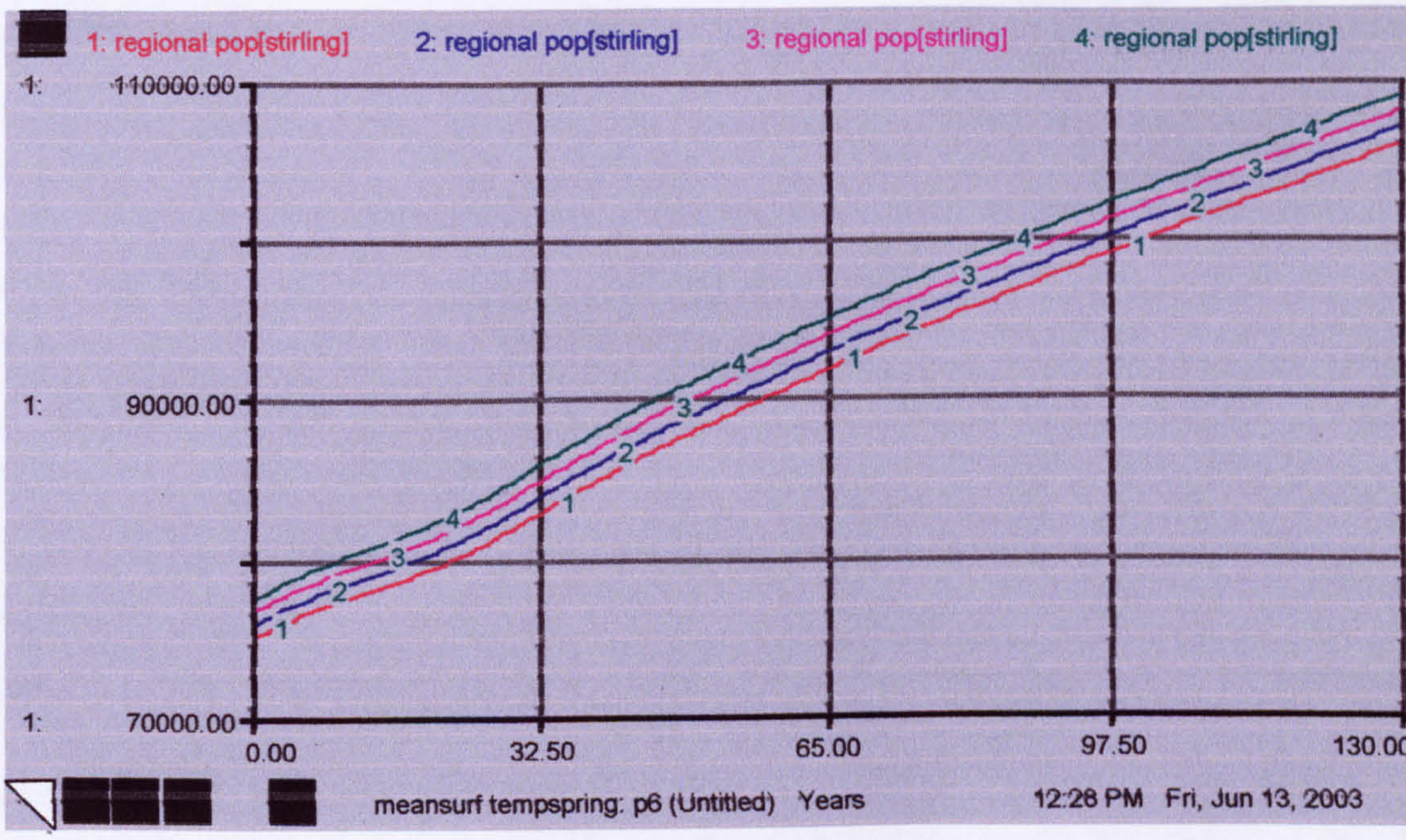


Figure 9.10 Sensitivity to changes in young population

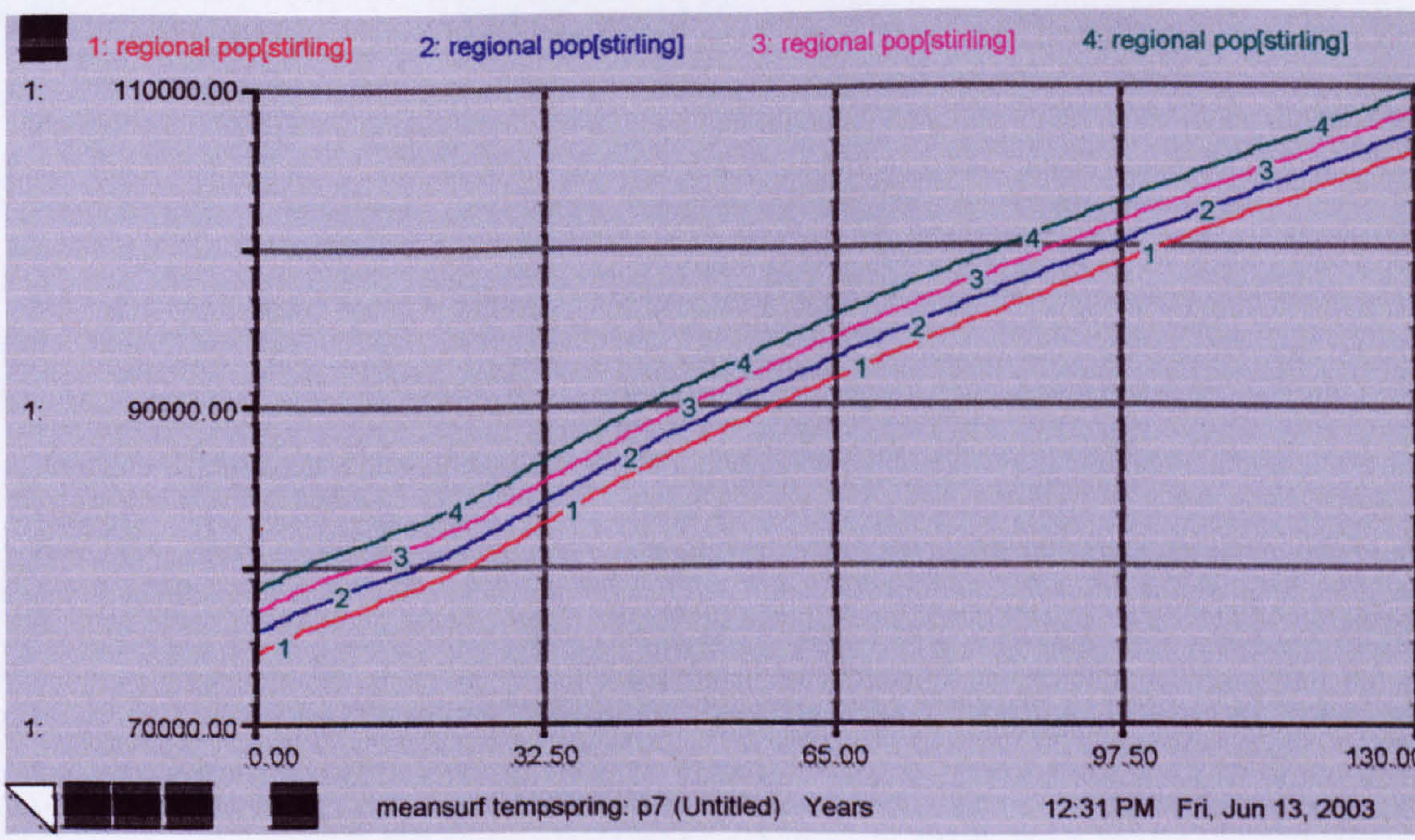


Figure 9.11 Sensitivity to changes in middle population.

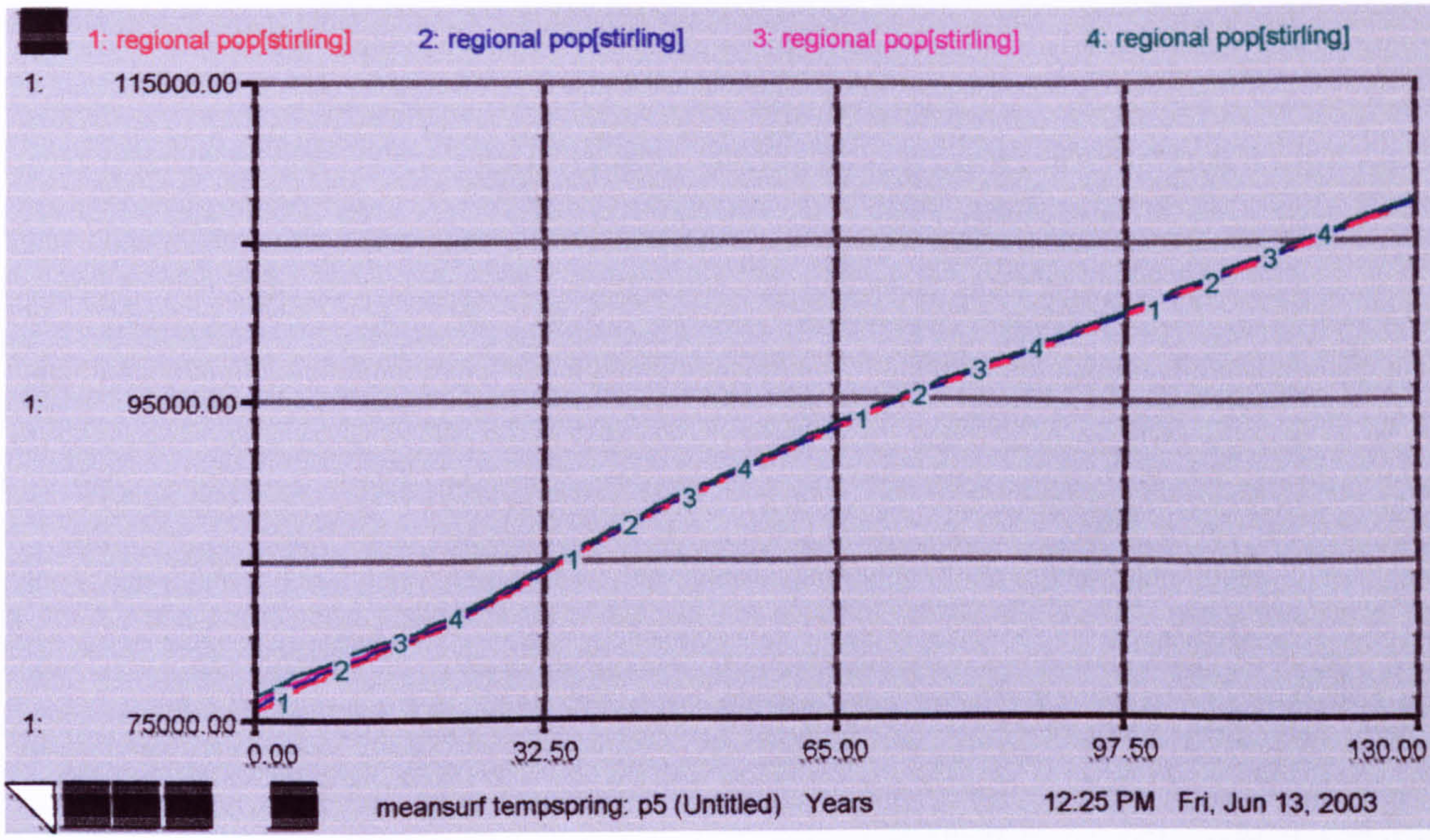


Figure 9.12 Sensitivity to changes in older population

In each case the initial value for each age cohort was altered by approximately 10%. It can be seen that changes to the number of people of working age has the greatest long term effect on the overall population of the region, with changes to the number of older people having a limited long term effect on the overall population of Stirling.

Within any population the birth and death rates are crucial in determining the long term population structure. The performance of the model was therefore tested to ascertain the impact that changes to the long term projections of these two variables would have on the regional populations.

Again only one region was chosen, this being Fife which shows the smallest effects of changing climate.

The long term projection for the birth rate in Fife is set at 10.1 per thousand of population. This is near to the lower level of the past changes, so a range of between 10 and 10.5 per thousand of population is investigated. Six runs are illustrated below in Figure 9.13, with the increment being 0.1. In addition, a figure of 10.8 and 11 births per thousand of population are included, which suggests that a figure of around 10.7 or 10.8 would be required to generate a stable population if Fife. Anything above this would produce a population increase if sustained for a considerable time.

This is a variable to which the model is sensitive, the long term projection from the GROS being the value used. Changes to this estimate could be included in the model, if and when this occurs.

The effect of increases to the death rate for any of the age cohorts would have the opposite effect to that of increases to the birth rate. Again the sensitivity of the model to such changes is such that long term forecasts could be included at a later date should they change. In general, the death rate for the regions shows far less variability than birth rate, and so the long term projections can be viewed with greater confidence.

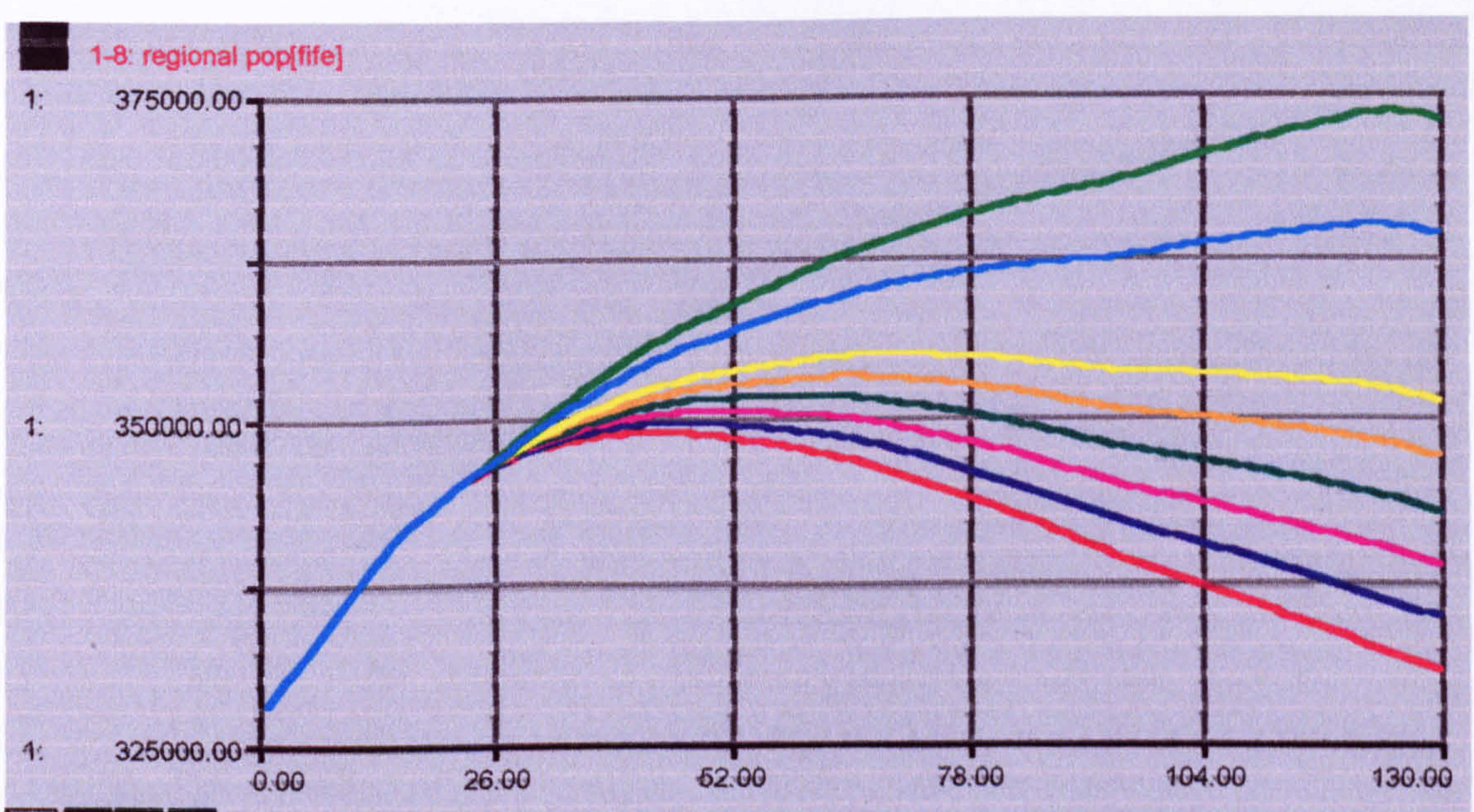


Figure 9.13 Sensitivity to changes in birthrate (Fife)

9.6. Emissions sector

Variables to be tested.

In the emissions sector the only variables which are to be tested are the value of per capita CO_2 and the assimilation rate. In both cases approximate values were used, there being no regional breakdown of per capita CO_2 emissions available and no figures relating to assimilation rates available on a regional basis.

Figure 9.14 shows the sensitivity of Argyll to changes in per capita CO_2 emissions, Figure 9.15 the sensitivity to changes in assimilation rate. The value for assimilation rate used in the model is 6.2 tons per hectare per year, the sensitivity runs use values between 5.9 and 6.5.

Per capita CO_2 emissions are set at 3.33 in the model, the sensitivity runs vary between 3.2 and 3.5.

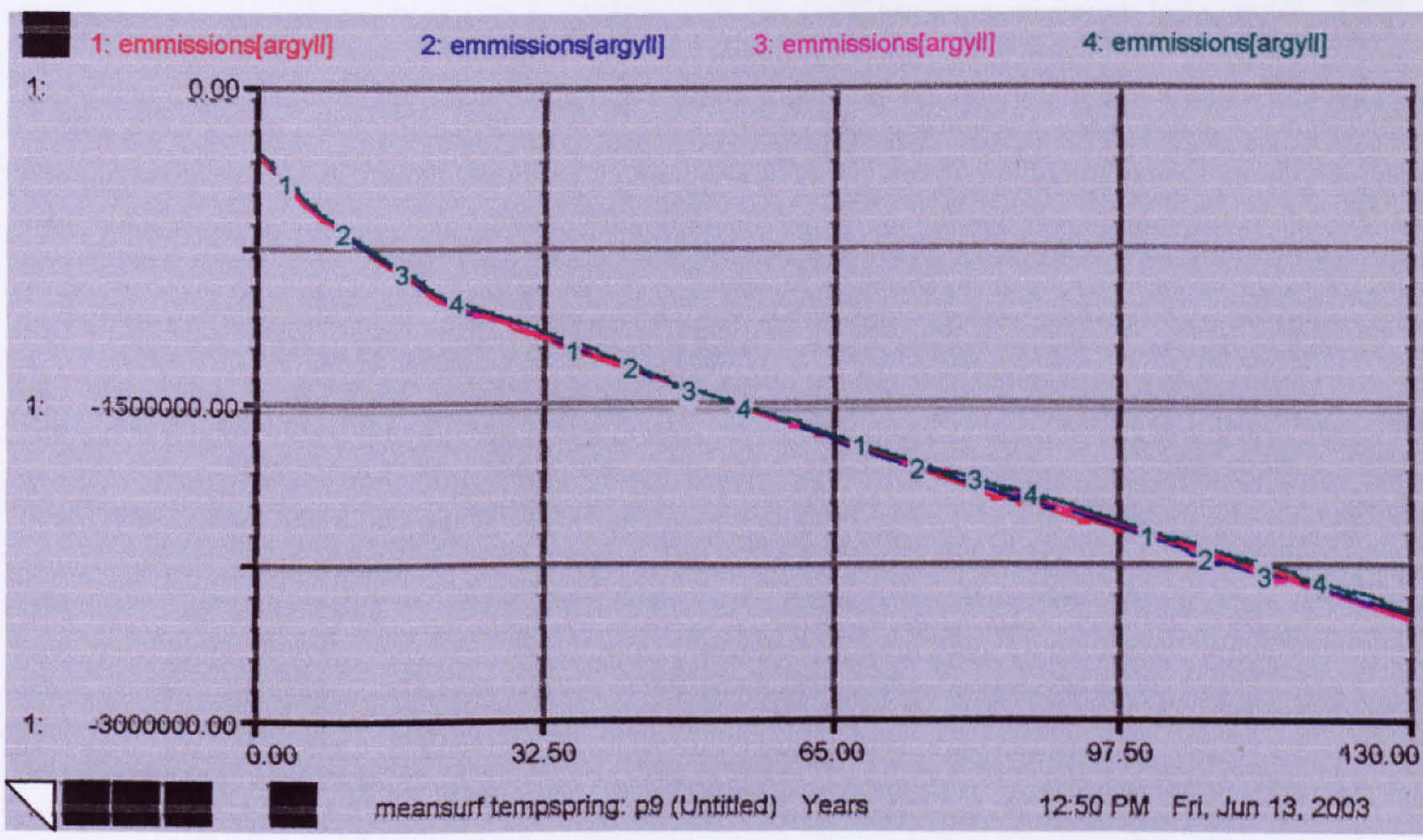


Figure 9.14 Sensitivity to changes to per capita CO_2 emissions. (Argyll)

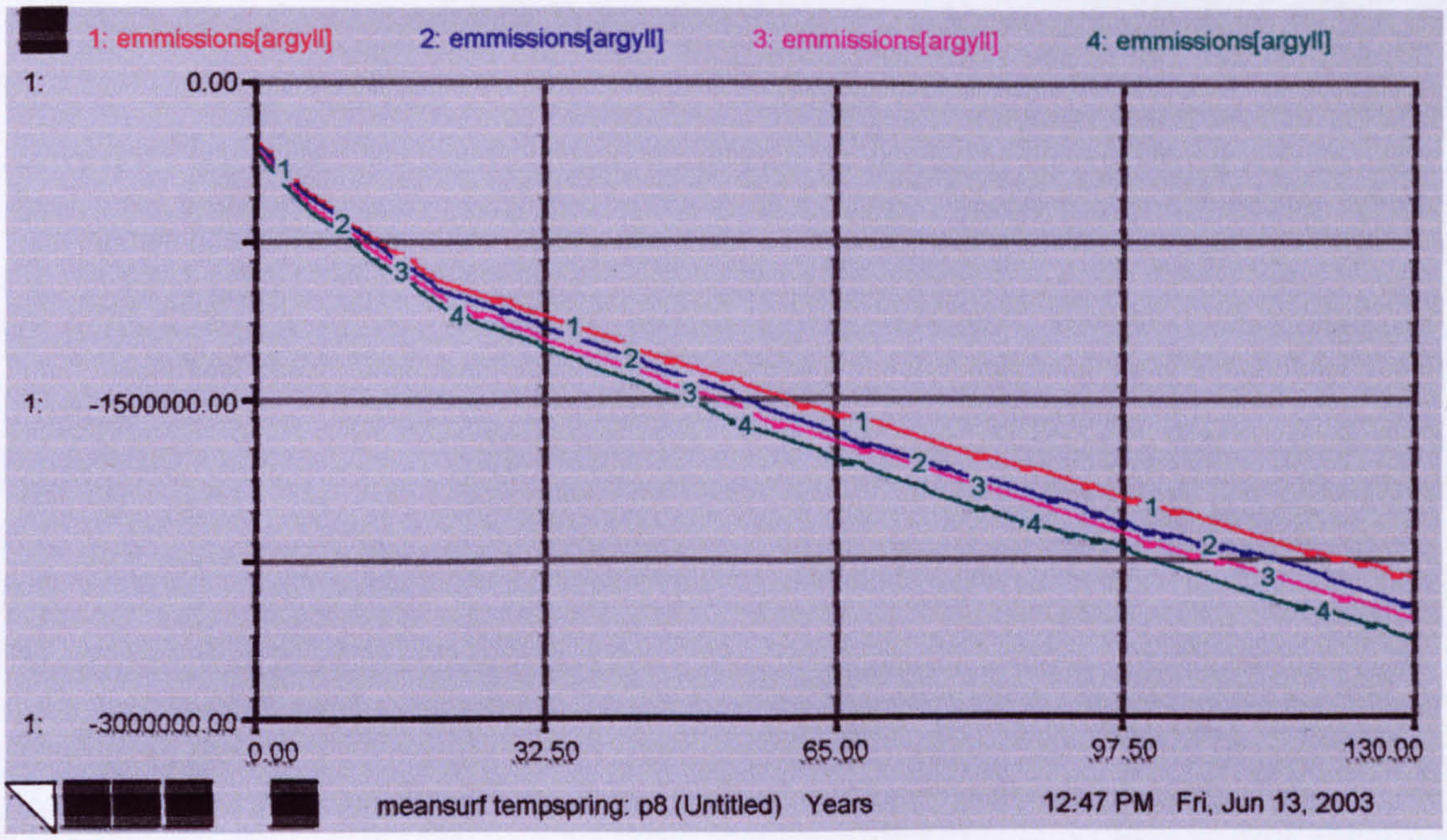


Figure 9.15 Sensitivity to changes in assimilation rate. (Argyll)

Changes to per capita CO_2 emissions have less effect on the overall emissions from Argyll than do changes to the assimilation rate, as a result of the large area of forestry within this region and relatively small population. The same values used for Fife yield the results illustrated in Figure 9.16 and Figure 9.17.

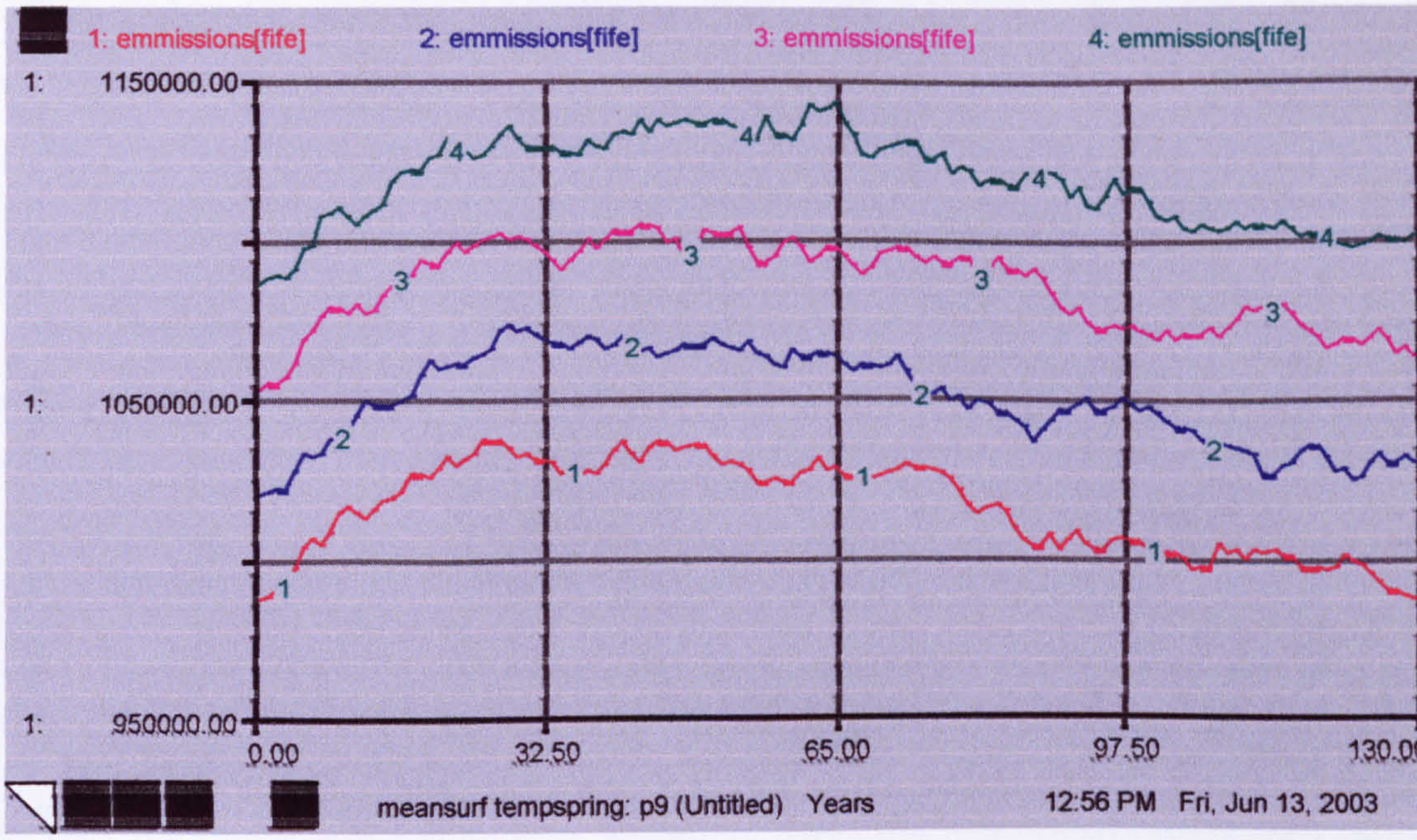


Figure 9.16 Sensitivity to changes in per capita CO_2 (Fife)

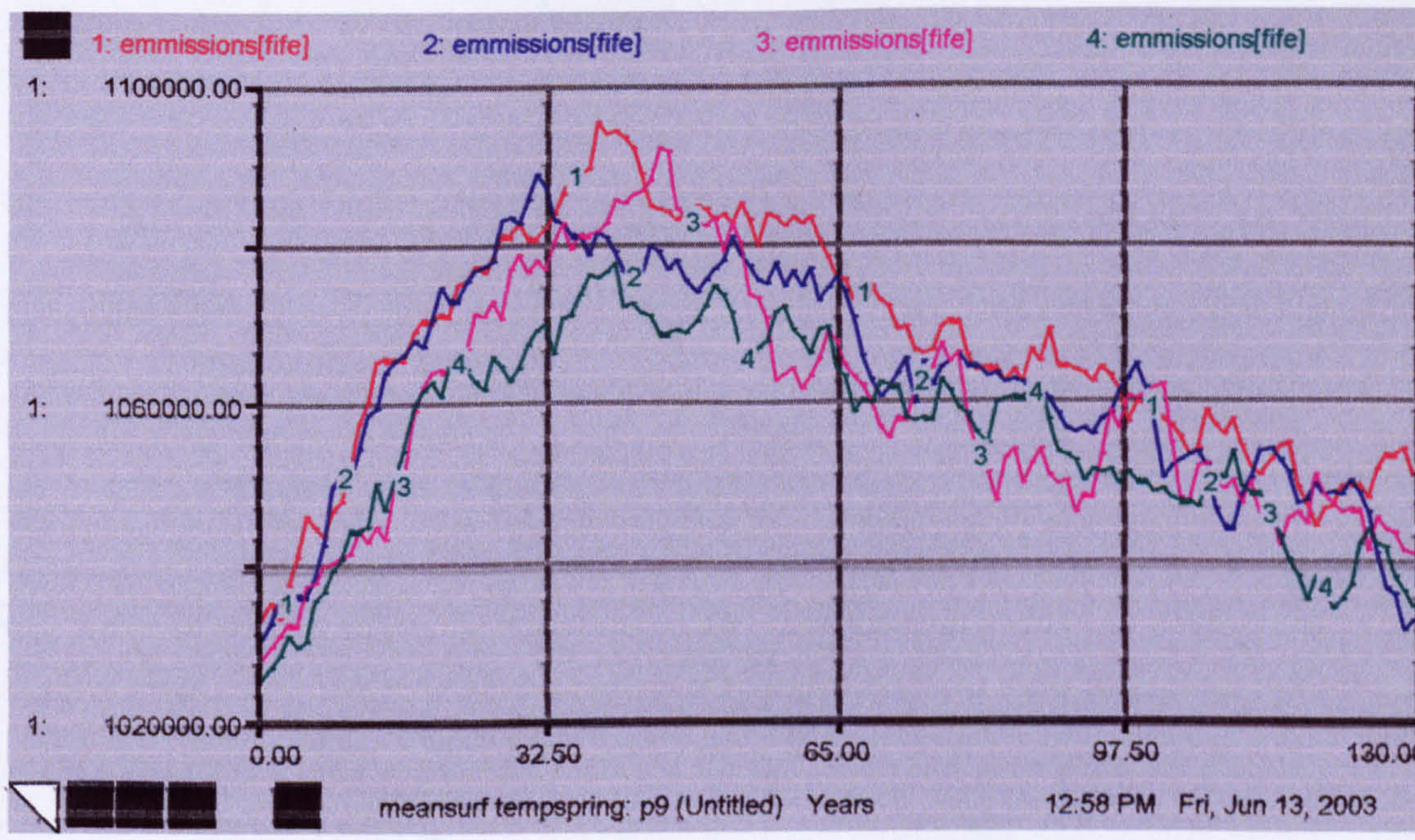


Figure 9.17 Sensitivity to changes in assimilation rate. (Fife)

It can be seen that in Fife, with a large population and relatively little forestry, the effect of changes to per capita CO_2 emissions have a significantly greater impact on overall emissions than do altered values for assimilation of CO_2 by forestry. In neither case does the pattern of output vary.

9.7. Employment sector

Variables tested

The variables against which the employment sector has been tested for sensitivity are the multipliers used in the generation of employment figures for the different sectors. The agricultural employment multiplier is set at 2.43. Comparisons have been made between 2 and 3 with four runs being made taking values of 2, 2.33, 2.67 and 3. The results are shown in Figure 9.18.

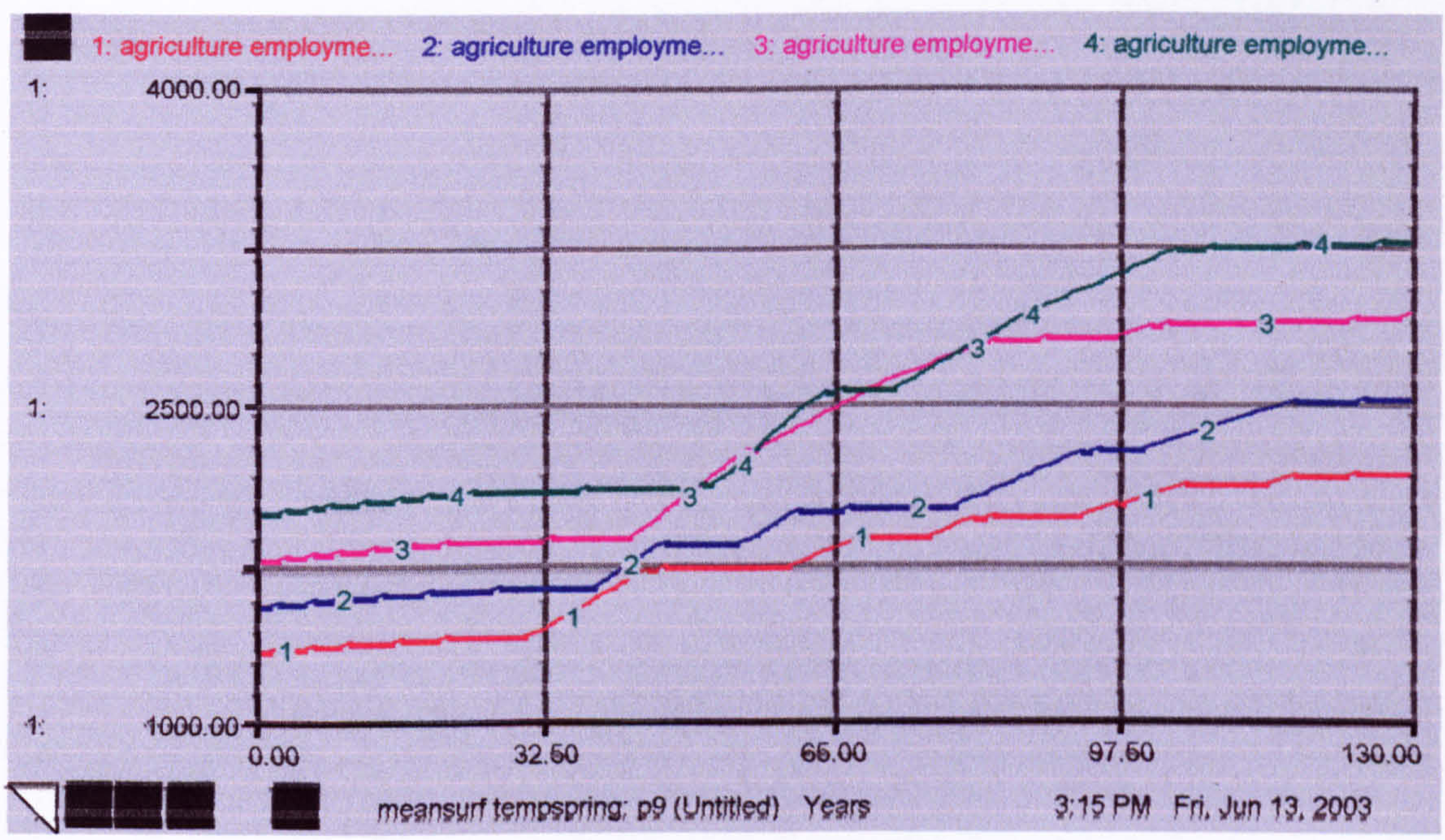


Figure 9.18 Sensitivity to changes in agricultural employment multiplier.

There is no significant impact from this set of values, the pattern remains the same and the final figures for agricultural employment are regularly stepped.

Figure 9.19 and Figure 9.20 show sensitivity tests for the forestry multipliers.

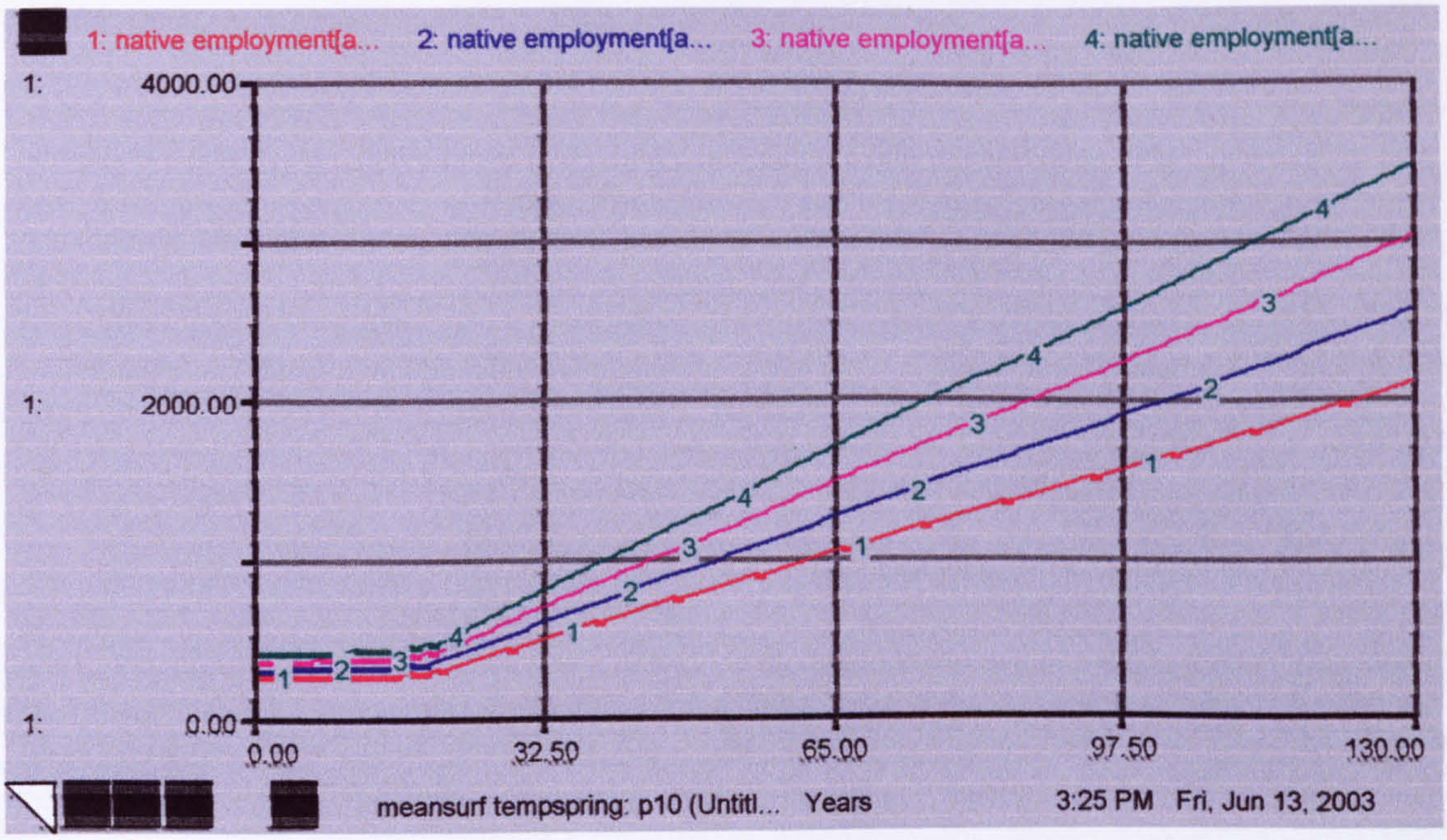


Figure 9.19 Sensitivity to changes in native employment multiplier; Argyll

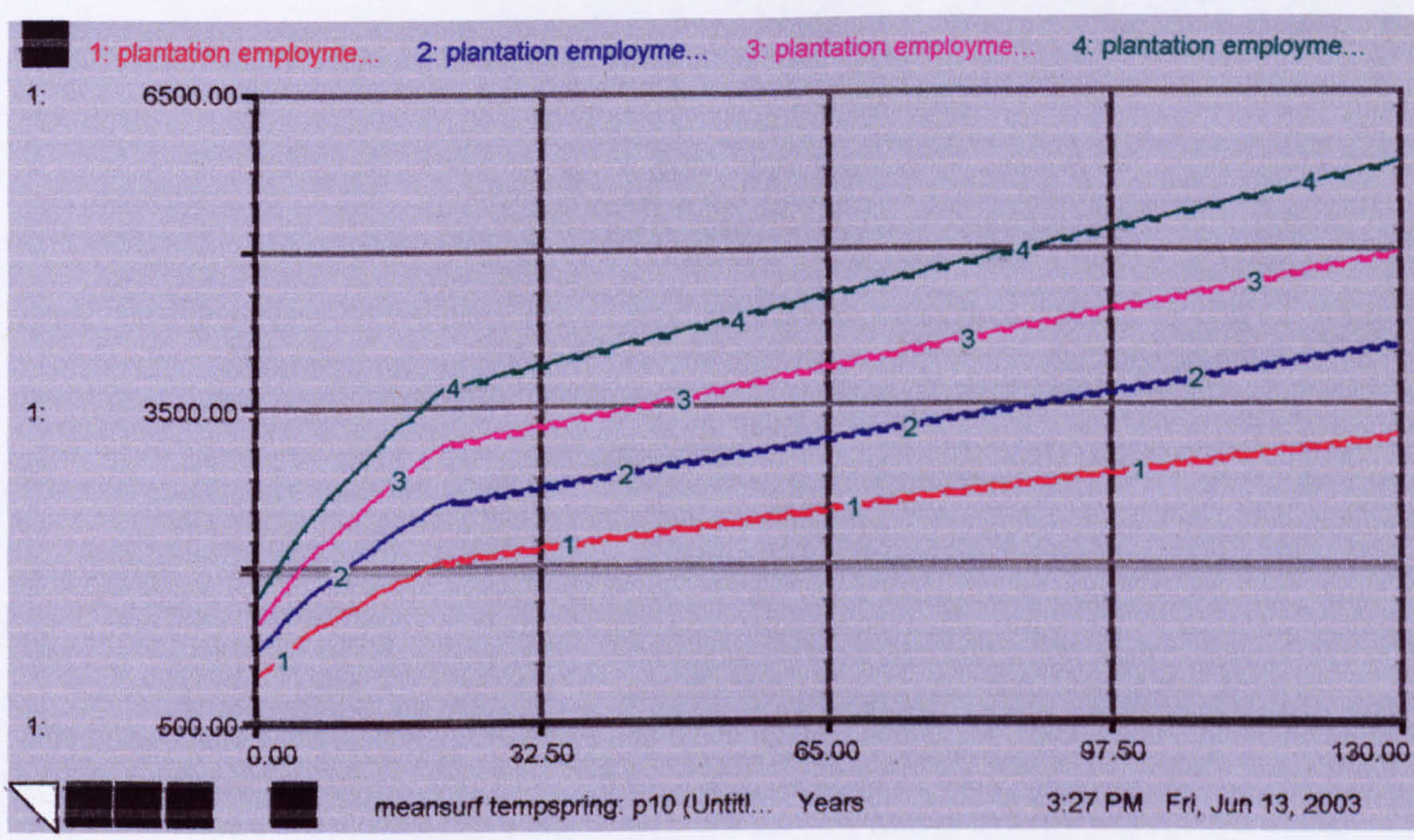


Figure 9.20 Sensitivity to changes in plantation employment multiplier; Argyll

The changes to employment within these sectors is much as would be expected from a change to employment multipliers, simply stepping up the overall employment in that sector by a fixed proportion.

9.8. Water Resources sector

Variables to be tested

Per capita per day consumption of water is one variable which requires testing in this sector. The other is the rate of evapotranspiration. Per Capita water consumption is set at 479 l/h/d, a figure for Scotland as a whole. A range of values between 400 and 550 were tested, with increments of 50 l/h/d. The resultant effects on the water resources is shown below in Figure 9.21. This shows that a considerable change in per capita water consumption in the Stirling region has no discernible effect on the overall water resources. These alternative values certainly have no effect on the pattern of available water.

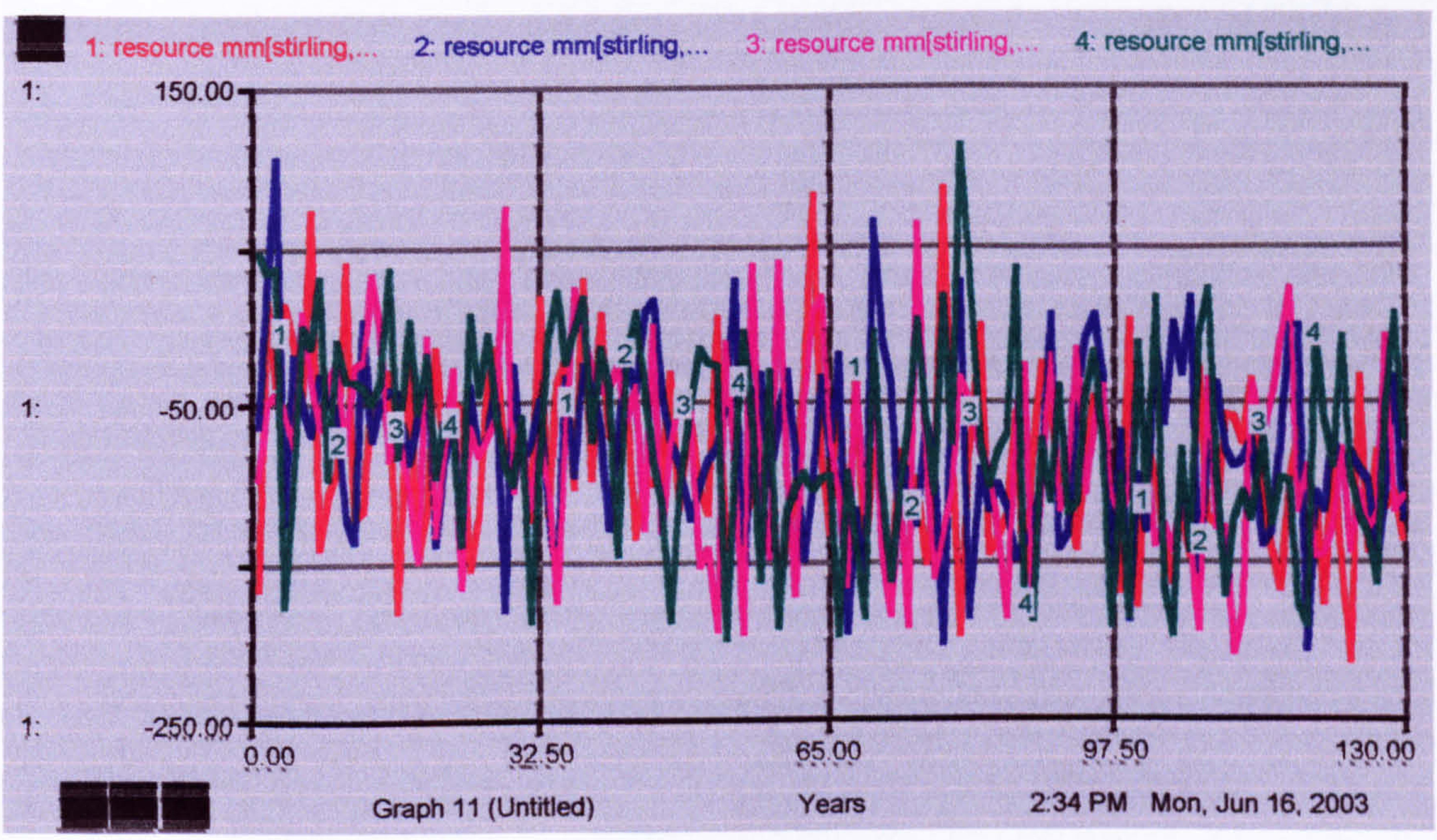


Figure 9.21 Sensitivity to changes in per capita water consumption,Stirling, summer.

The second variable to be tested is the rate of evapotranspiration. This is included in the model as a separate value for each season and for each region. The same structure exists for each region, so one region (Stirling) will be used for the sensitivity tests.

The results for spring are shown in Figure 9.22. This uses the figures for evapotranspiration of 135, 145, 155 and 165 (around 20% variation), which allow for changes around the figure used in the model, 149, to be examined. It can be seen that the highest of these values, 165 (green) does reduce the overall water resource, this being responsible for the graph being consistently lower than the graphs of the resource using the other figures.

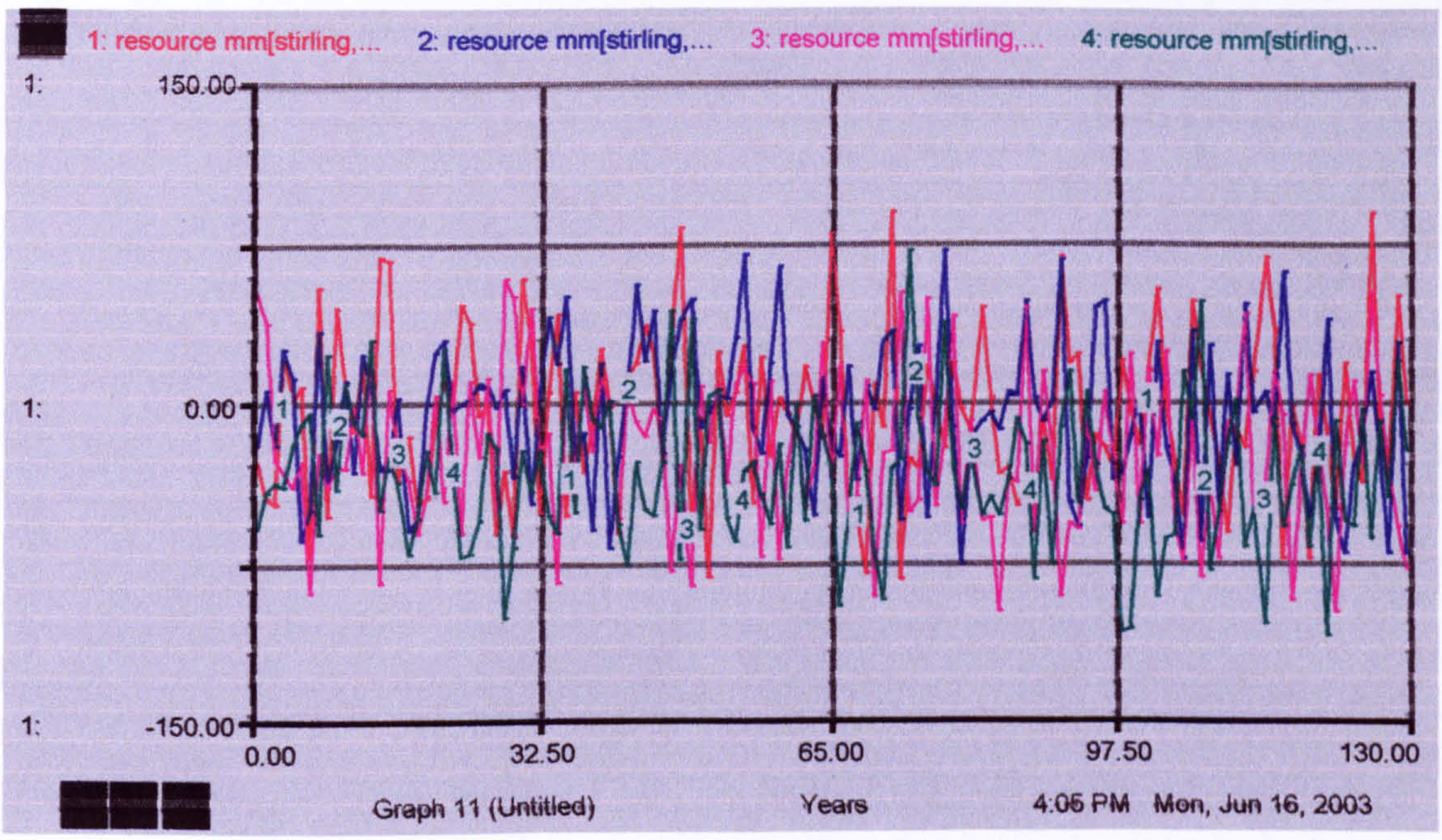


Figure 9.22 Sensitivity to changes in rates of evapotranspiration.

The effect on the other seasons was found to be similar.

Runoff, as a percentage of precipitation, was tested with values of 50%, 57%, 63% and 70% being used. This represents a significant adjustment (20%) to the volume of water being lost through runoff. The results shown in Figure 9.23 indicate that this has a greater effect on the available resource than the change in evapotranspiration, resulting in regular moisture deficits under the higher values(purple and green). This variable removes a fixed percentage of incoming precipitation and is very important in determining the amount of water available.

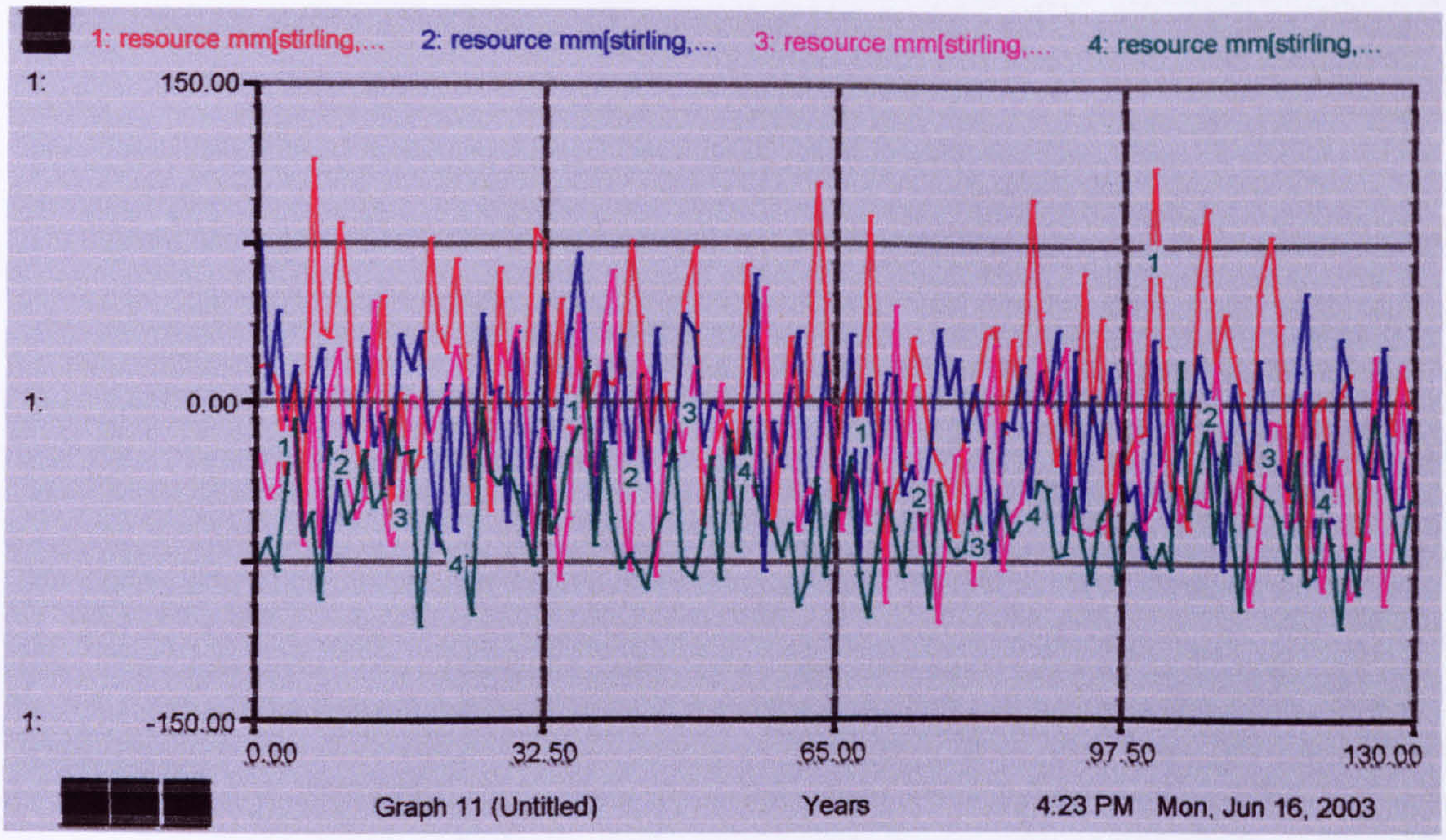


Figure 9.23 Sensitivity to changes in runoff;Stirling, spring.

9.9. Housing sector

Variables to be tested

The only variable which requires testing for sensitivity in the Housing sector is the projected household size. There has been a trend towards smaller households over the past few decades and this trend seems set to continue. The estimates from the GROS (General Registrar of Scotland 2000) give projections for each region. These have been used and extended for this century. Figure 9.24 shows the result of changing this value which has been initially set at an average household size of 1.8 persons per household in Argyll and Fife and 1.86 persons per household in Stirling as the long term projection. Varying this between 1.7 and 1.9 for the region of Fife yields the results illustrated in Figure 9.24.

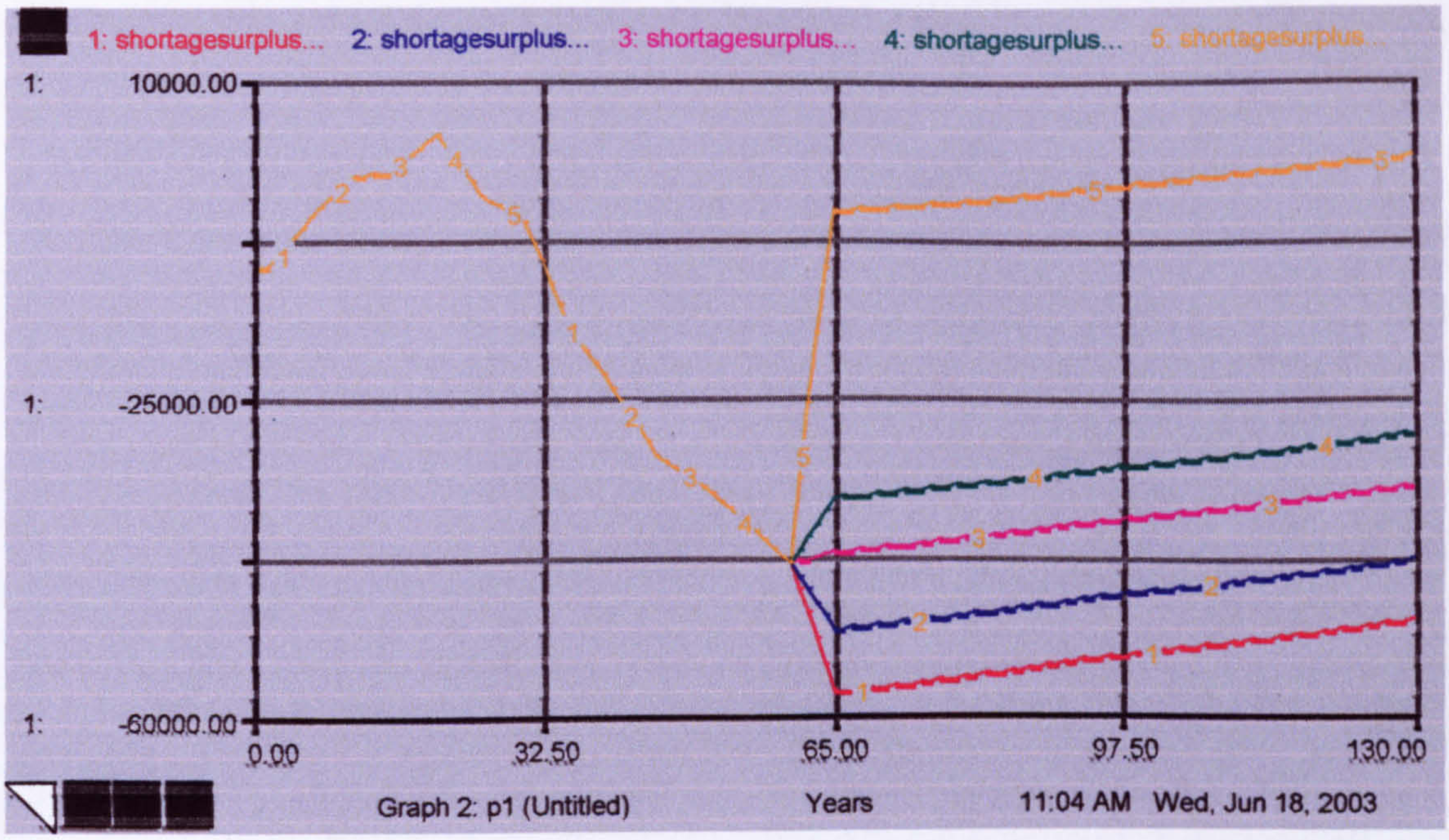


Figure 9.24 Sensitivity to changes in household size, Fife.

The long-term figure is introduced at TIME = 60 in the model representing a change after 60 years of simulated time. The effect can be seen on the projected shortage or surplus of housing. Essentially the effect that larger household size has on the availability of housing is to reduce the scale of the housing shortage which the model is projecting. The graph also shows the result of increasing the long term household size to 2.3, a level equivalent to that of the present day (line 5). The effect on housing demand is quite marked.

9.10. Land Use sector

Variables to be tested

Within the land use sector, the total area under consideration for each of the regions remains constant throughout runs of the model. The purpose of this sector is to track changes in land use with flows between the stocks controlling the rate of change. These flows have been set at values which are either determined by data sets covering the past few decades or have been hypothesised as resulting from increased temperature. Varying these flows has the effect of altering the rate at which the changes in land use take place. The complexity of the logical statements defining the rate of flow which depends on temperature means that altering these rates would be a major task. To assess the impact of this temperature induced flow, it is therefore possible to run the model with this contribution turned on or off. Examining this for the different scenarios gives some indication of the sensitivity of the model to this particular parameter. The effect will be to change the values associated with the different land use categories. The main impact this will have is to alter the employment figures for each region. As a result, the sensitivity of the model will be assessed by examining the agricultural employment figures in the region most affected by changes to agriculture and forestry, namely Argyll.

Figure 9.25 shows the impact on agricultural employment in Argyll of switching on and off the flow associated with temperature change under the conditions of the four CO_2 scenarios. In addition, it shows the employment associated with one run of the model without climate change or land use change, and one run of the model with just constant climate. The difference between the two lower lines on the graph is due to the changes in land use which are an extrapolation of the trends apparent from the data. The control of the flow from rough grazing to crops and grass also controls the agricultural employment figures. As more land is converted to crops and grass under the climate change scenarios, there is an increase in employment. The pattern of change in the agricultural employment is consistent with the assumption that increased temperatures will allow land to be used more intensively, requiring a larger workforce. Any apparent discrepancies between the rates of change of land use, and hence employment between, for example, the high and medium high scenarios, is simply due to in-built variability of temperatures being reflected in the running mean of temperature. This in turn affects the rates at which the land use change occurs.

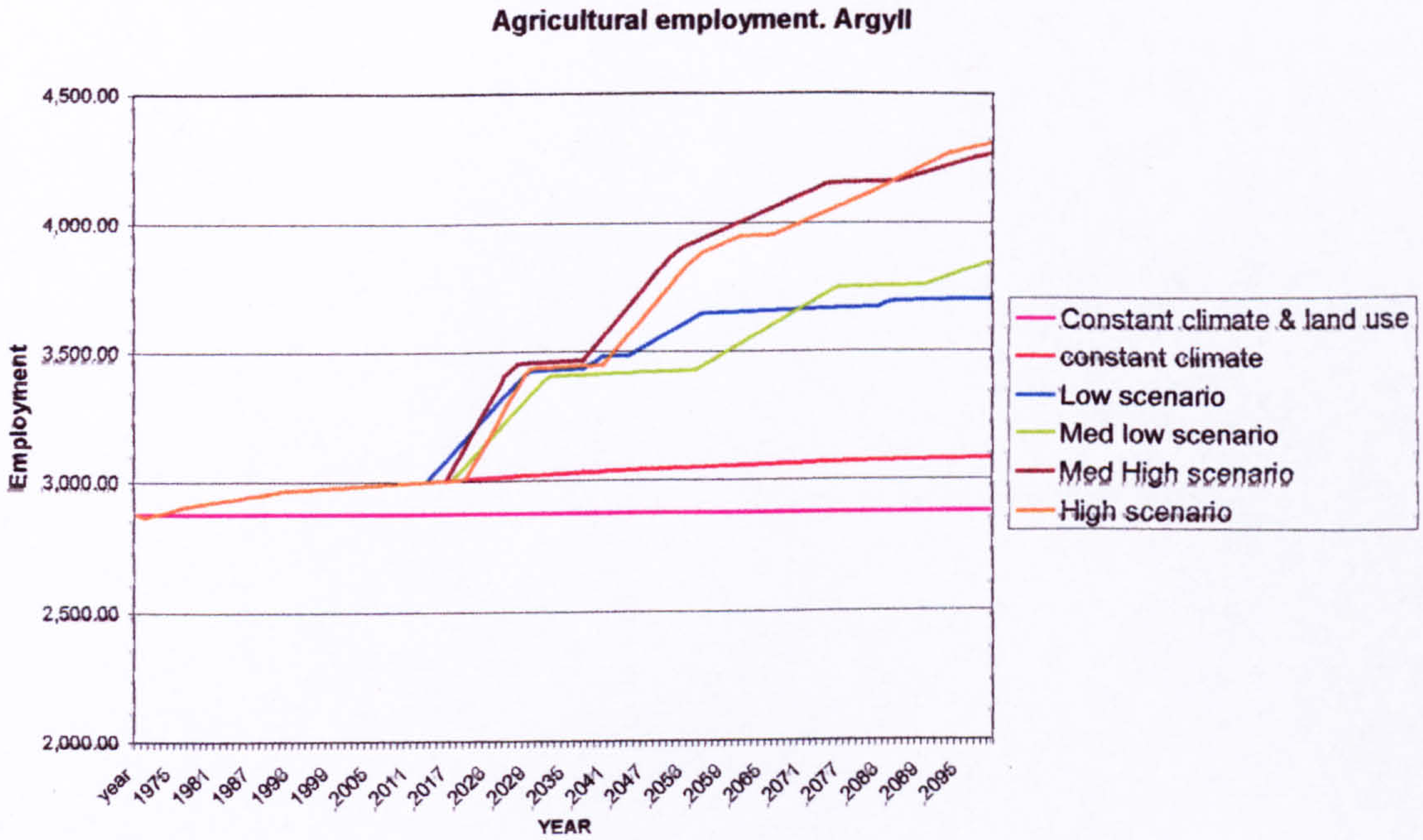


Figure 9.25 Sensitivity to changes in temperature relating to agricultural employment.

9.11. Summary

The different variables tested in the above section all have an effect on the model when a range of values is used. The scale of the effects vary but in no case does the model respond by generating a completely different pattern of output. All the results are consistent with the theory used in the model construction, and those variables for which the values are hypothesised show no dramatic impact on the structure of the output.

Within reasonable limits, the response of the model to parameter changes shows consistency and a degree of predictability in the pattern of output. The actual percentage changes brought about by changes to the parameters are shown below in Table 9.2.

Parameter	Value	% change	Output measured	% change
Sensitivity	0.0103	9.3	Stirling temp	22
te	0.34	19	Stirling temp	17.5
Fb	0.9285	10	Stirling temp	13.3
Daylength	7	12	Stirling temp	3.2
Albedo	0.313	10	Stirling temp	13
Ocean warmth	1.3×10^9	8	argyll temp	6
Fa	0.815	13	Stirling temp	26
Birthrate	10.1	5	Population Fife	7
Assimilation rate	6.2	10.2	Emissions, Argyll	11.4
Per capita CO2	3.3	9.4	Emissions, Argyll	11
Per capita water	479	14	Water resource Fife	2
Evapotranspiration	149	22	Water resource Stir	32
Runoff	79.5	10.5	Water resource Stir	13
Mean household size	1.8	12	Population Fife	27
Agricultural multiplier	2.43	50	Labour demand Argyll	7.4

Table 9.2 Percentage changes to parameters and output.

This sensitivity analysis shows no surprising changes to the model behaviour when the values of variables are altered. The two parameters from the climate sector which show greatest percentage change to output in relation to the change in the parameter are "sensitivity" and "fa". Both of these are involved in the absorption of long wave radiation from the Earth's surface and directly contribute to the mean surface temperature. The results here are for the Medium high scenario, the results from other scenarios will differ as the rates of CO_2 increase are different. This indicates that the calibration of the model which set the value of "sensitivity" was important as small changes to this can have significant effects on temperature. In the Housing sector the value which represents the mean household size has a significant effect on the calculation of housing shortage or surplus. Small changes to this parameter have a significant impact on the demand for housing.

The pattern as indicated by the graphs shows that the output is stable, no changes occur in the pattern of the output with the exception of the birth rate under relatively large changes. Here the population curve changes from exponential growth to exponential decay within a small range of changes to the birthrate. No other parameters have such a significant effect on the pattern of output from the model.

It is therefore possible to use the combined model to explore the impacts of climate change on some of the social and economic aspects of the three regions of Scotland chosen for the study.

Chapter 10 Results from combined model

10.1. Introduction

The numerous feedback loops identified previously give an idea of the complex nature of the model. The number of linkages between sectors means that changes occurring within one sector have an effect through a number of other sectors. In particular the effect of changing climatic variables influences land use, tourist numbers and water resources. Such linkages can be illustrated by reference to the upper layer map generated in Stella. Figure 10.1 shows where such connections are made.

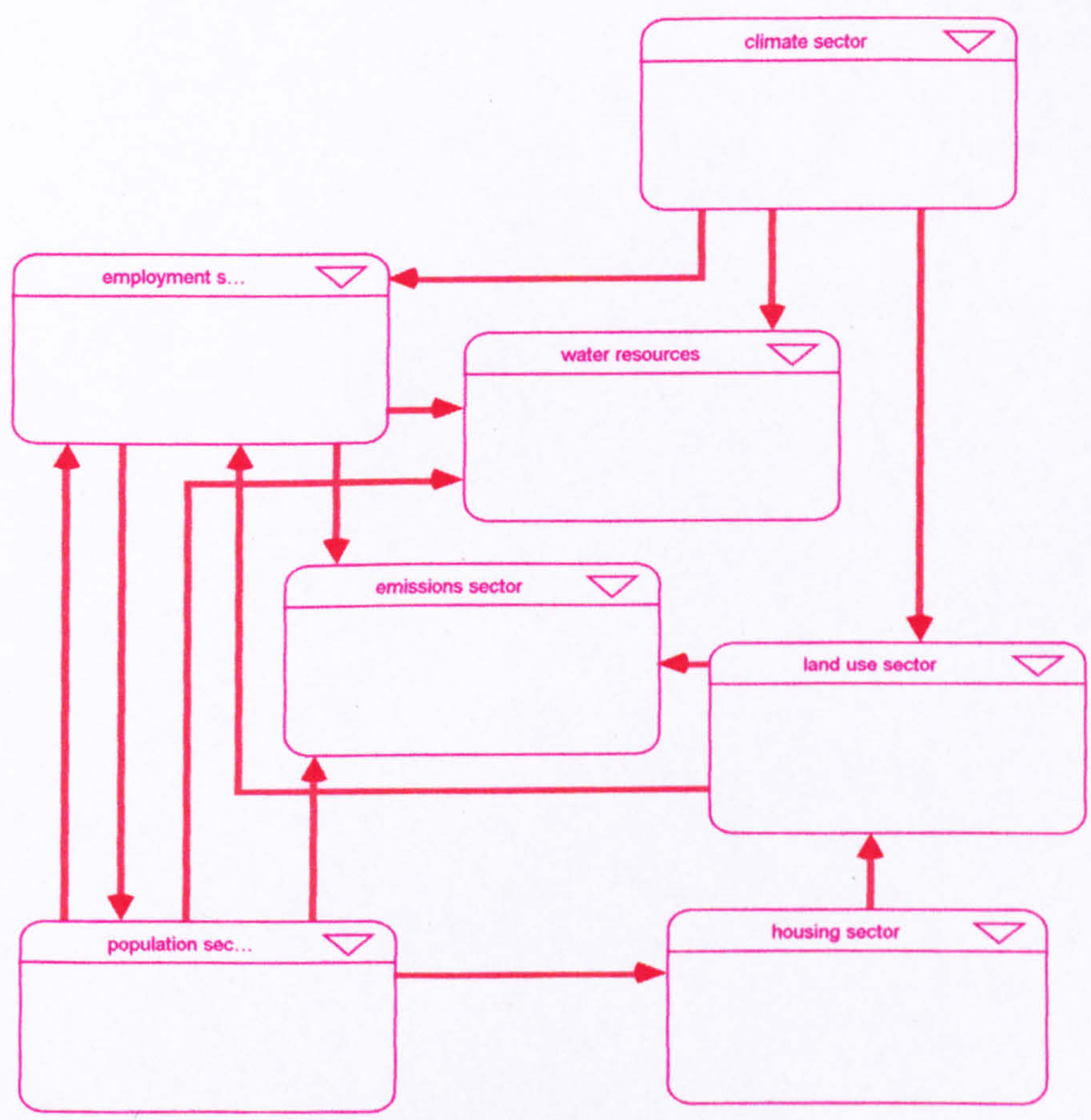


Figure 10.1 The structure of the combined model, upper layer of Stella.

Some of the limitations of the system dynamics approach were discussed in Chapter 3. Because of the time scale of the simulation it is not possible to include a number of factors which are more than likely to influence the outcome of, for example, the land use sector. Factors which would be included in a short term model or a disaggregated model of the economy, such as an input/output model, cannot be included in this model. The model is therefore run as an "all thing being equal" investigation of the potential impacts of climate change on the three regions. It is therefore not possible to use the output as a predictive tool to establish exact numbers of, for example, tourist related jobs towards the end of the 21st century. The output should rather be viewed as predictive of longer term trends, establishing the potential impacts of climate change without necessarily quantifying accurately such changes. In the case of water resources it is assumed for the purposes of model construction that the infrastructure which delivers water supplies to these regions remains the same. The model output can then be seen as the consequences of not addressing the potential problem. It is unlikely that no action will be taken in the coming decades to address potential water shortages, so the extent of drought conditions discussed in section 3 are unlikely to happen. However an understanding of the consequences of inaction is a valuable tool in planning of infrastructure.

In order to assess the impact of climate on the various sectors included in the model it is first necessary to run the model with the climate sector "turned off". Stella allows this to be done using the Sector Specs option. By switching off the climate sector the model is then run with the initial values of all state variables in this sector remaining constant. In effect this means that mean surface temperature is set at the mean value for the period 1970-2000. Subsequent runs can then be made with the different climate scenarios and the effects on a range of variables compared.

Similarly, other sectors can be turned off, for example the employment sector, allowing the effect of the assumptions made in the construction of this sector to be assessed and its impact on the overall functioning of the model to be measured.

This, in effect, allows a range of experiments to be carried out to gauge the scale of the socio-economic effects of different aspects of the model. This allows an "all things being equal" scenario to be investigated.

In addition to the effects that different sectors have on the projections generated by the model, there is also the effect that the different climate change scenarios have. Four separate versions of the model were run, and comparisons between them made to assess the impacts of the different rates of change of atmospheric CO_2. These were then compared to the run of the model with constant climate.

This results in this Chapter will therefore be split into six sections, each dealing with a different sector of the model. In each case the relevant output will compare the results of a run under conditions of constant climate with runs under the conditions of Low, Medium Low, Medium High, and High climate change scenarios. The impacts of each of these scenarios will be presented for each of the three regions of the study, and, where appropriate, seasonal output will be included. To facilitate the comparison of the different scenarios, tabular data was exported to Excel where graphs were created.

10.2. Employment Sector

The main drivers for change in the employment sector are land use changes altering the pattern of agricultural and forestry employment, and changes to the numbers of tourists visiting the regions which generate tourist related employment. Due to the variability built into the climate sector, ten runs of the model were made and the mean values calculated for each year of the simulation. This smoothes out the curves in the graphs and allows for a clearer comparison of the different scenarios to be undertaken. In each case the model was initially run with the climate sector "turned off", thus generating a constant temperature regime. Additional runs were then made for the Low, Medium

Low, Medium High and High scenarios and the following figures illustrate the impact of these climate change scenarios for the three regions.

10.2.1. Tourist related employment.

Figure 10.2, Figure 10.3and Figure 10.4 show respectively for Argyll, Stirling and Fife the effect that increased temperatures have on the numbers of jobs relating to the tourist industry. In each case there is an increase in employment, with the Low and Medium Low scenarios generating similar increases and the Medium High and High scenarios showing a greater effect. The results for Argyll and Stirling are generated by the same function, this being the area covered one Area Tourist Board. Given the built in variability of the climate sector, different runs of the model will generate different increases in tourist numbers. The graphs in Chapter 7 illustrate the range of results generated by the Stella model. The following graphs should therefore be interpreted as showing a mean value, about which there will be bands of variability. Precise numerical forecasts are therefore not possible with this method. However a comparison between different scenarios indicated the impact that climate change could have within the tourism sector of the economy.

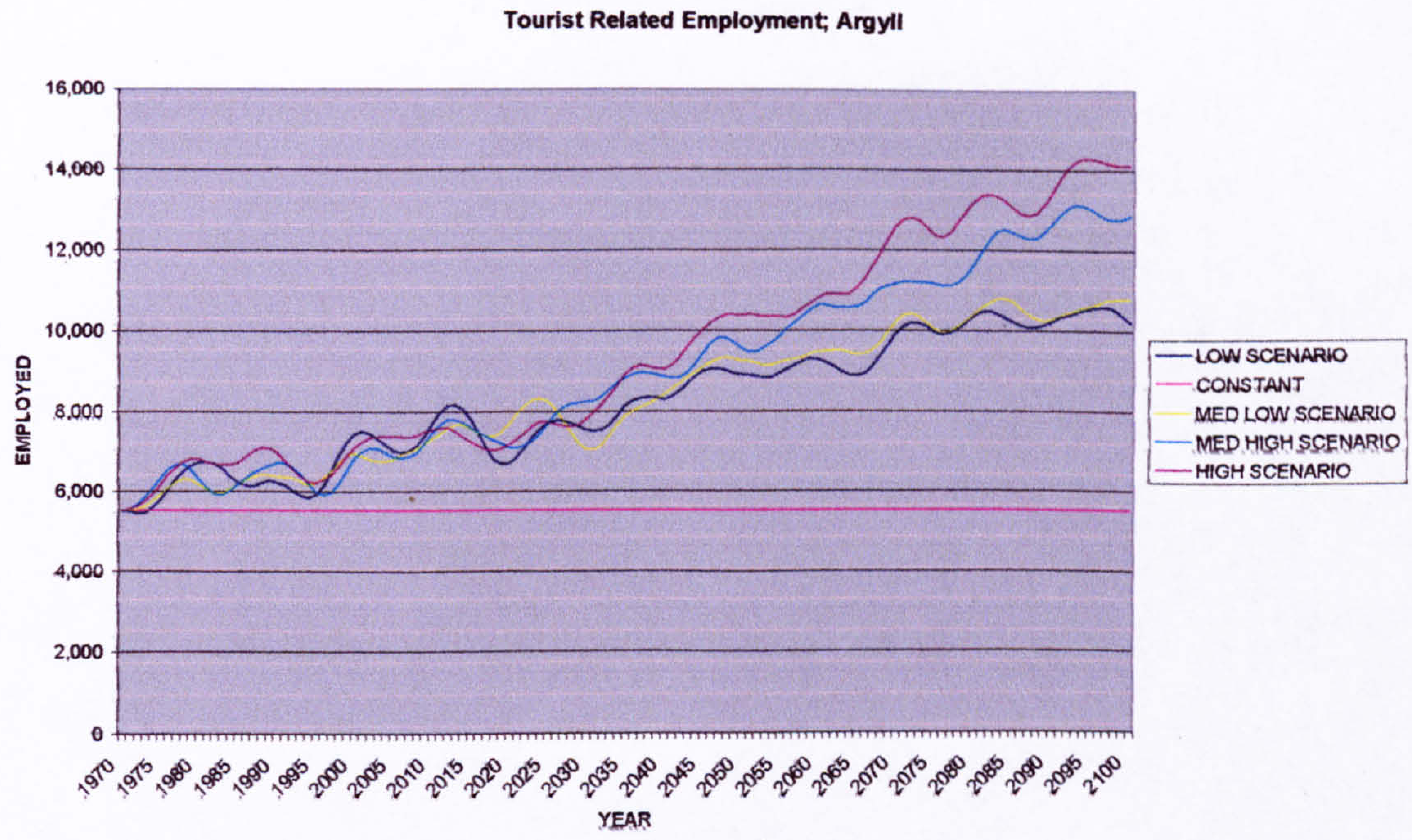


Figure 10.2 Tourist related employment, Argyll

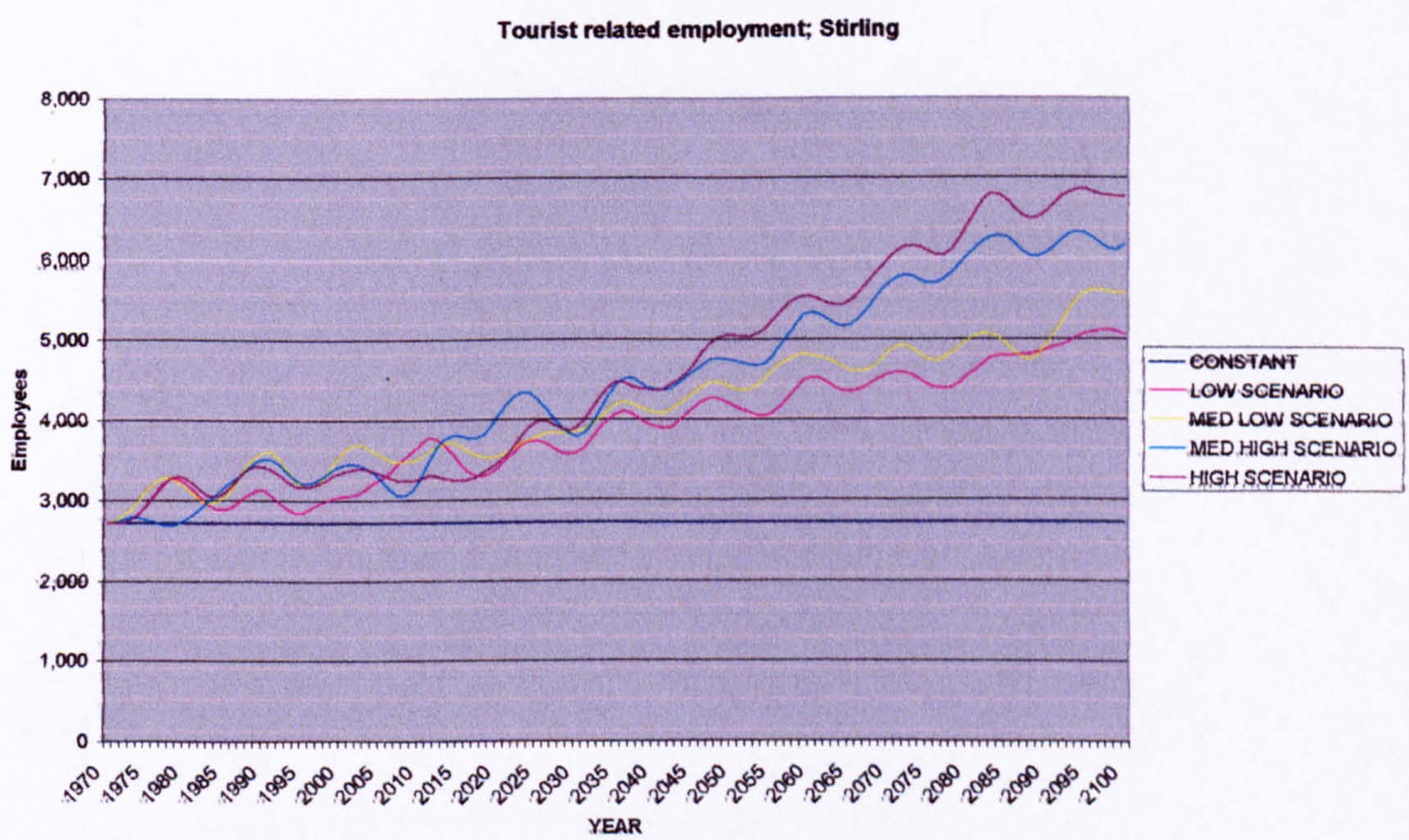


Figure 10.3 Tourist related employment, Stirling

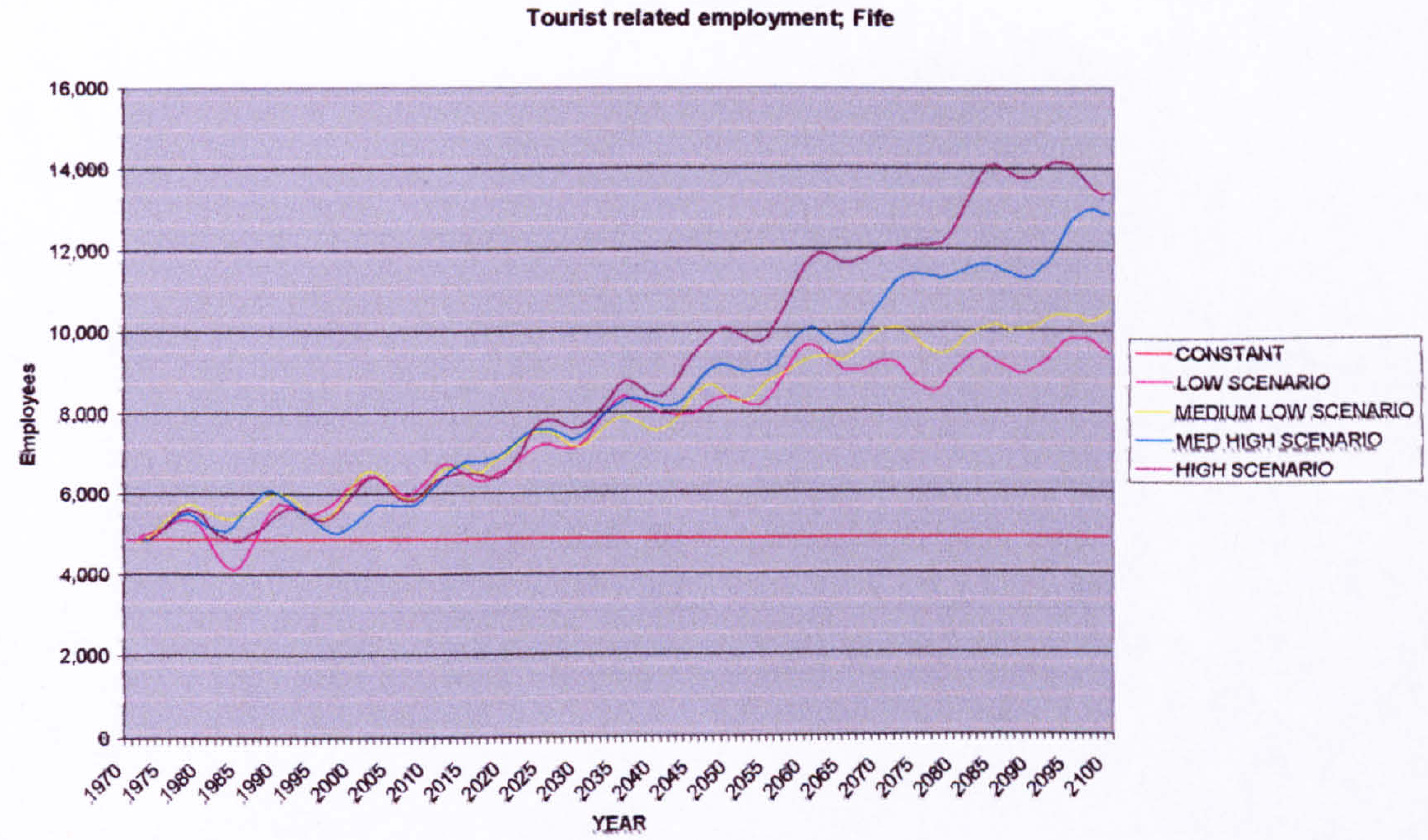


Figure 10.4 Tourist related employment, Fife.

There is a similar pattern to all three graphs, though the rate of change in Fife is greater than in the other two regions. This results from differences in the tourist markets of the regions, and the different activities undertaken by visitors. It takes fewer visitors to generate one tourist related job in Fife than it does in either Argyll or Stirling.

In all cases higher mean surface temperature creates the conditions for a growth in tourism, with the benefits of increased employment being felt in all three regions.

10.2.2. Agricultural employment

Changes in agricultural employment are driven by increases in the area of land deemed suitable for agriculture, in particular the changes from rough grazing to arable and improved grassland. The rate at which these changes take place is controlled by the rate of climate change. As a result, the scenarios with a more rapid increase in temperature accelerate the land use change. This in turn generates changes in agricultural employment, the requirement for labour being far greater for arable and improved grassland than it is for rough grazing.

The model is limited in the factors which can be included as drivers for change in this sector. The model is identifying potential changes rather than predicting actual changes. Factors such as the Common Agricultural Policy are certain to be transformed and this is considered to be of central importance to the agricultural sector (Kerr et al. 1999). It is however a valuable exercise to attempt to understand the potential that will exist under conditions of climate change, subsequent changes to the CAP could be designed with a view to realising this potential.

Figure 10.5, Figure 10.6 and Figure 10.7 illustrate the changes to agricultural employment in the three regions under the different climate change scenarios. It can be seen that the changes to employment are far more pronounced in Argyll and Stirling than in Fife. This is because most of the land in Fife is already utilised in a relatively intensive manner, with very little land becoming available as temperatures increase. Again precise numerical forecasts are not really possible. The variability of the climate simulations means that a broad band of possible outcomes exists above and below the lines generated by the model. It is still apparent however that potential benefits exist and that there is a contrast between the different climate change scenarios and between the different regions of the study.

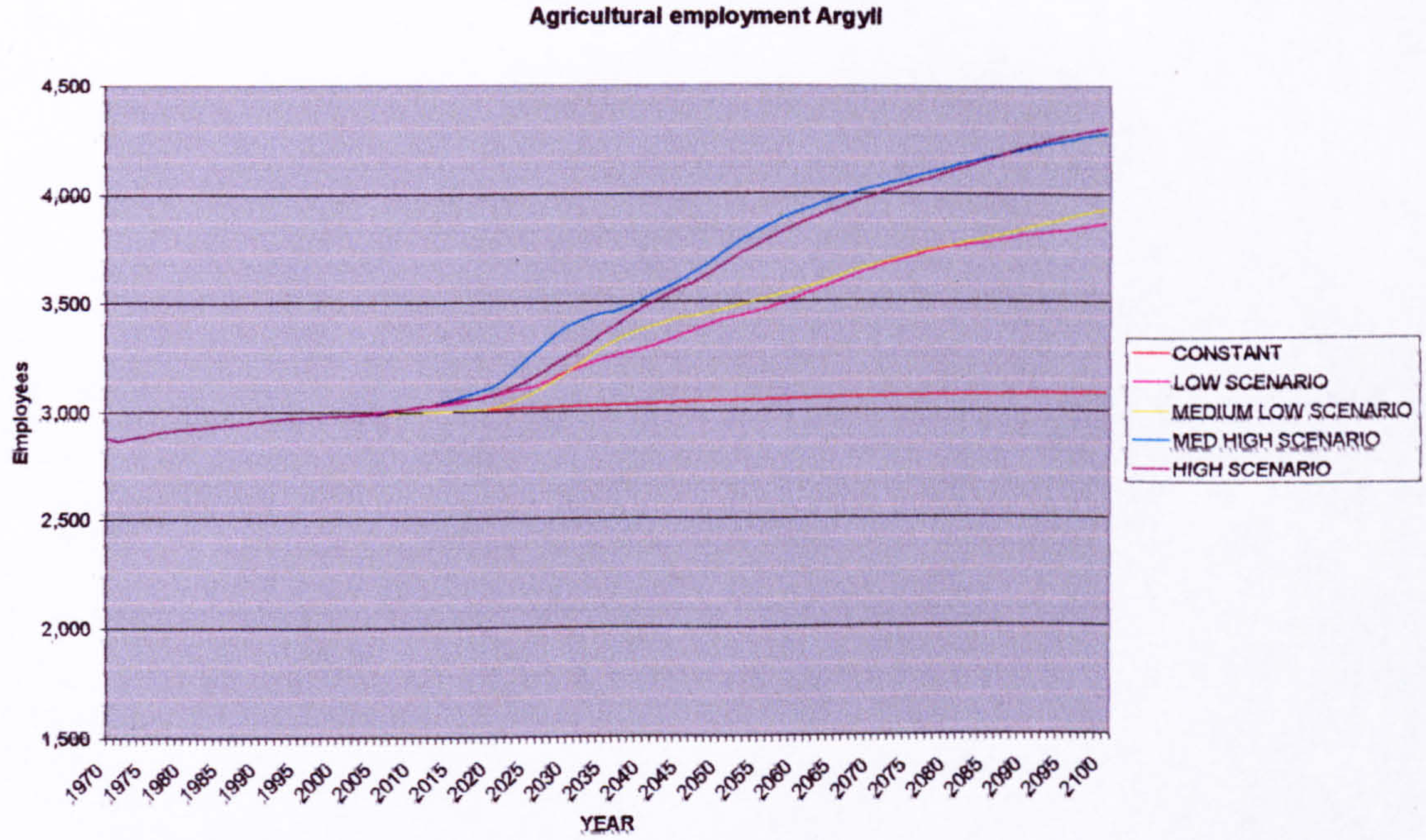


Figure 10.5 Agricultural employment, Argyll.

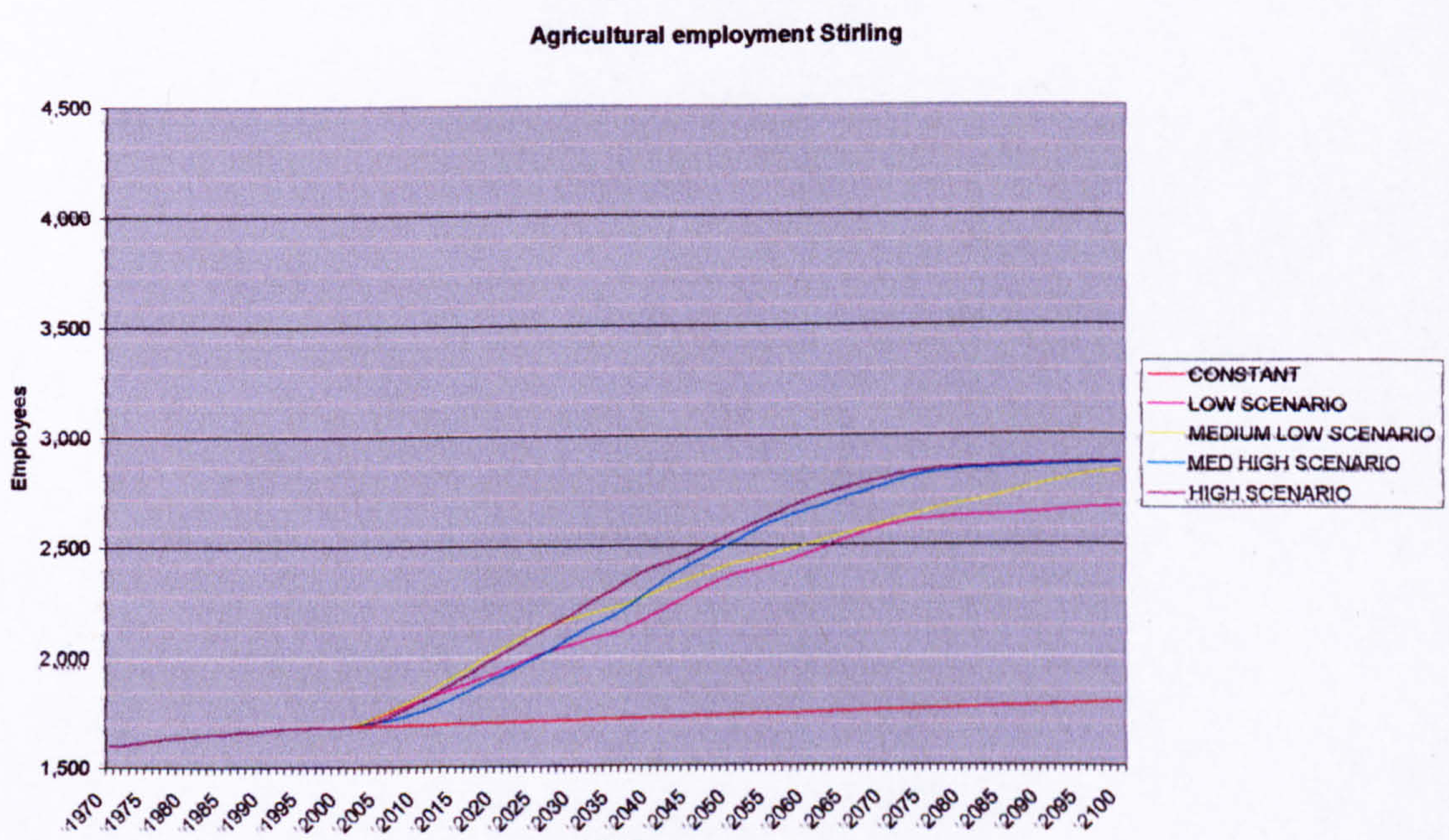


Figure 10.6 Agricultural employment, Stirling.

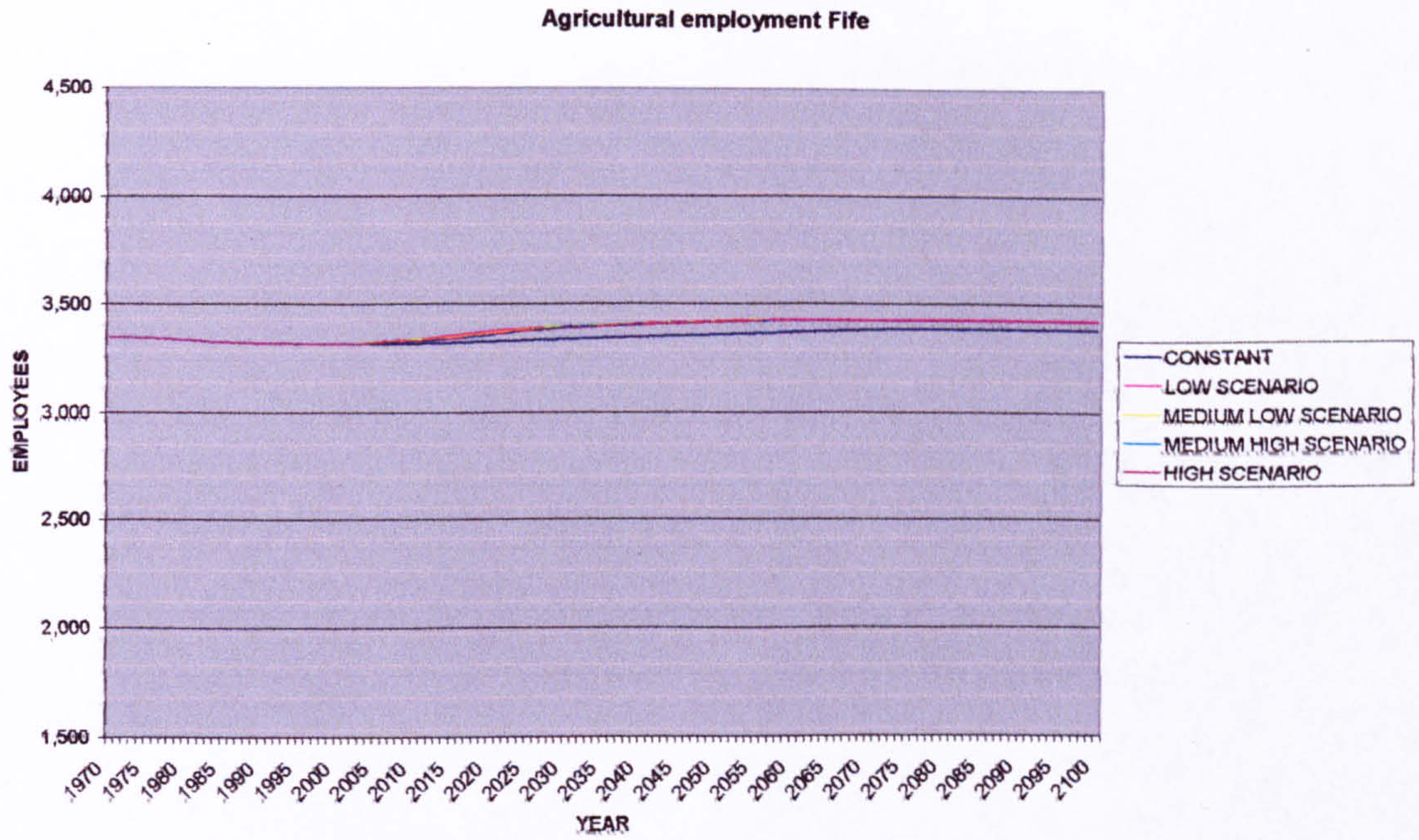


Figure 10.7 Agricultural employment, Fife.

Although the numbers of employees illustrated represent a small proportion of the total workforce of the regions it does represent a potential for an increase in rural jobs resulting from climate change.

10.2.3. Forestry related employment

The changes to forest cover generated in the simulation are independent of climate factors, merely continuing the trends established during the latter part of the 20th century. As a result, there is no significant difference between the different climate scenarios. The employment consequences of continued reforestation of Scotland are, however, significant, especially in the West where large tracts of forestry already exist. All three regions are represented on a single graph, Figure 10.8, and although all regions show an increase in forestry related employment, the figures for Stirling and Fife are overshadowed by the changes in Argyll.

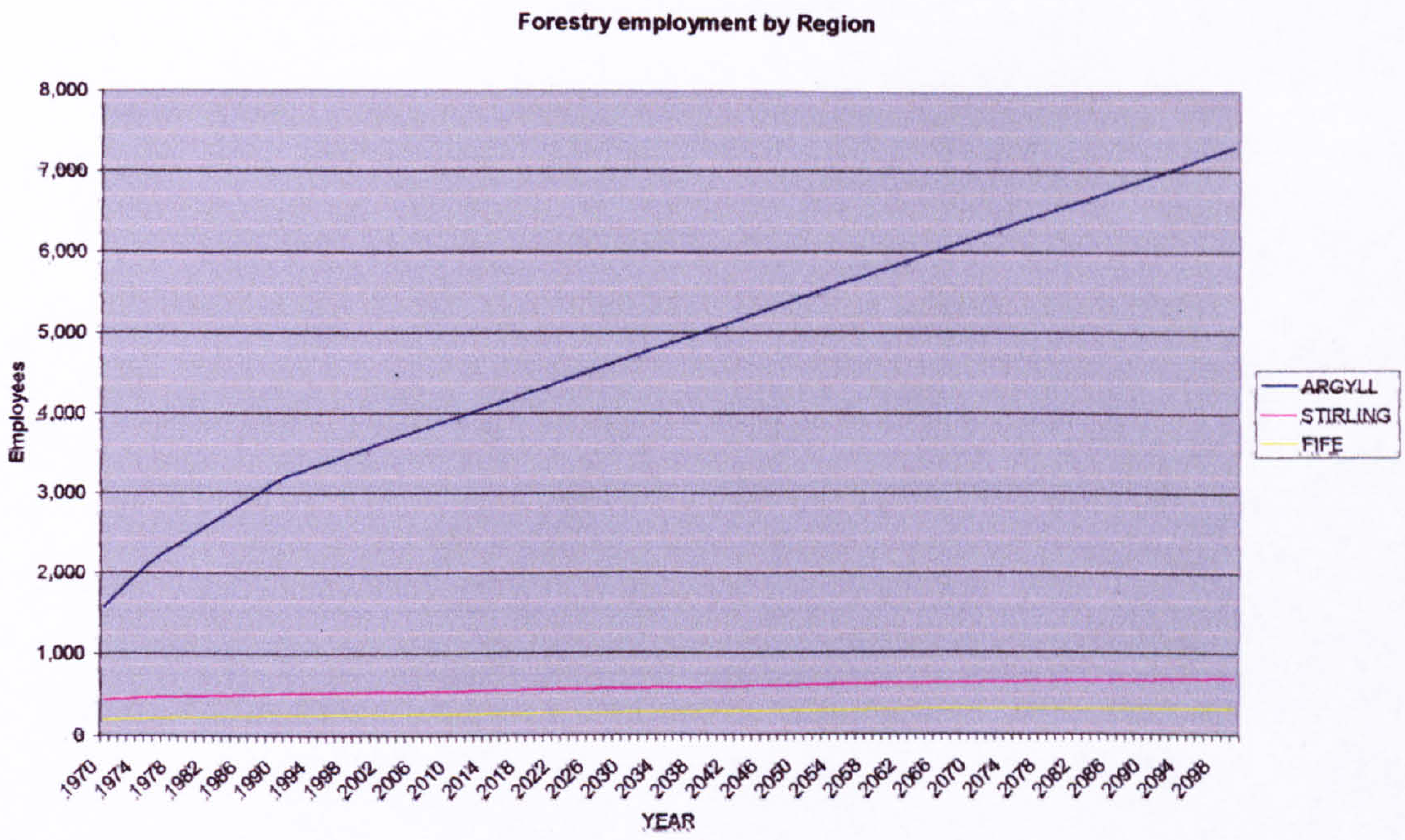


Figure 10.8 Changes to forestry employment; Argyll, Stirling and Fife.

10.2.4. Unemployment

The above sectors, tourism, agriculture and forestry, at present account for roughly 25% of the workforce of Argyll, but a lower percentage of the workforce in Stirling and Fife at around 13% and 11% respectively. Changes to the numbers employed in these sectors are likely to have a more significant impact on overall employment statistics in Argyll than would be the case in Stirling or Fife. Figure 10.9, Figure 10.10 and Figure 10.11 illustrate the effects on the overall numbers of unemployed in the three regions. In each case, one run of the model was carried out with constant temperature. This was followed by five runs for each scenario, from which the mean was calculated and used to generate the curves.

Each graph shows a lower number of unemployed under conditions of climate change, and the greater the temperature increase, the greater is the drop in unemployment. This is particularly significant in Argyll where a labour shortage develops under all scenarios by the middle of the century. The model compensates for this by allowing in-migration to mitigate the labour shortage. Hence the graphs flatten out with constant demand for labour being evident but never increasing in size.

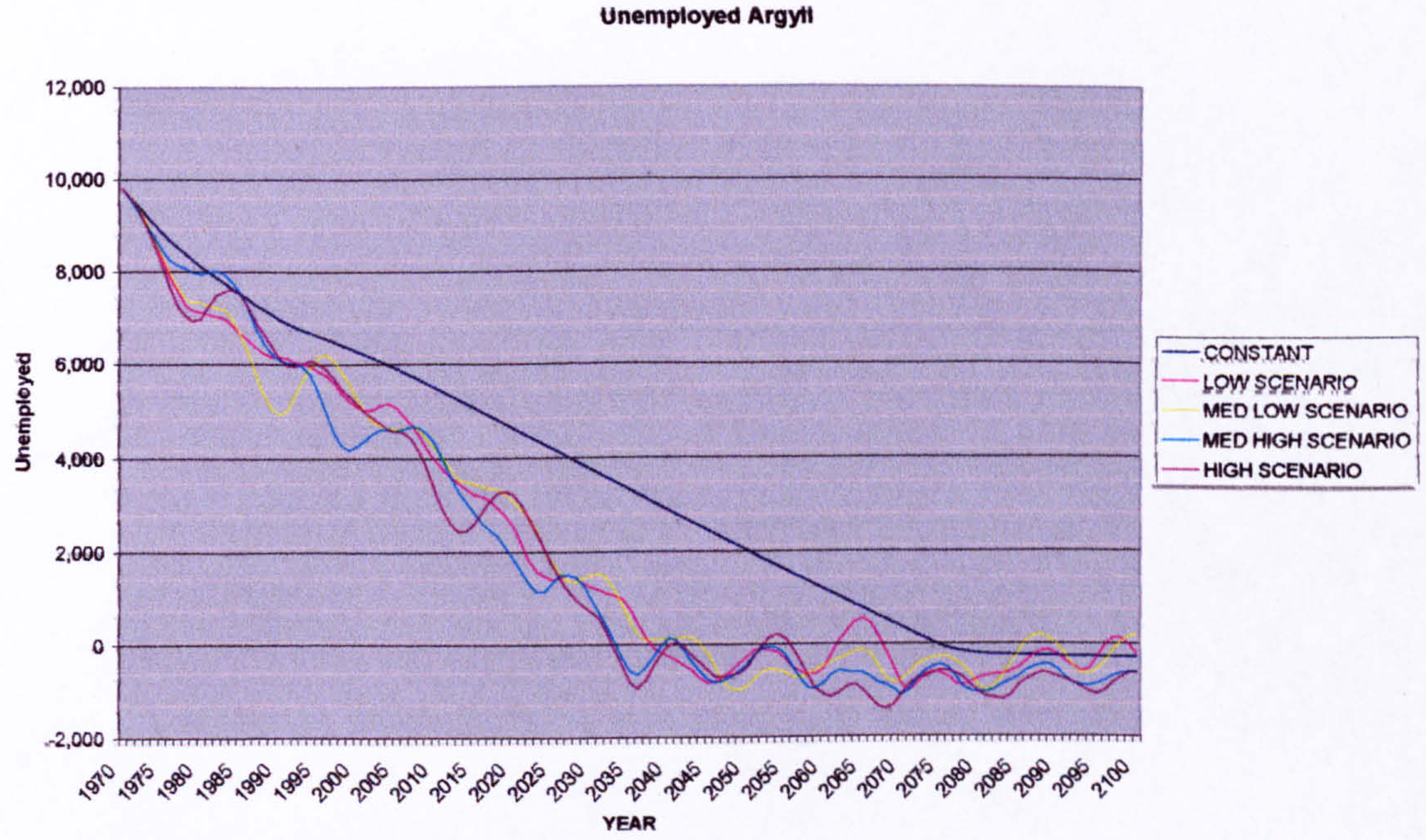


Figure 10.9 Projected unemployment, Argyll

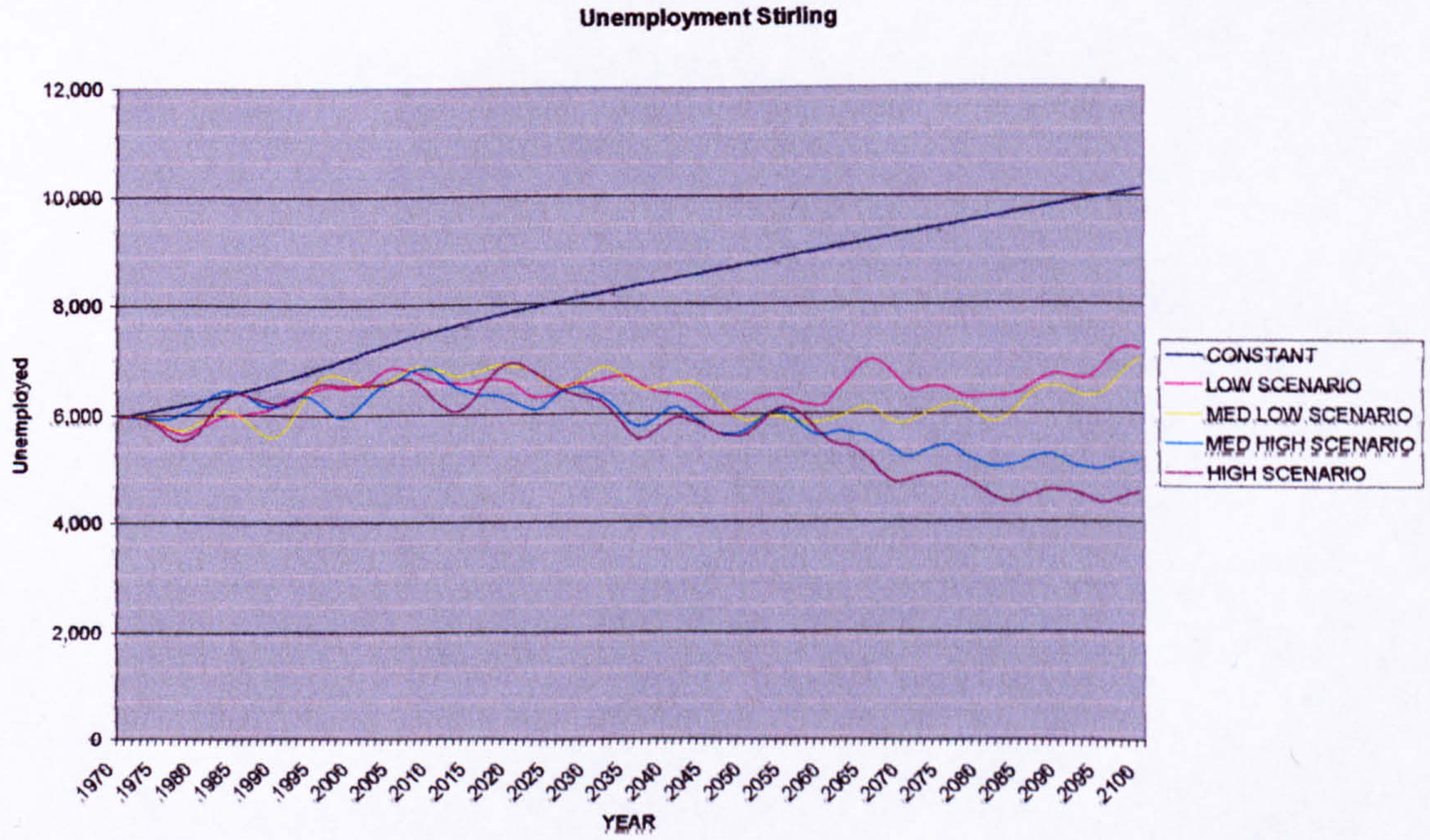


Figure 10.10 Projected unemployment, Stirling.

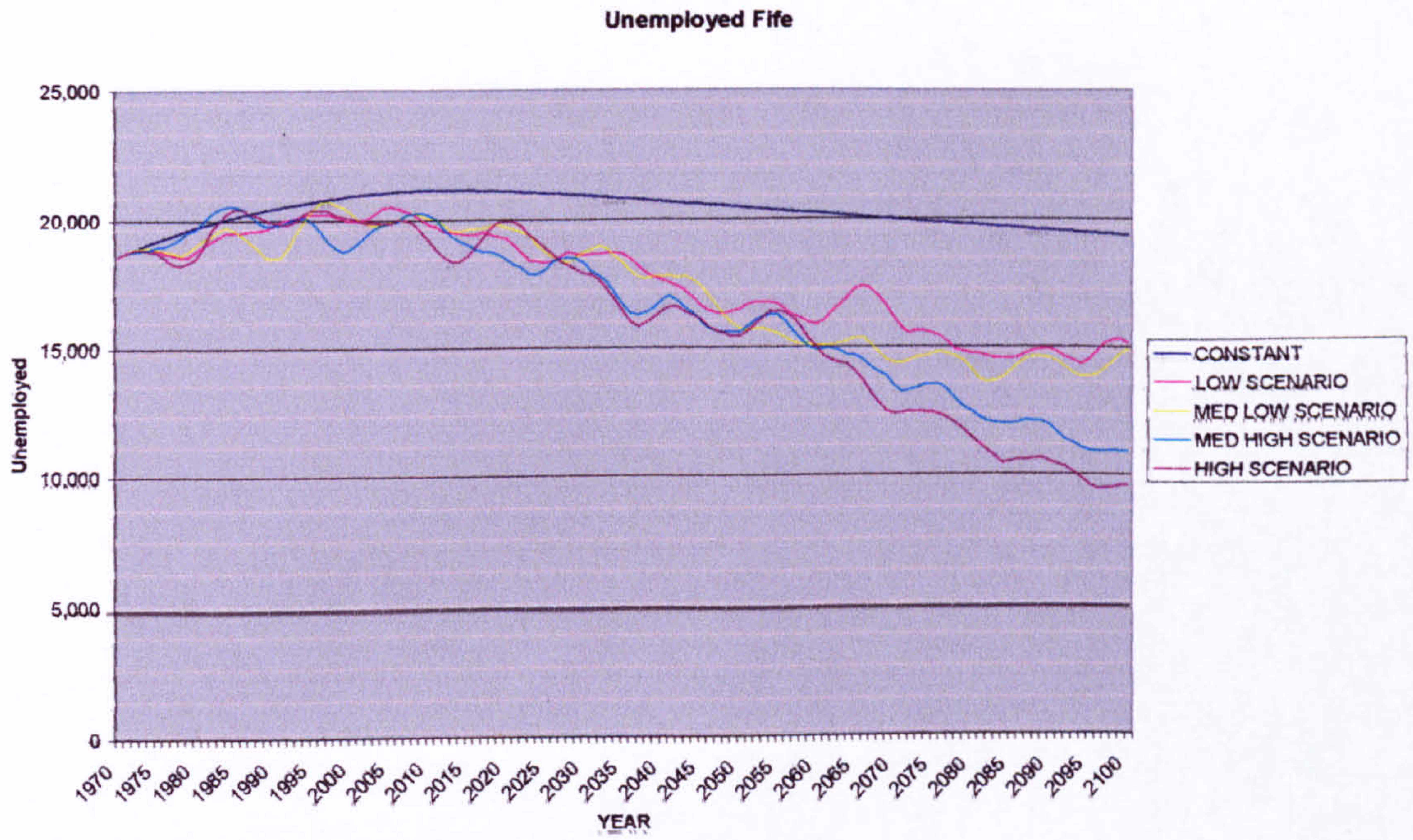


Figure 10.11 Projected unemployment, Fife.

The curve representing the simulated unemployment under conditions of constant climate varies according to the region. This is caused by the overall projections for population for each region being dependent on different birth and death rates, as well as on different migration rates. The effect of climate change on the respective populations of the regions can be seen in the description of results from the population sector.

10.3. Water resource sector

The water resource sector performs calculations to determine the net resource on a seasonal basis for each of the regions. Total precipitation across the region is calculated and runoff, evapo-transpiration and use by the population subtracted. The results can then be presented in terms of a number of litres or as a surplus or deficit in mm of precipitation. Under all conditions of climate change, the rate of evapo-transpiration increases. Human use depends on the population projections, which are downward for

Argyll and Fife but upwards for Stirling. In addition there is the use by tourists, which makes an important additional demand on resources. Under the conditions of climate change, all scenarios indicate an increase in tourist numbers. The loss through runoff is considered to remain constant as a percentage of precipitation for each region and each season.

10.3.1. The effects on water resources during summer

In order to investigate the effect of climate change on summer resources five runs of the model were made for each of the four scenarios. The section of output representing 1970-2000 was then extracted and examined. This shows considerable contrast between the regions, with deficits common in the East but rare in the West. To achieve an indication of the potential for drought conditions, it is assumed that during the past three decades the East of Scotland has experienced 3-4 serious summer droughts. The output for Fife from the five runs of the model were then analysed to find the extreme deficit in water resources which occurred in the simulation, on average 3-4 times during this period. It was found that a deficit in resources of 200mm or greater occurred at this desired frequency.

This figure of a deficit of 200mm or more during the summer months was then used as an indicator of potential drought conditions. The model output for the periods from 2000-2030, 2030-2060 and 2060-2090 were then examined to find how the different climate change scenarios affected the frequency of this simulated drought. The results of this experiment are shown below in Table 10.1, Table 10.2 and Table 10.3. They show that Argyll is unlikely to experience drought conditions except under the conditions of the High scenario, when, by the middle to late part of this century, the frequency of droughts is equivalent to that experienced by the drier East of the country at present. A very similar picture is presented for the Stirling region, with little or no indication of drought conditions until the end of this century under the conditions of the High scenario. Fife, on the other hand, shows a steady increase in the frequency of droughts, under all scenarios. The probability of a summer drought increases from approximately 1 in 10 to 1 in 3 by the end of the century under the low and medium low scenarios. Under the medium high scenario it becomes 1 in 2, and with the high scenario the probability of drought exceeds that of non-drought conditions by the latter half of the century. At present little land in Fife is irrigated, this being restricted mainly to potatoes. Extraction from rivers is a common source of such water. Lower river flows could compromise this source for agricultural use. The public supply in Fife is already supplemented by water provided by the neighbouring region of Angus, this may be a trend which will need to be developed in the future.

Argyll	low	med low	med high	high
1970-2000	0	0	0	0
2000-2030	0	0	0	0
2030-2060	1	1	1	1
2060-2090	1	0	3	5

Table 10.1 Drought frequency, Argyll.

Stirling	low	medlow	medhigh	high
1970-2000	0	0	0	0
2000-2030	0	0	0	0
2030-2060	0	0	0	1
2060-2090	1	1	1	4

Table 10.2 Drought frequency, Stirling.

Fife	low	medlow	medhigh	high
1970-2000	3	3	4	4
2000-2030	4	4	5	6
2030-2060	7	6	8	10
2060-2090	11	10	15	18

Table 10.3 Drought frequency, Fife.

This is a statistical exercise, the results of which are determined by the assumption of the frequency of droughts during the last three decades of the 20th century. What it illustrates is that there is a definite decrease in water resources across the country during the summer months. The frequency of droughts, regardless of the absolute level at which this is set, increases across the country, with the most dramatic impacts being apparent in the East of the country. In Fife, the frequency of drought conditions is likely to increase by a factor of 2 to 3 under the Low and Medium Low scenarios, with an increase by a factor of 4 or greater under the conditions of the Medium High and High scenarios.

This would suggest that water shortages could become a significant problem during the summer months in the drier East of the country.

10.3.2. The effects on water resources during winter

The UKCIP02 model indicates an increase in precipitation for all regions during the winter months of December, January and February. The implications of such increases are widespread, with the potential for flooding being of significance. In addition to increases in total precipitation there is the prospect of more intense rainfall events, further adding to the risk of floods.

In order to assess the risk from flooding, the model would have to be adapted to generate precipitation events over a 24 hour period rather than just seasonal totals. Although seasonal totals might be a guide to an increased risk of flooding due to soil saturation, without the finer resolution flood risk cannot be forecast.

10.4. Emissions sector

The emissions sector calculates the net carbon balance of the regions by subtracting assimilation by forestry from the total amount of carbon emitted by the population, including tourists. The size of the resident population is important, as is the number of tourists visiting the region, when determining the total emissions. Per capita carbon emissions have been set at a constant level, but it would be informative to examine the effects of changes to this figure on the long term carbon balance.

Areas of forestry are important, as is the rate of carbon assimilation by forests. As was demonstrated in the sensitivity tests, the net carbon balance of Argyll is more sensitive to this parameter than either of the other two regions. Fife was more sensitive to changes in the per capita emissions figure as a result of its greater population.

Structural changes to energy supply, the cost of fuel and efforts to reduce carbon emissions by taxation or other means are likely to have a significant impact on carbon emissions during the 21st century. These cannot be included in the model as their form is not yet known. The fundamental differences between the regions are, however, likely to remain, as is the contribution to assimilation performed by the forested areas. Net emissions can be calculated and the effects of reductions in per capita output examined.

Initially the effect of climate change on emissions will be investigated by running the model with the climate sector "switched off", then making subsequent runs corresponding to the four climate change scenarios. The impact of warmer climates can then be assessed before experiments to determine the effect of reducing the per capita carbon output are performed.

10.4.1. Net emissions

The results shown in Figure 10.12, Figure 10.13 and Figure 10.14, represent the mean values obtained from 5 runs of the model. The lines represent future carbon emissions under conditions of no climate change (red), and one for each of the four scenarios, Low (purple), Medium Low (yellow), Medium High (blue) and High (black).

In each case it can be seen that the overall trend, with per capita emissions fixed at 3.33 tons per person per year, is for the higher scenarios to be associated with higher emissions. One major contribution to this increase is the additional numbers of tourists associated with the higher summer temperatures, their contribution being included in the overall totals.

Argyll, shown in Figure 10.12, is a net sink for carbon. As forestry continues to expand, the amount of carbon assimilated increases, well beyond any impact from tourist numbers. The difference between the four scenarios appears minimal, with a slight reduction in the overall balance being evident.

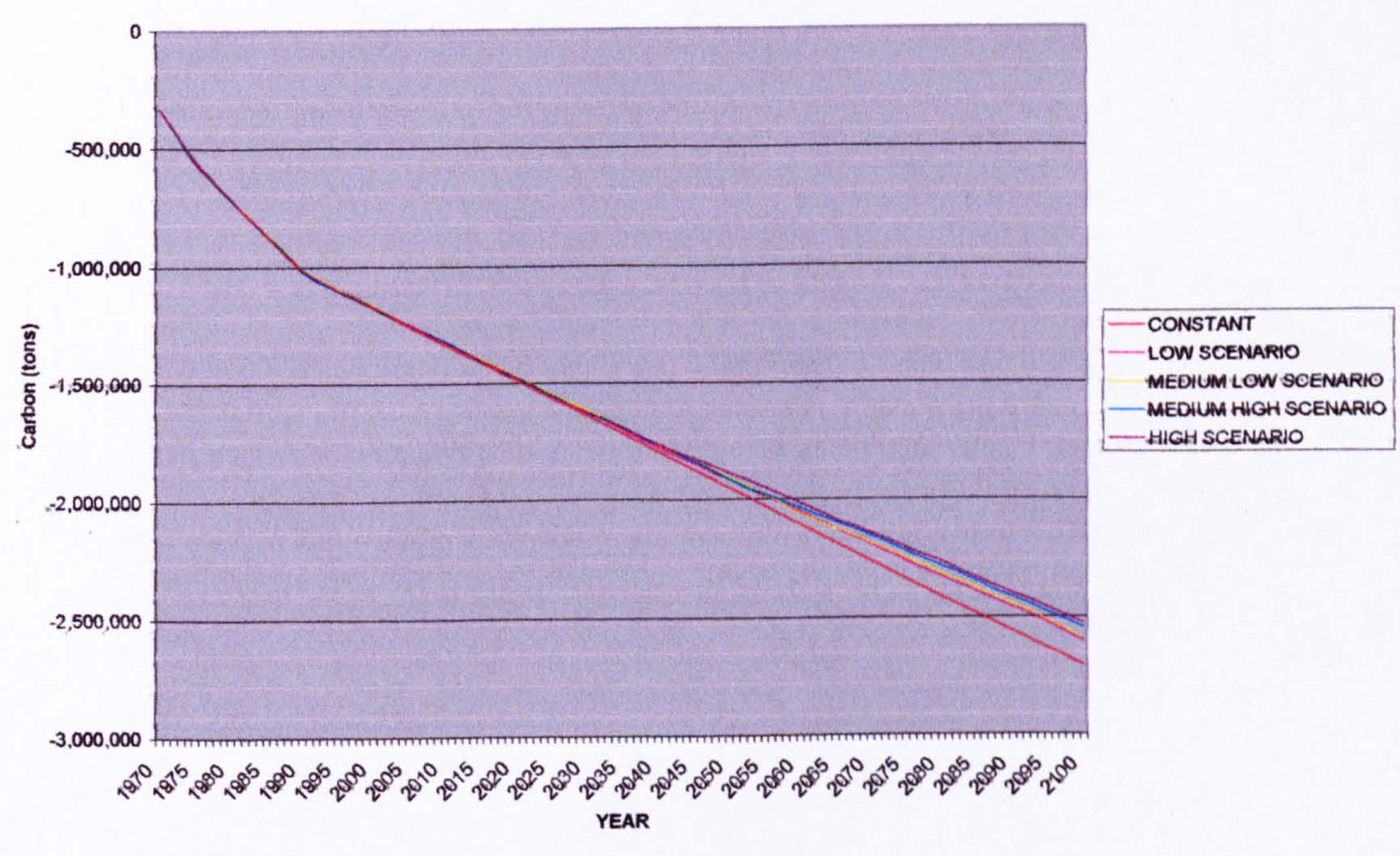


Figure 10.12 Carbon balance for Argyll

The results for Stirling are similar in that there is an increase in the total emissions under conditions of more rapid climate change. The overall situation shows that Stirling is a net emitter of carbon, and the quantity increases under all climate change scenarios. The upward trend in emissions is caused partly by an increase in tourist numbers but is also caused by an increase in the resident population over time. The emissions for Stirling are shown in Figure 10.13.

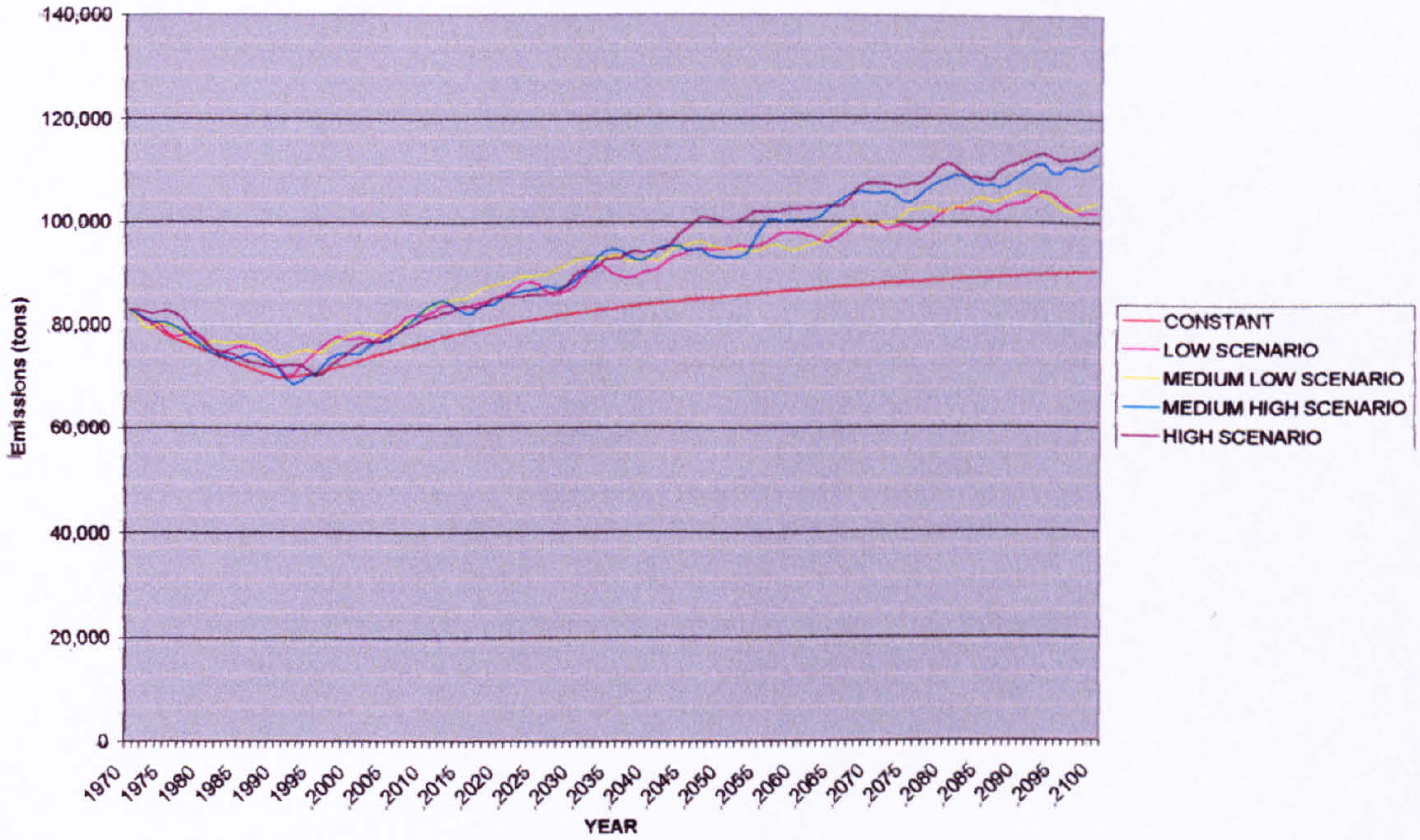


Figure 10.13 Carbon balance for Stirling.

Fife has the largest population of the three regions as well as the smallest area. Emissions here are considerably higher than for Stirling but the graph indicates that all climate scenarios follow a down ward trend, the rate of which depends on the strength of the warming trend. As with the other regions the higher climate change scenarios produce a higher net emission of carbon than do the less rapid climate change scenarios. The impact of increased tourism however does not cancel out the effect of a declining population, so the overall downward trend continues.

The results for fife are illustrated in Figure 10.14.

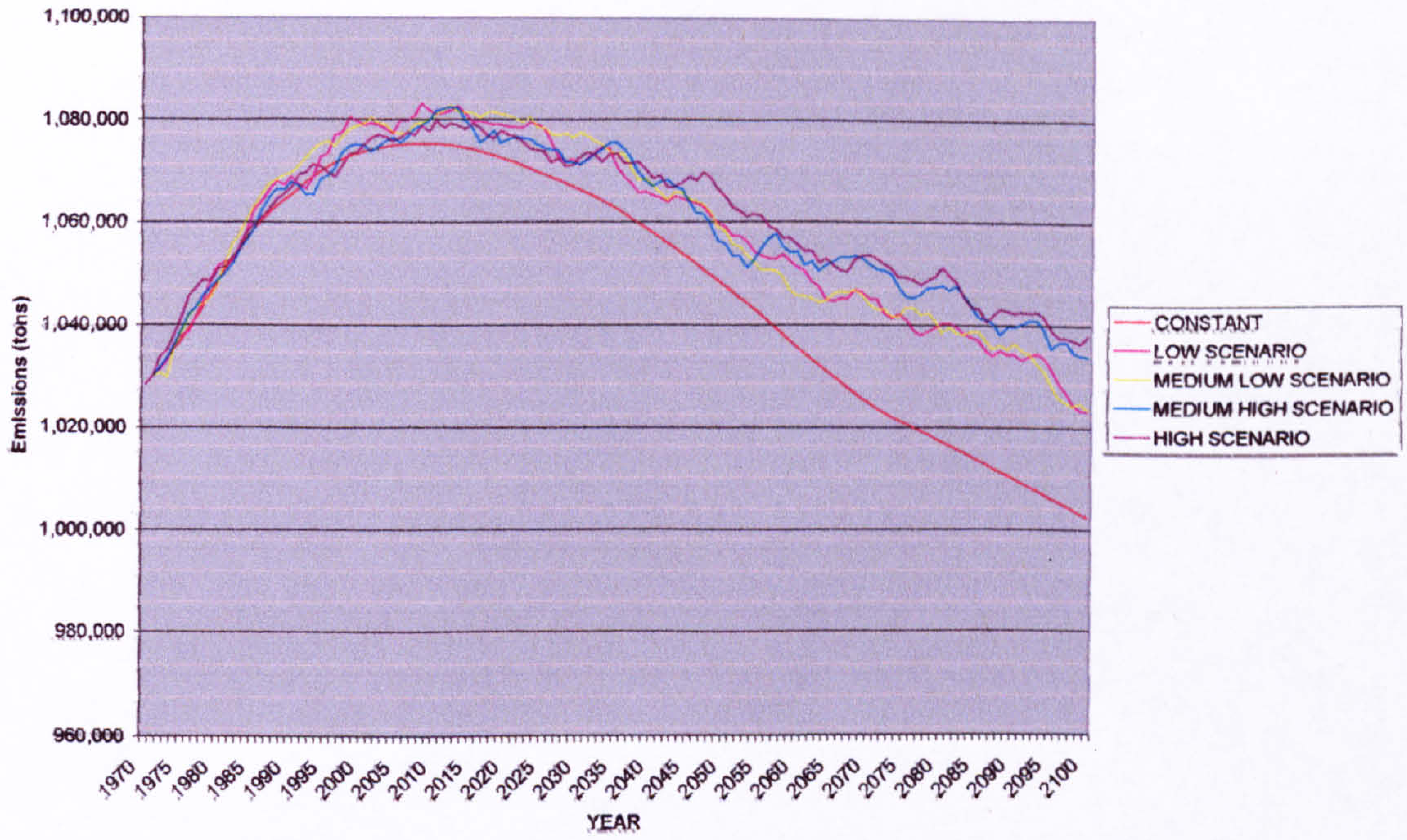


Figure 10.14 Carbon balance for Fife.

Argyll represents a net sink, with both Stirling and Fife being net emitters of carbon. Taking all three together and calculating the total emissions for the three regions gives the results in Figure 10.15. This shows that the scale of the assimilation in Argyll is sufficient to absorb much of the emissions from the population in the other regions.

This graph illustrates that under all four climate change scenarios the combined totals are less than zero by the start of the 21[st] century and continue to fall for the length of the simulation. The emissions from Stirling are small compared to those of Fife, but both are outweighed by the scale assimilation by the forests of Argyll.

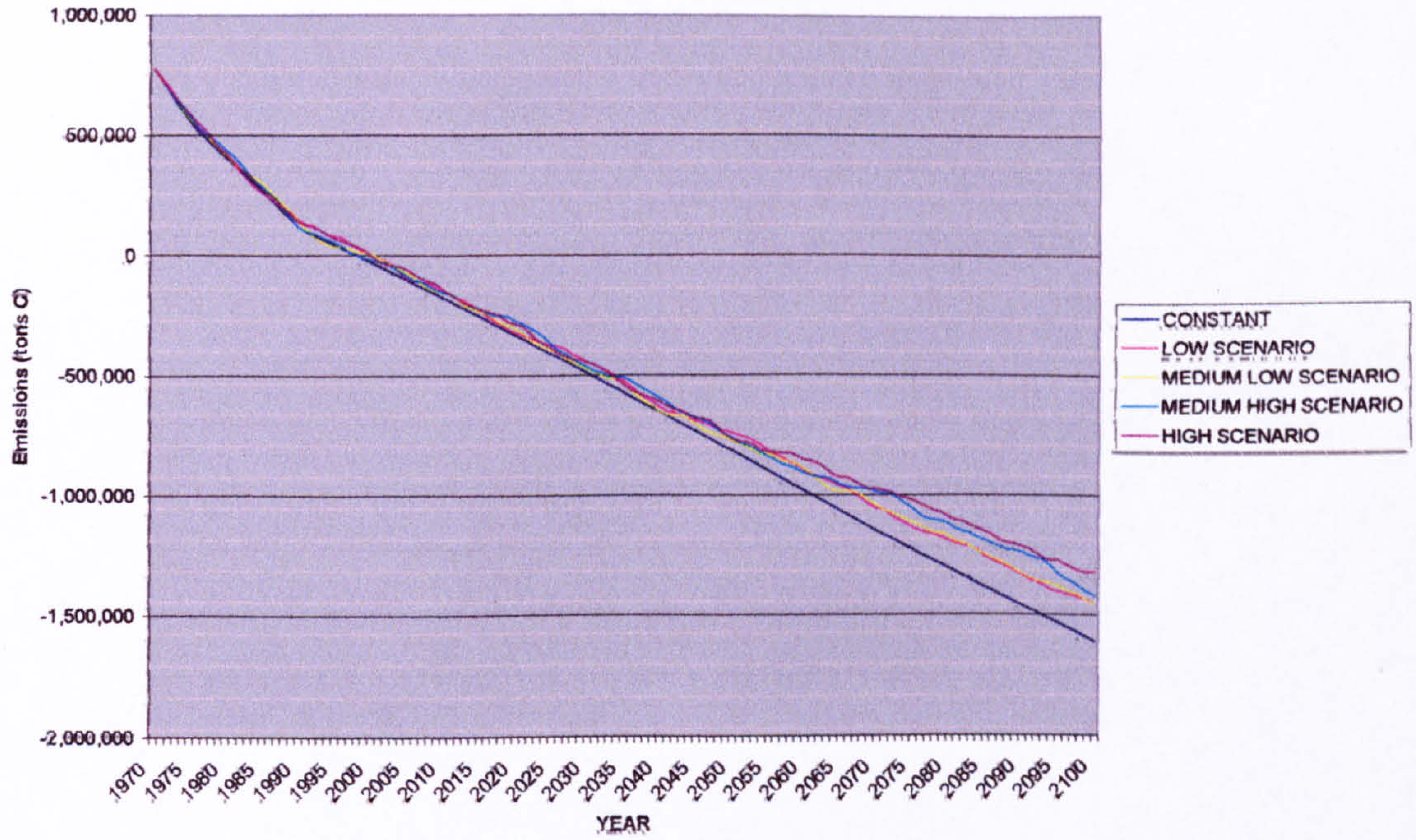


Figure 10.15 Combined carbon balance for the three regions.

10.4.2. Changes to per capita emissions

All the above results assume a constant rate of carbon emissions per head of population. The impacts of achieving reductions in per capita emissions are now investigated, setting three targets to be met by the end of the century.

The first is to assess the impact of a 20% reduction by the end of the century, then a 30% reduction and finally a 50% reduction. This is achieved by the use of a RAMP function in Stella, which gradually reduces the per capita emissions figure through time. For a 20% reduction, this function reduces per capita emissions by 0.0067 tons per year for the length of the simulation, starting at the year 2000. For an eventual 30% reduction, the figure is 0.01 tons per year and for a 50% reduction it is 0.0167 tons per year.

When run under the conditions of all four climate change scenarios, it is found that the contrast between these emission targets is far greater in magnitude than the contrast between the climate scenarios. The graphs produced are very similar, so in each of the regions only one scenario is presented.

Figure 10.16 shows the results for Argyll, where the changes to per capita emissions have relatively little impact on the overall shape of the graph. The small population combined with the large area of forest means that changes to per capita emissions have a limited impact on the carbon balance of Argyll.

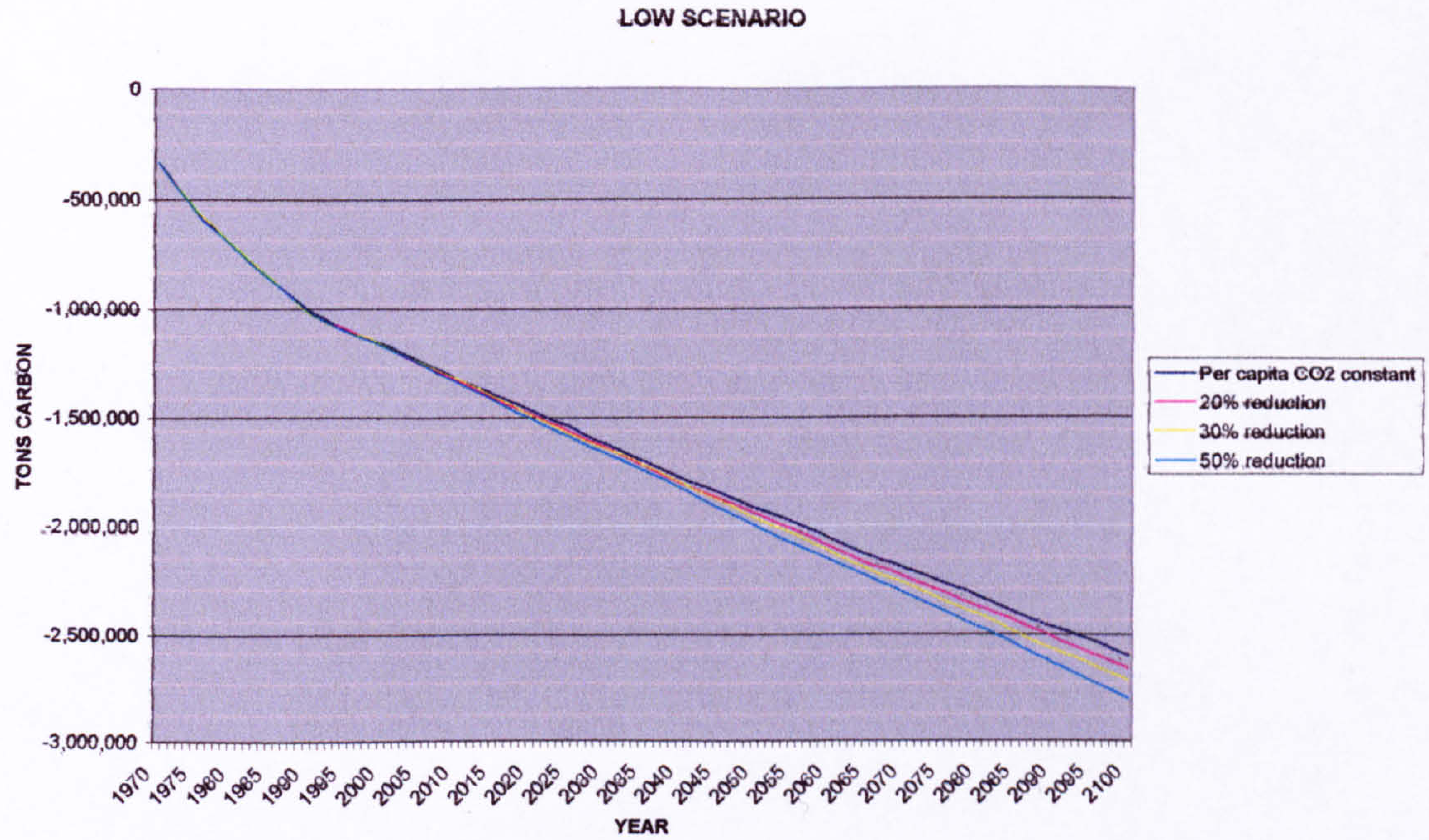


Figure 10.16 Results of changes to per capita emissions for Argyll.

For Stirling the results are different, the increasing population of this region generating an increase in emissions as illustrated in the previous section. The impact of reductions in per capita carbon emissions is quite marked and it can be seen that the 30% target takes Stirling to a carbon neutral position by the end of the 21st century. With a 50% reduction target being met the region becomes a net sink for carbon by around the middle of this century. These results are shown in Figure 10.17

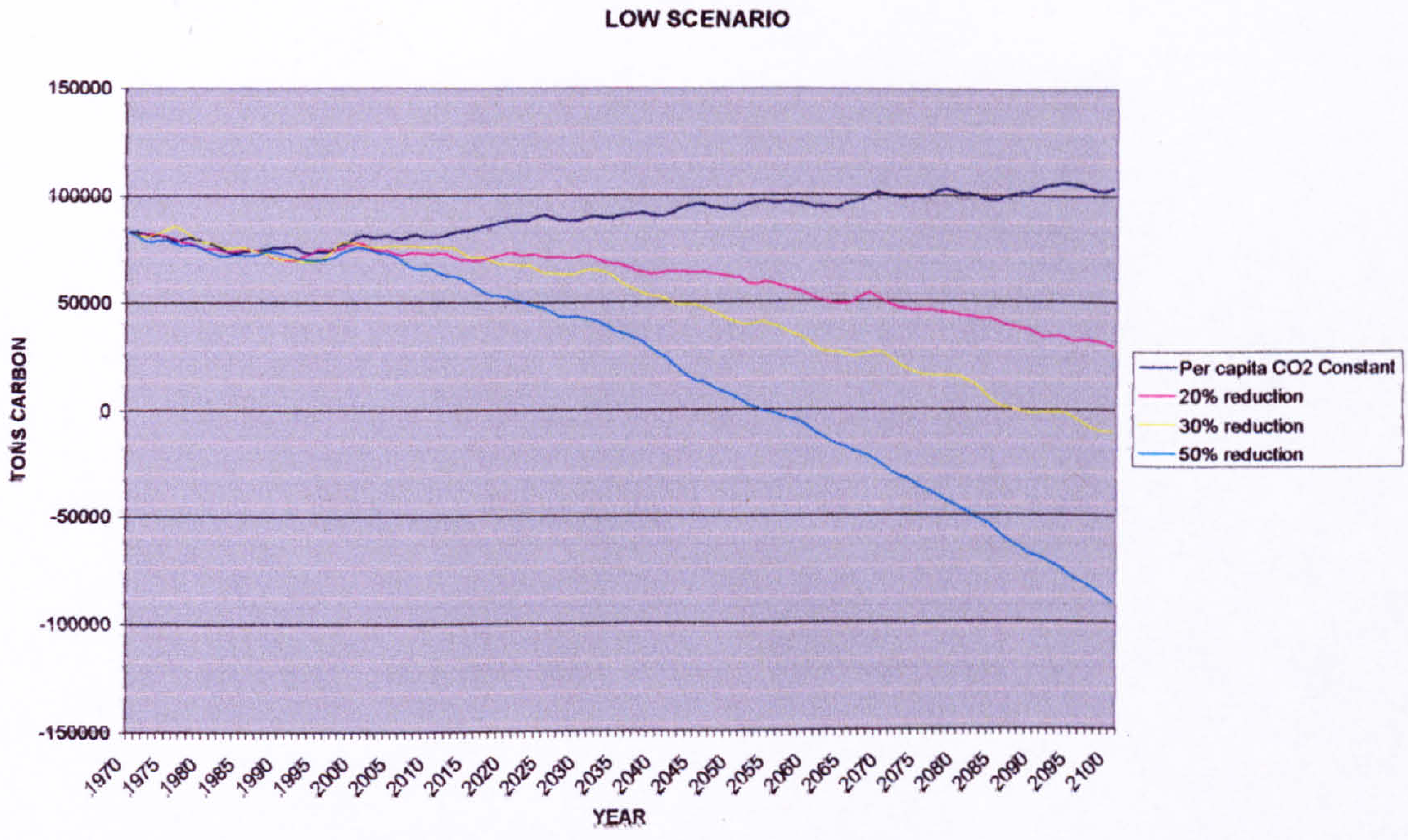


Figure 10.17 Results of changes to per capita emissions for Stirling.

Fife, with the highest population, is the region most affected by reductions in per capita carbon emissions. Although it never reaches a zero emissions state under these simulations, the scale of the reduction in terms of tons of carbon is greatest. Figure 10.18 shows the projected carbon balance for Fife. This shows that with the 50% target being met, there is a reduction in emissions of around half a million tons of carbon per year. The scale of this reduction is greater in magnitude than the increases due to climate change by a factor of around 10.

Even the 20% reduction target by the end of the century would produce a reduction in emissions four times greater than the increases due to the High climate scenario.

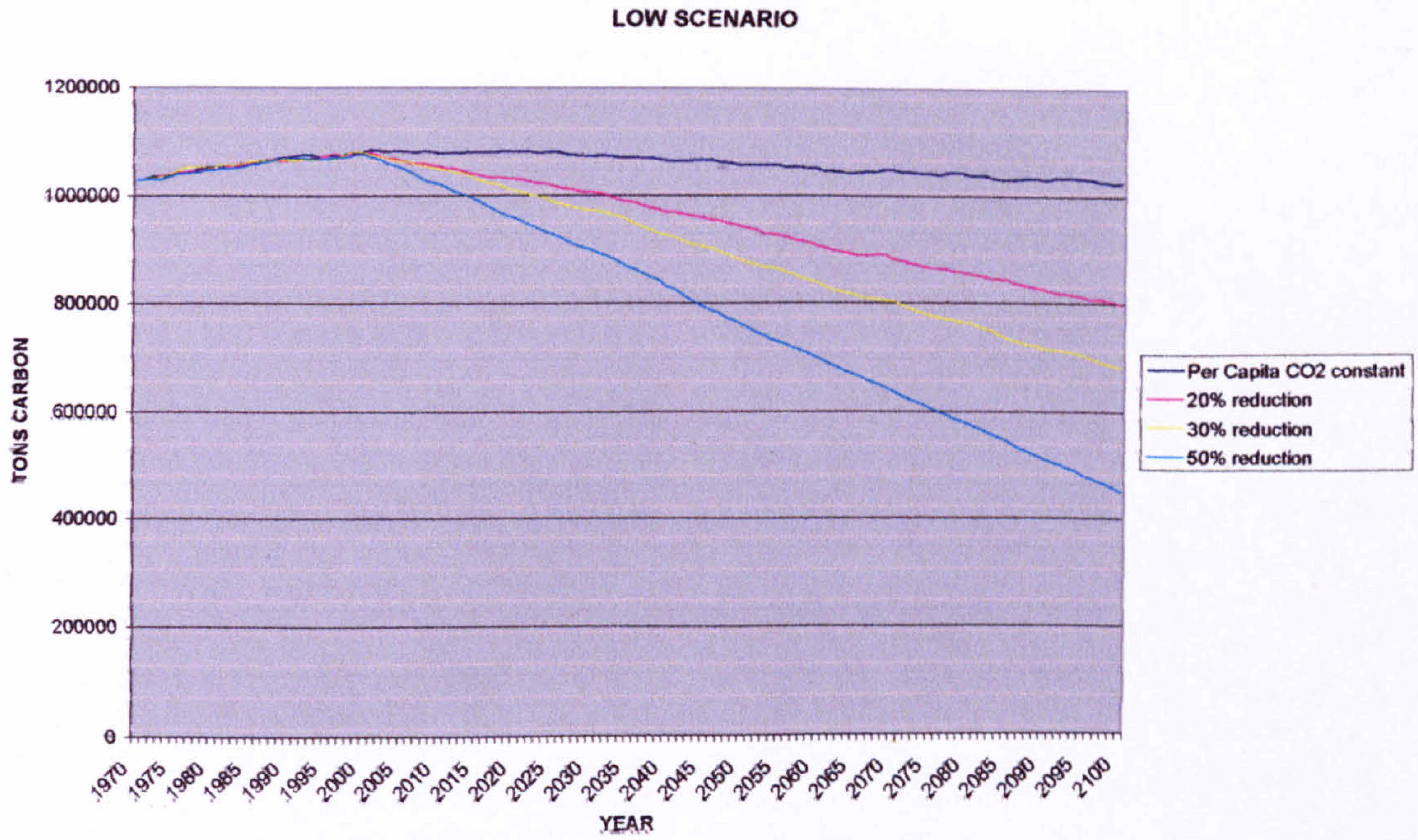


Figure 10.18 Results of changes to per capita emissions for Fife.

10.5. Land Use

The main impacts on land use in the model are those derived from the extrapolation of trends identified in the historical data, and the projected increases in intensive land management resulting from the increase in temperature associated with the four climate change scenarios.

The model deals with land which is classified as urban, crops and grass, rough grazing and forestry. This does not represent the entire land surface. Areas, which are not at present classified as belonging to these categories, are excluded, for example areas used for recreation or field sports or high montane vegetation which is unproductive even for rough grazing. The model redistributes the areas of land associated with these four categories without expanding the total area, by utilising land which presently has different classifications.

In general, there can be seen to be a reduction in rough grazing in all regions, resulting from the growth of both forestry and intensively managed crops and grass. The increases in the area land for building, although significant, do not represent a major shift in land use in any of the three regions.

The following sections deal in turn with each of the land use categories, comparing the impacts associated with the four climate change scenarios with a model simulation based on a constant climate regime.

10.5.1. Urban

Any increase in the area of urban land in Stirling and Fife is caused by either growth in the population or changes to the mean number of residents in each dwelling. For these two regions there is no increase in urban land due to climate change alone. Argyll is the region which shows no connection between the population trends and the provision of new housing. In the model, the growth of 1% per annum which has occurred over previous decades is continued, therefore no impact of climate change is apparent.

In all cases, the area of land classed as urban increases, as illustrated in the following figures. In Argyll (Figure 10.19), this growth continues slowly yet nevertheless exponentially, as it is generated by a simple 1% increase per year. In Stirling (Figure 10.20) the population is projected to grow and this, combined with the decreasing size of the average household, leads to a continued growth in the urban area. Fife (Figure 10.21) shares this decrease in mean household size, but there is a projected decrease in population. This has the effect of levelling off the area required for housing by the second decade of the 21st century.

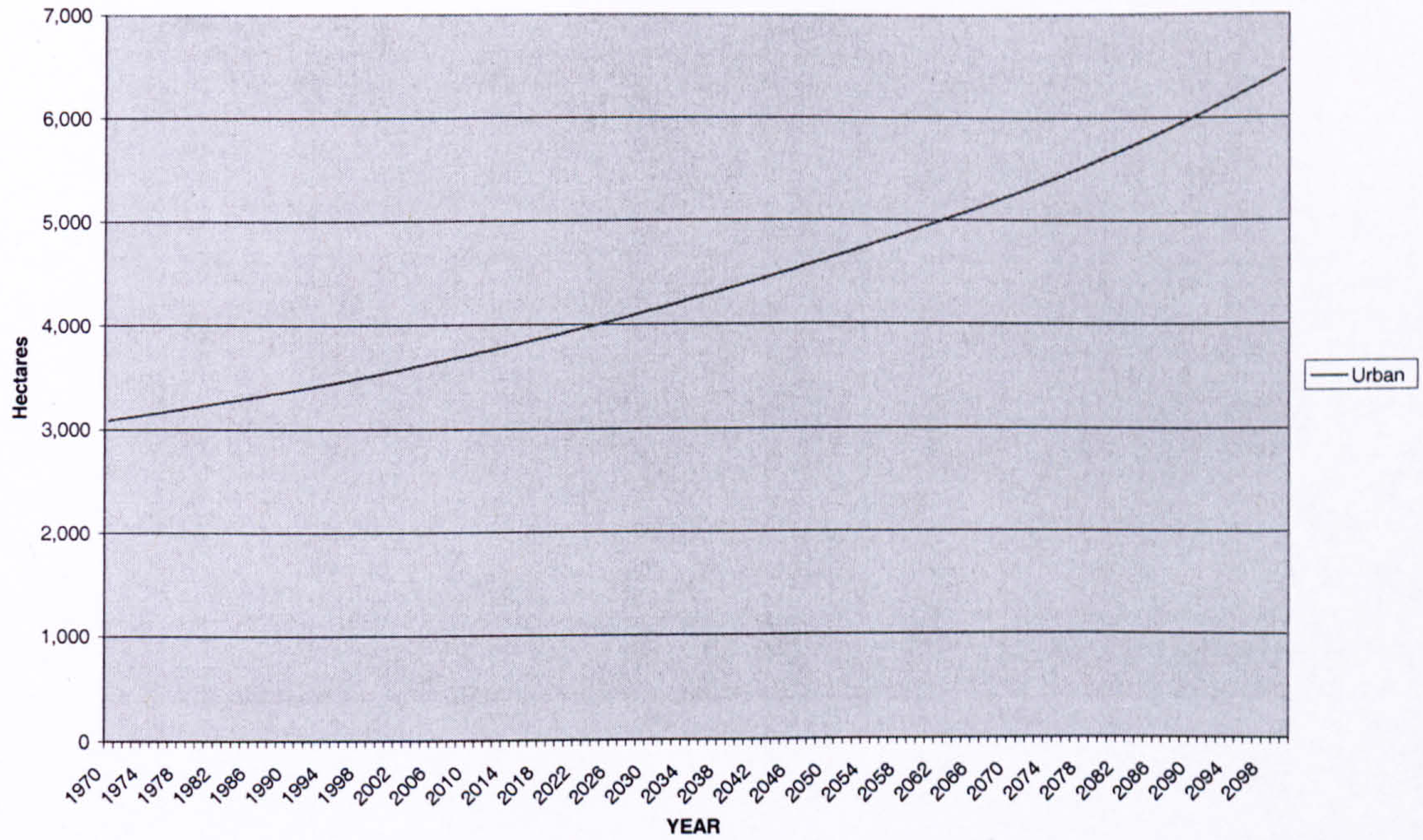


Figure 10.19 Projected urban area for Argyll.

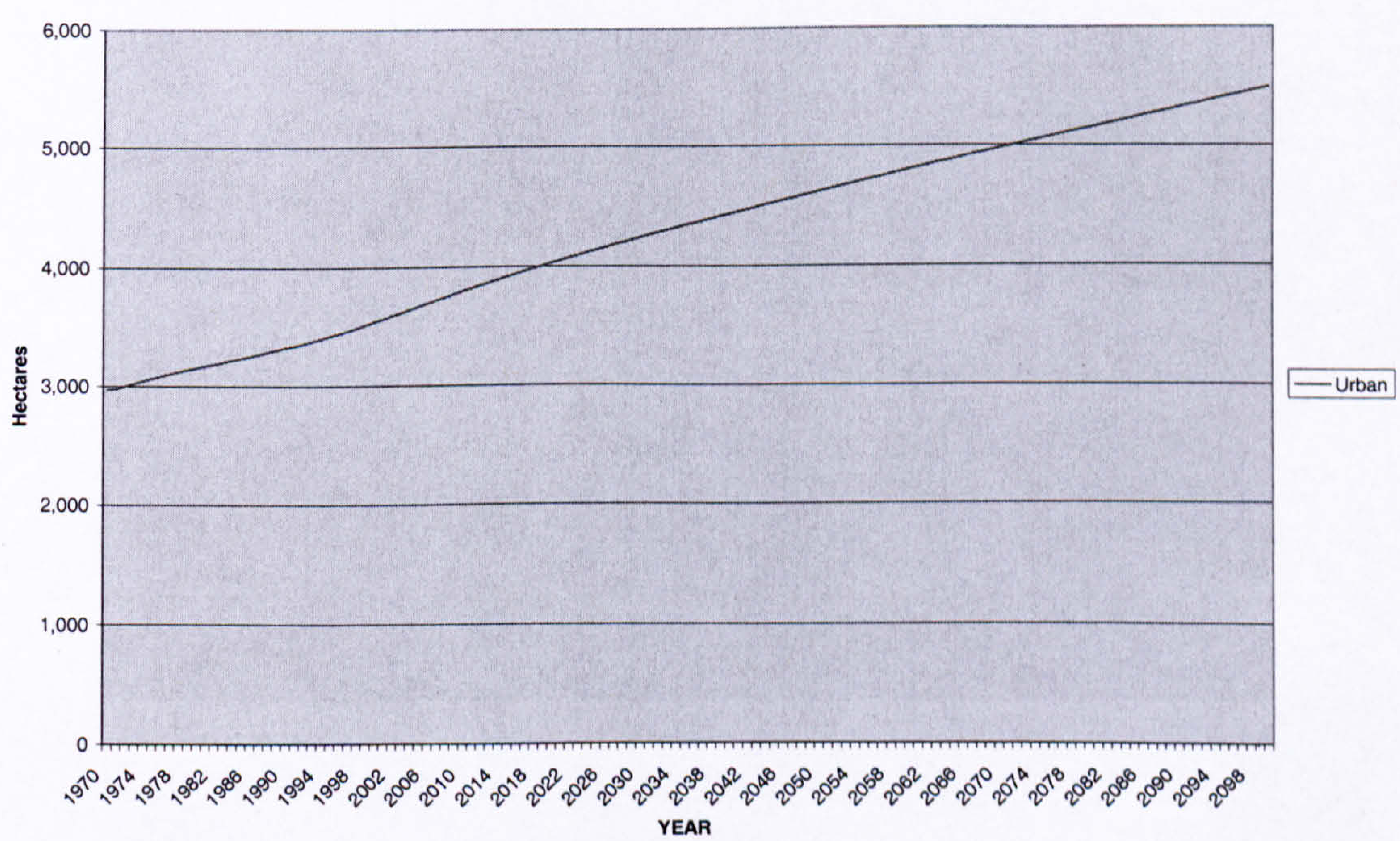


Figure 10.20 Projected urban area for Stirling

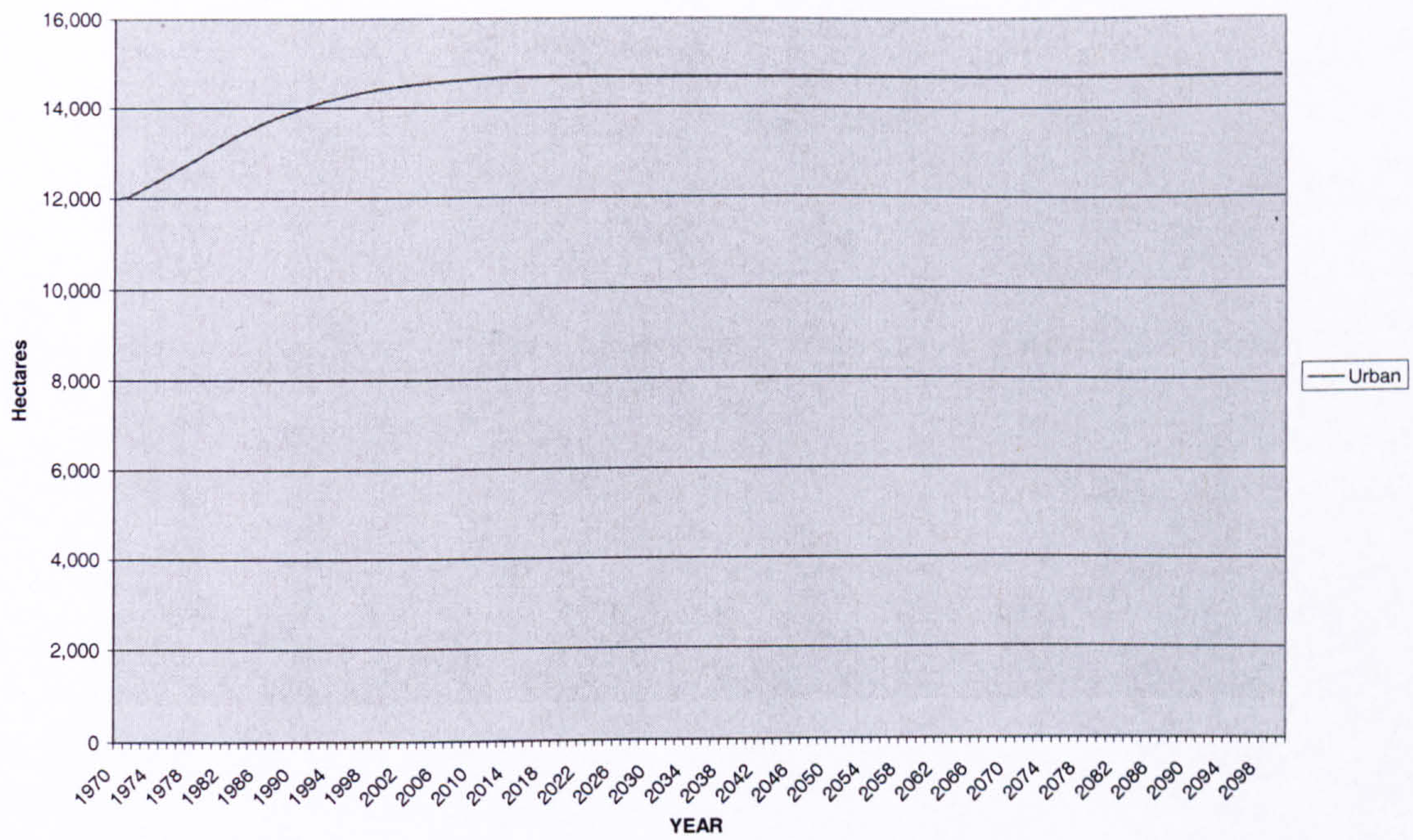


Figure 10.21 Projected urban area for Fife.

10.5.2. Crops and grass

Over the past decades there has been a general trend in all three regions towards less land being classified as agricultural. Despite this, there has also been an increase in the area of intensively managed land, at the expense of rough grazing. Crops and grass together represent at present less than 10% of the agricultural land in Argyll, around 40% of the agricultural land in Stirling and over 90% of the agricultural land in Fife.

The conversion of land to improved grassland has been the main reason for the increase in this land use category, though these figures indicate that the potential for change is less in the East and far greater in the west. Soils, slope, aspect and climate all play a part in developing the land use potential. In terms of climate, the increased growing season, reduced summer precipitation in the west and higher mean temperatures predicted by climate models, (UKCIP 2002) should combine to encourage the expansion of this type of land management.

The following figures (Figure 10.22, Figure 10.23 and Figure 10.24) illustrate the model output for no climate change, i.e. an extrapolation of current trends, and for each of the four climate change scenarios up to the year 2100 (mean of 5 runs). The scale of the changes can be seen to be far greater in Argyll than in Fife, largely because very little additional land is available in the East. The implications of this in terms of employment and population can be seen in section 10.2 and section 10.7. The expansion of crops and grass is more rapid under the Medium High and High scenarios and represents almost a doubling of the area of potential improved land by the end of the century in both Argyll and Stirling. I feeror bars similar to those used in Chapter 7 were included with these results there would be an overlap of results from the different scenarios. Precise predictions are not possible, as variability in the climate will inevitably influence the output from this sector. However all scenarios show an upwards trend with higher rates of change of atmospheric CO^2 generating more rapid changes to land use.

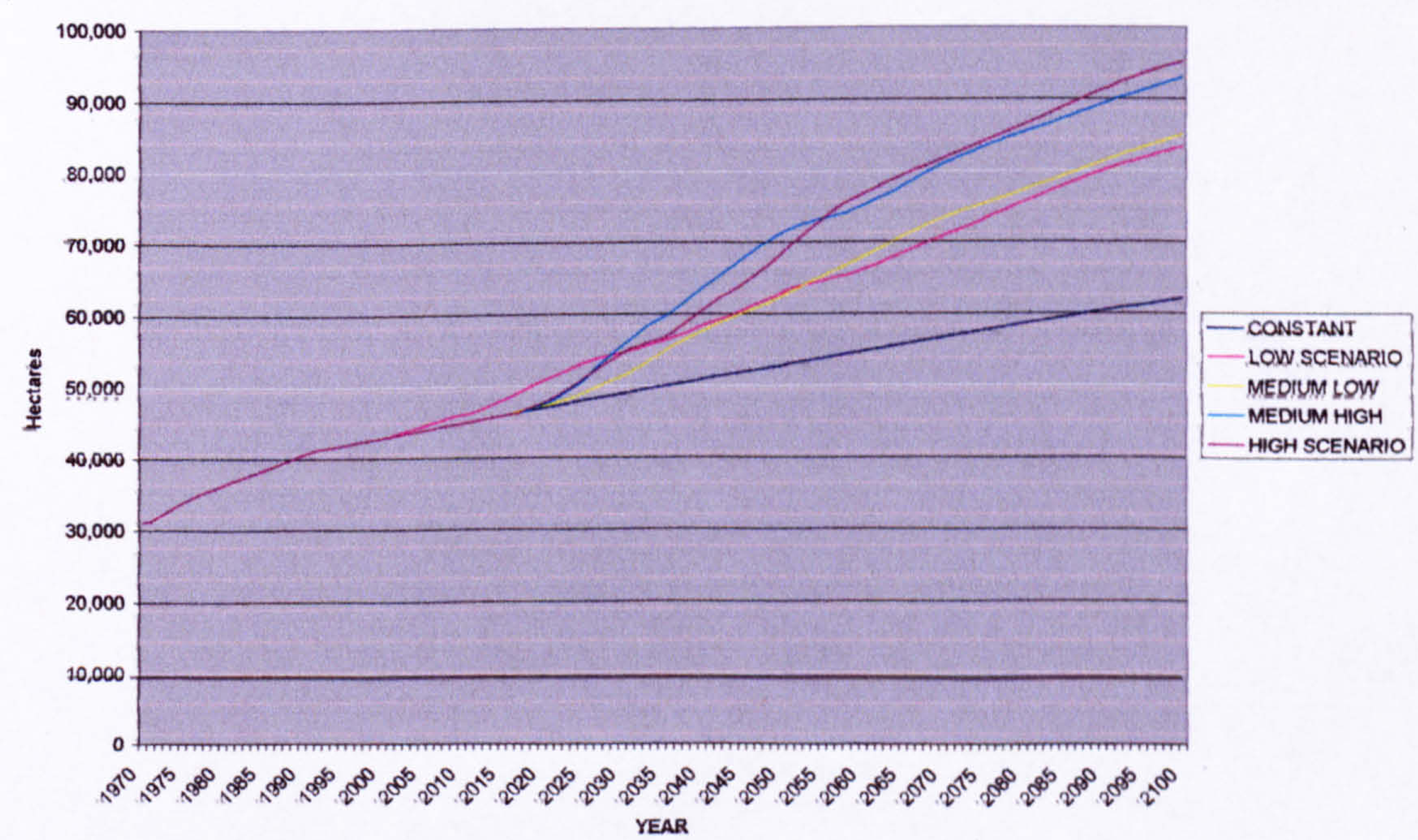


Figure 10.22 Area of crops and grass, Argyll.

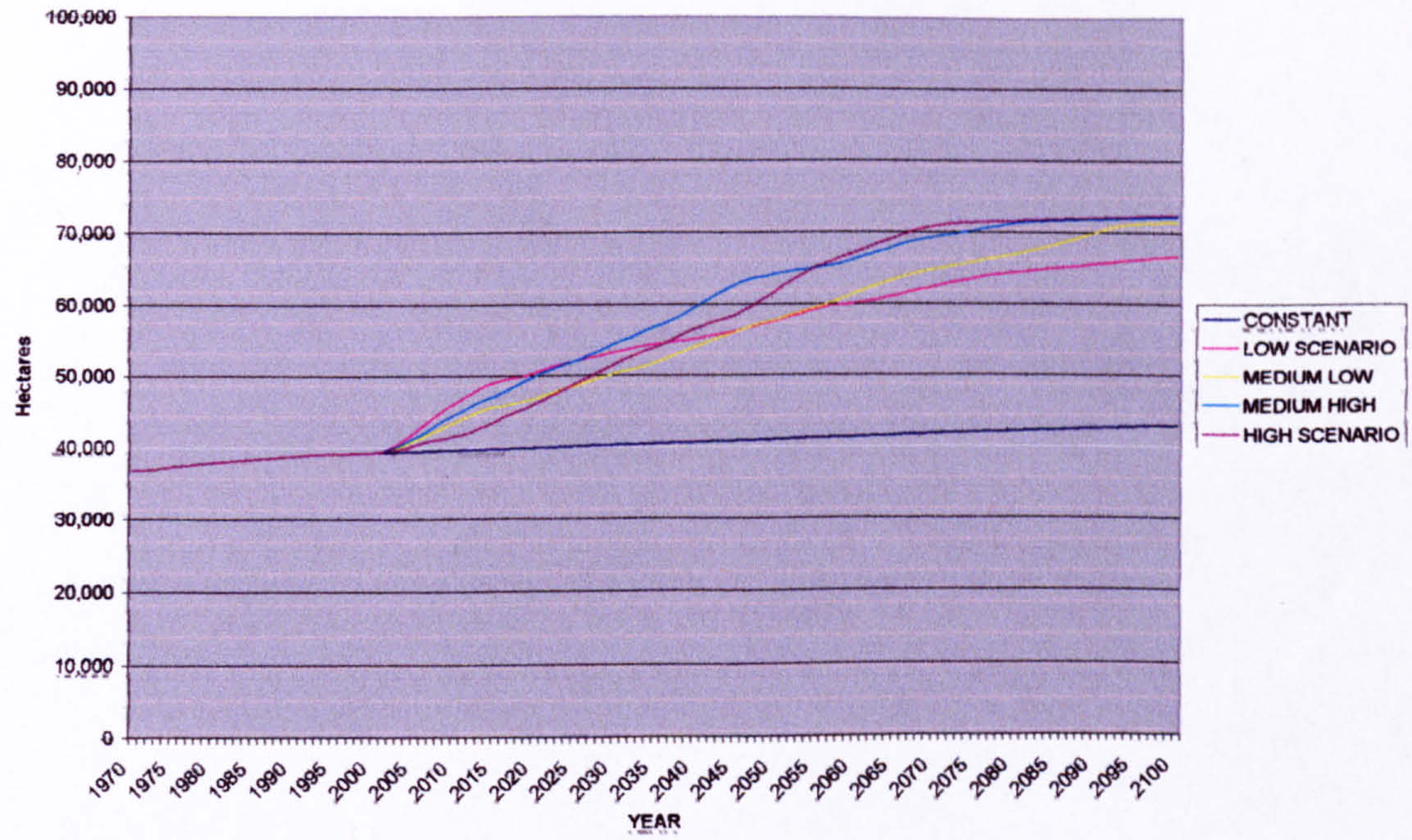


Figure 10.23 Area of crops and grass, Stirling.

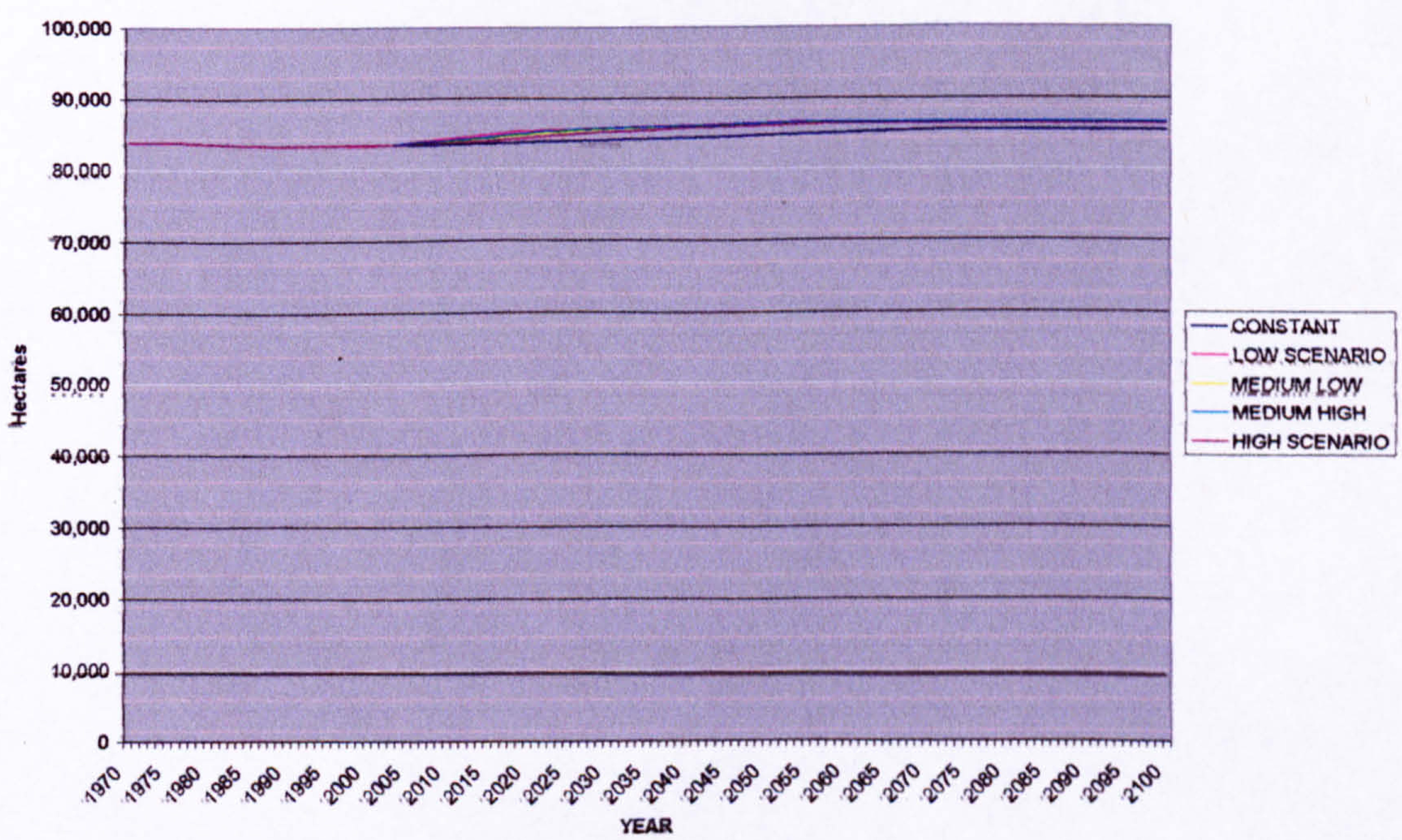


Figure 10.24 Area of crops and grass, Fife.

All the above figures (Figure 10.22, Figure 10.23 and Figure 10.24) were drawn with the same vertical scale to emphasise the contrast between the impacts in the three regions.

10.5.3. Rough grazing

Areas of rough grazing have been in decline, partly due to the increase in more intensive farming and partly due to the expansion of forestry. The decline under the conditions of climate change is seen to continue, as illustrated by Figure 10.25, Figure 10.26 and Figure 10.27, where again the mean of 5 runs of the model was used.

The graph representing rough grazing in Argyll shows little apparent difference between the results for the different scenarios. The scale of these differences is measured in tens of thousands of hectares and is therefore quite significant.

The changes in Stirling involve smaller areas but are still quite dramatic, while Fife loses all rough grazing land by the final quarter of the century, climate change merely hastening the loss. This does not take into account the possibility that land, at present not classified as agricultural, could become rough grazing, as warmer temperatures increase vegetation growth at higher altitudes.

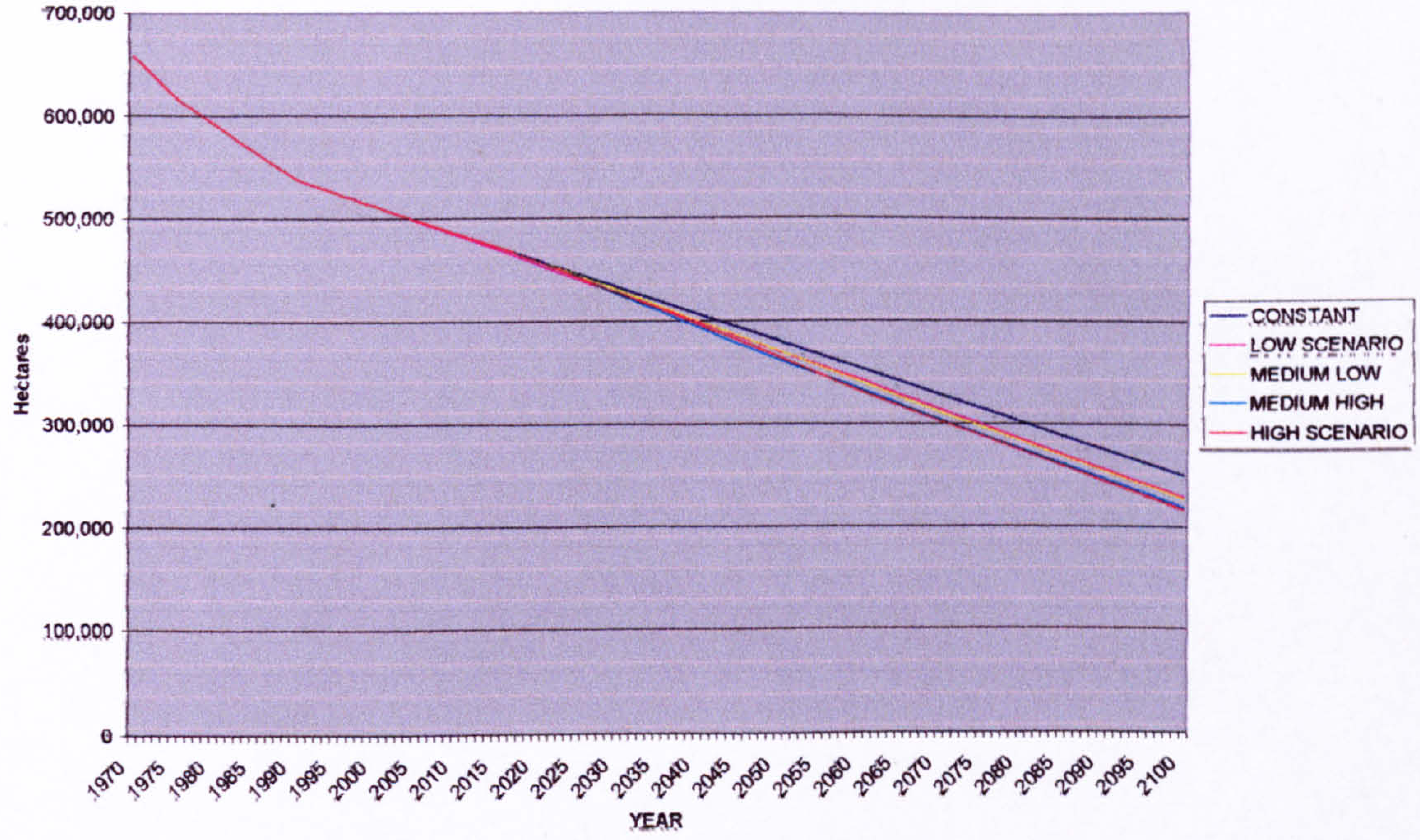


Figure 10.25 Rough grazing , Argyll.

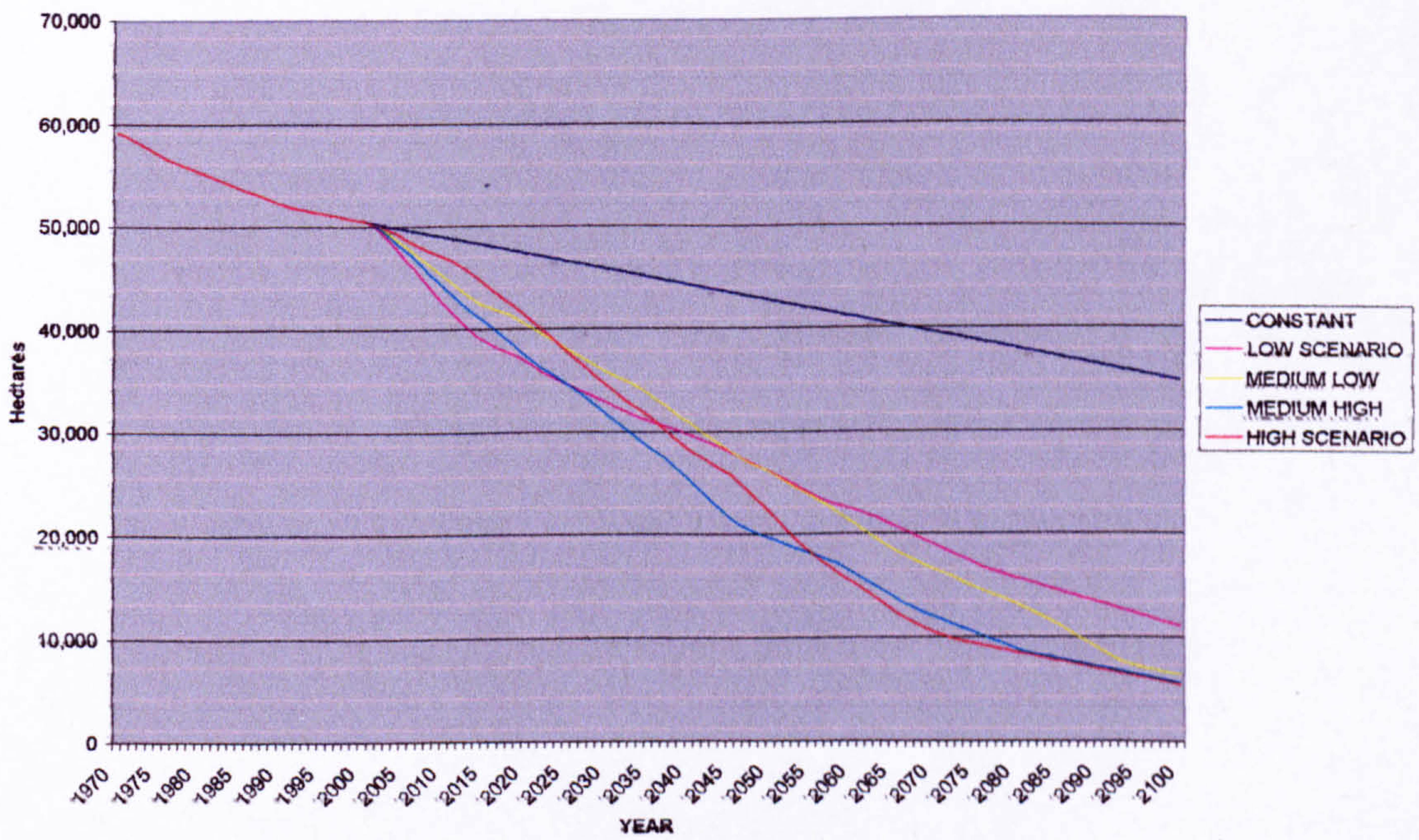


Figure 10.26 Rough grazing, Stirling.

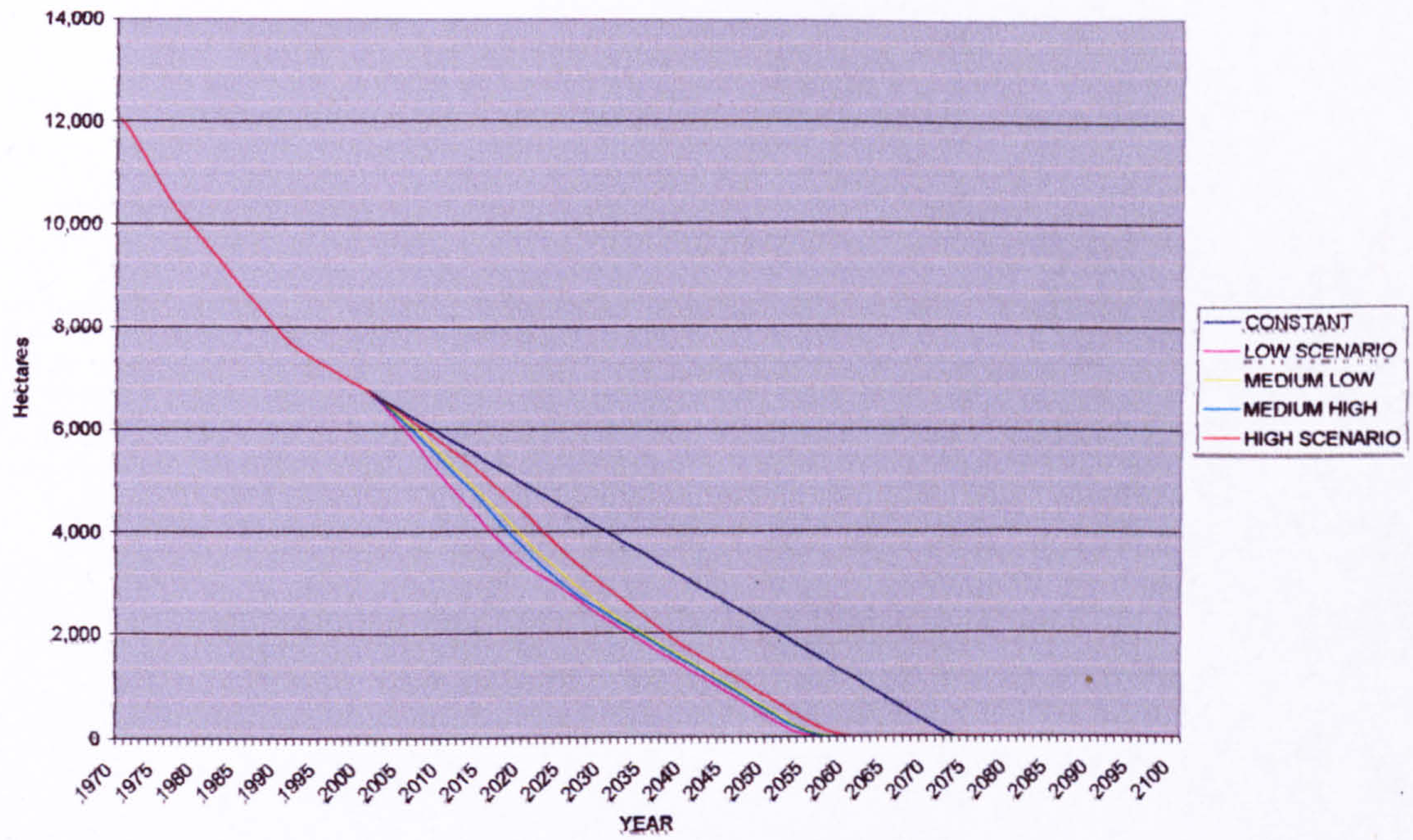


Figure 10.27 Rough grazing, Fife.

10.5.4. Plantation Forestry

Plantation forestry saw a rapid expansion during the last half of the 20th century, this in part explaining the reduction in rough grazing which occurred during this period. Payments in the form of grants and tax incentives hastened this process during the 1970's and 1980's, sometimes in areas which were of great conservation interest, such as the flow country of Caithness. A change in the legislation then provided an added incentive to plant native species such as Scots pine, birch, oak and other broadleaved species.

Table 10.4 shows the current Grants available for new planting and natural regeneration in Scotland (CKD Finlayson Hughes 2002).

Forest type	Grants per hectare for areas > 10 Ha.
Broadleaves and Native pinewoods	
Planting	£1050/Ha
Natural regeneration	£525/Ha plus 50% of initial costs such as fencing
Commercial conifers	
Planting	£700/Ha
Natural regeneration	£ 325/Ha plus 50% of initial costs such as fencing

Table 10.4 Forest grants 2002.

In addition to the above grants there are supplements payable in the case of planting on improved grassland, arable land or rough grazing which is part of a farm business and where the areas does not exceed 200 Ha.

The profitability of forestry activities declined as cheap imports became more abundant, particularly from the Baltic States of the former Soviet Union. As a result, the emphasis has shifted from commercial forestry activities towards forestry with a variety of uses, recreation and conservation being among these.

However, the planting of new commercial forests and the restocking of harvested areas has not ceased. The rate has simply declined from the peak which was reached during the 70's and 80's. The model reflects this by assuming that the level of grants and incentives will remain as at present providing the driver for increases in forest cover. This favours native species and broadleaved planting, but, nevertheless, still makes the commercial planting of exotic species a realistic option for landowners and forestry companies.

The following figures, (Figure 10.28, Figure 10.29 and Figure 10.30), illustrate the projected areas of commercial plantations in each of the regions for the coming century. It is worth noting that in Fife the area levels off, with no land becoming available for this activity as other land uses prevail. This is the only region which shows a contrast between the run of the model with climate held constant, and the runs associated with higher CO_2 levels. The difference between these scenarios results from the more rapid expansion of crops and grass with the warmer temperatures.

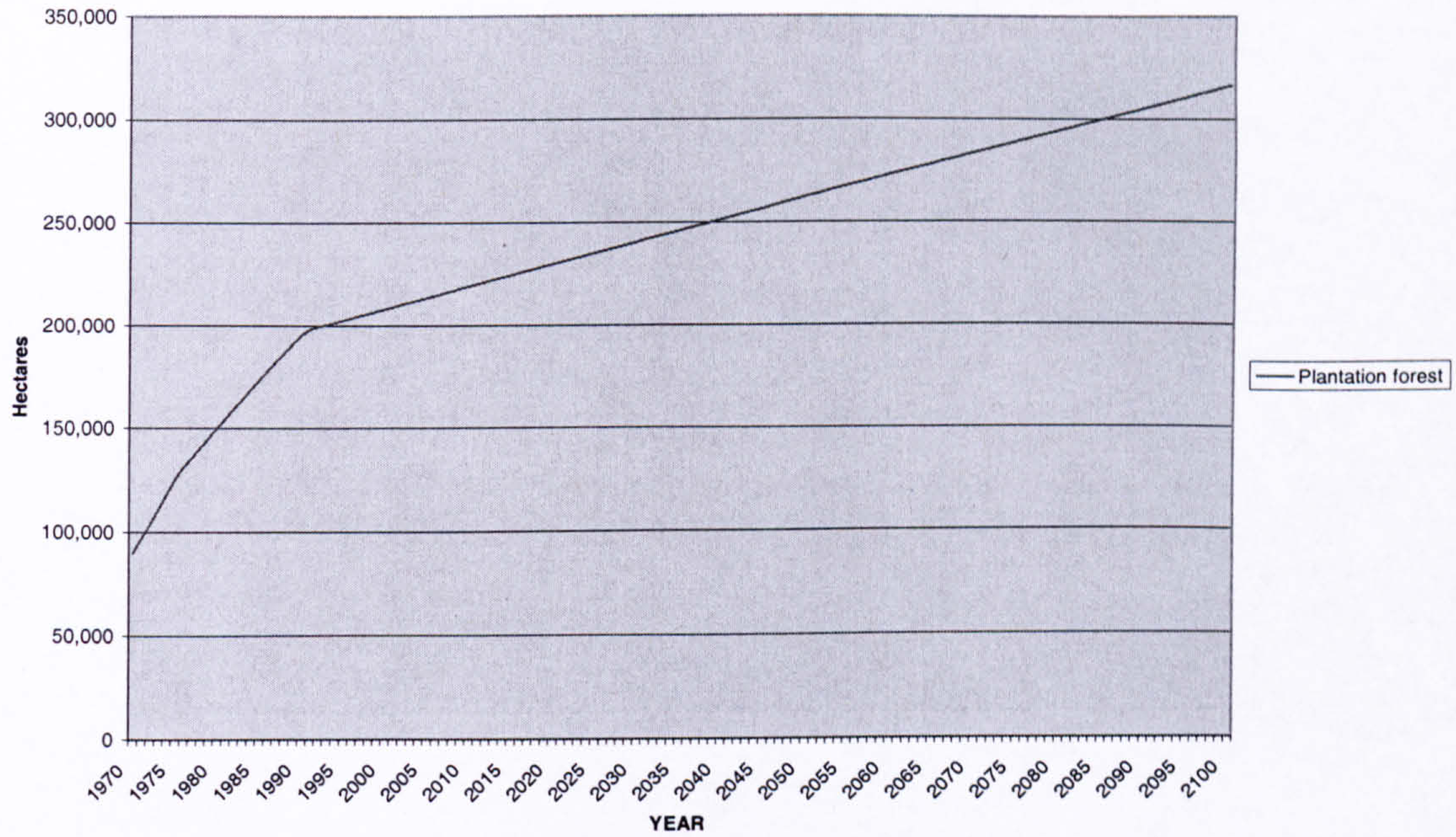


Figure 10.28 areas of plantation forestry, Argyll

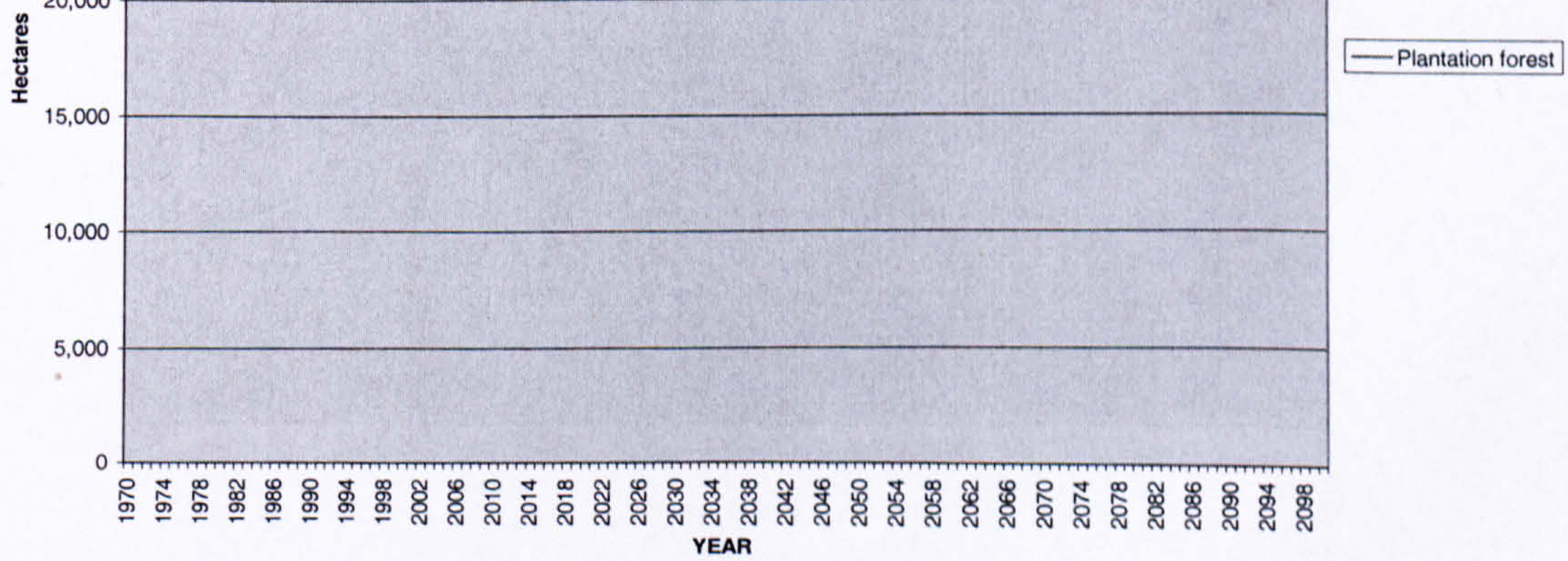


Figure 10.29 Area of plantation forestry, Stirling.

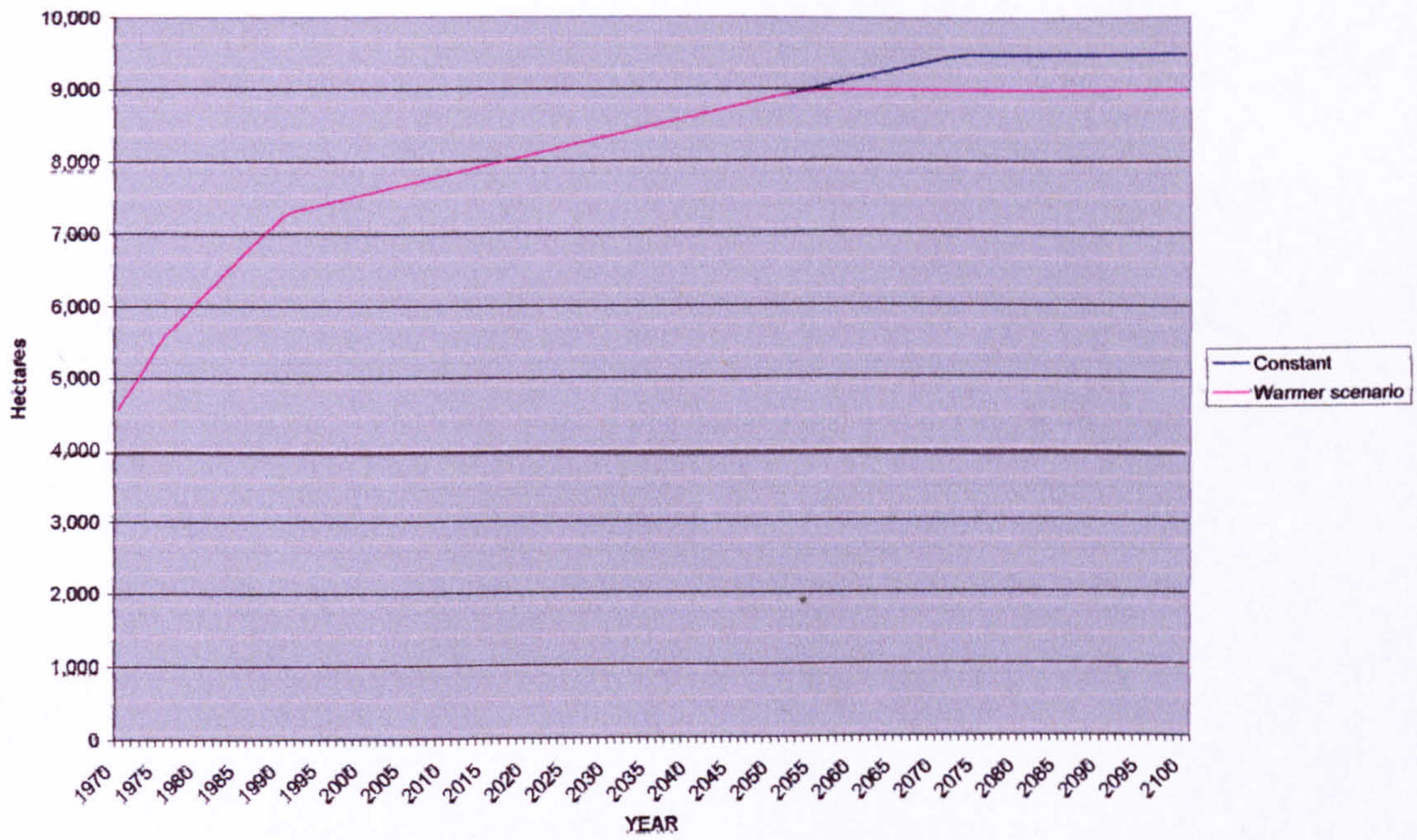


Figure 10.30 Area of plantation forestry, Fife.

10.5.5. Broadleaved and Native Species

The grants described in Table 10.4 have had the effect of increasing the area of native pinewoods and broadleaved forest dramatically. During the 1970's and 1980's around 1% of new planting was of this type, by the late 1990's this figure had risen to 55% of new planting. Although the rate of planting declined over this period, this does still represent a significant increase. The model allows these trends to continue, with the lower rate of planting, but with the proportion devoted to native pine and broadleaved species remaining the same as at present. Again Fife is the only region to show a contrast between the area of this type of forestry associated with constant climate and the climate change scenarios. In the other two regions there is sufficient rough grazing to allow the expansion of forestry as well as the expansion of crops and grass at the rates built into the model.

Figure 10.31, Figure 10.32 and Figure 10.33 show the projected areas of native pine and broadleaved forest in each of the regions through to the end of this century.

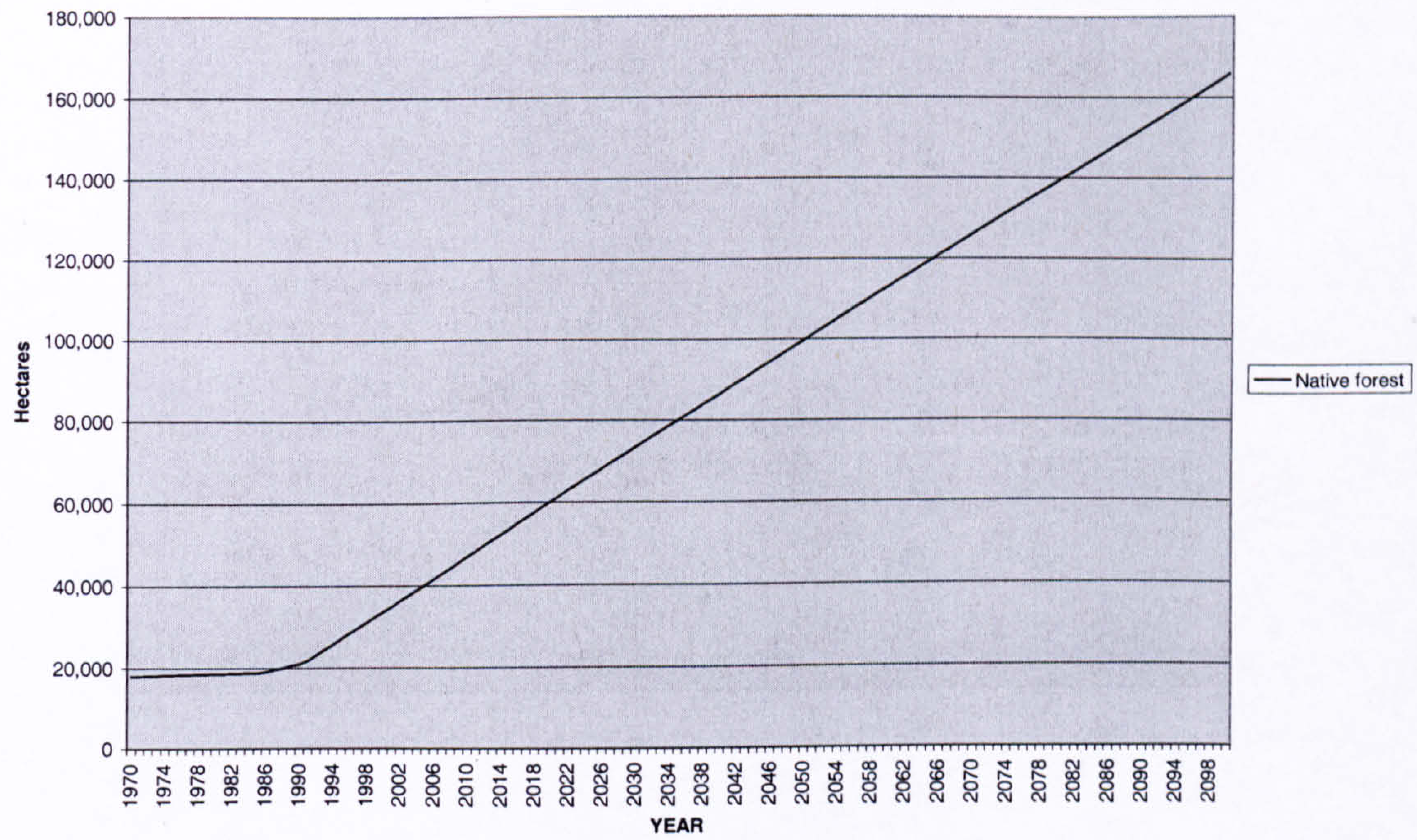


Figure 10.31 Area of broadleaved and native species, Argyll

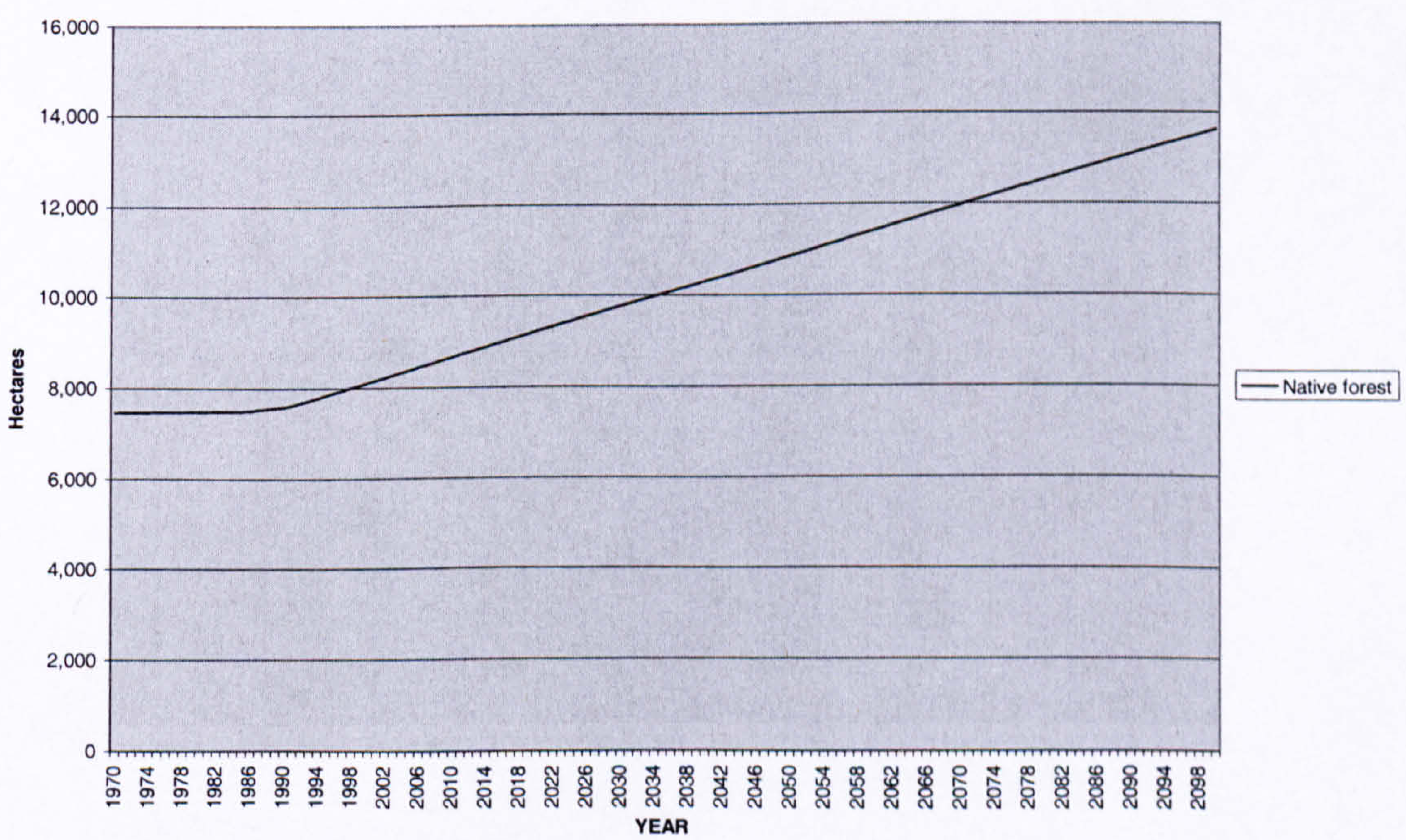


Figure 10.32 Area of broadleaved and native species, Stirling.

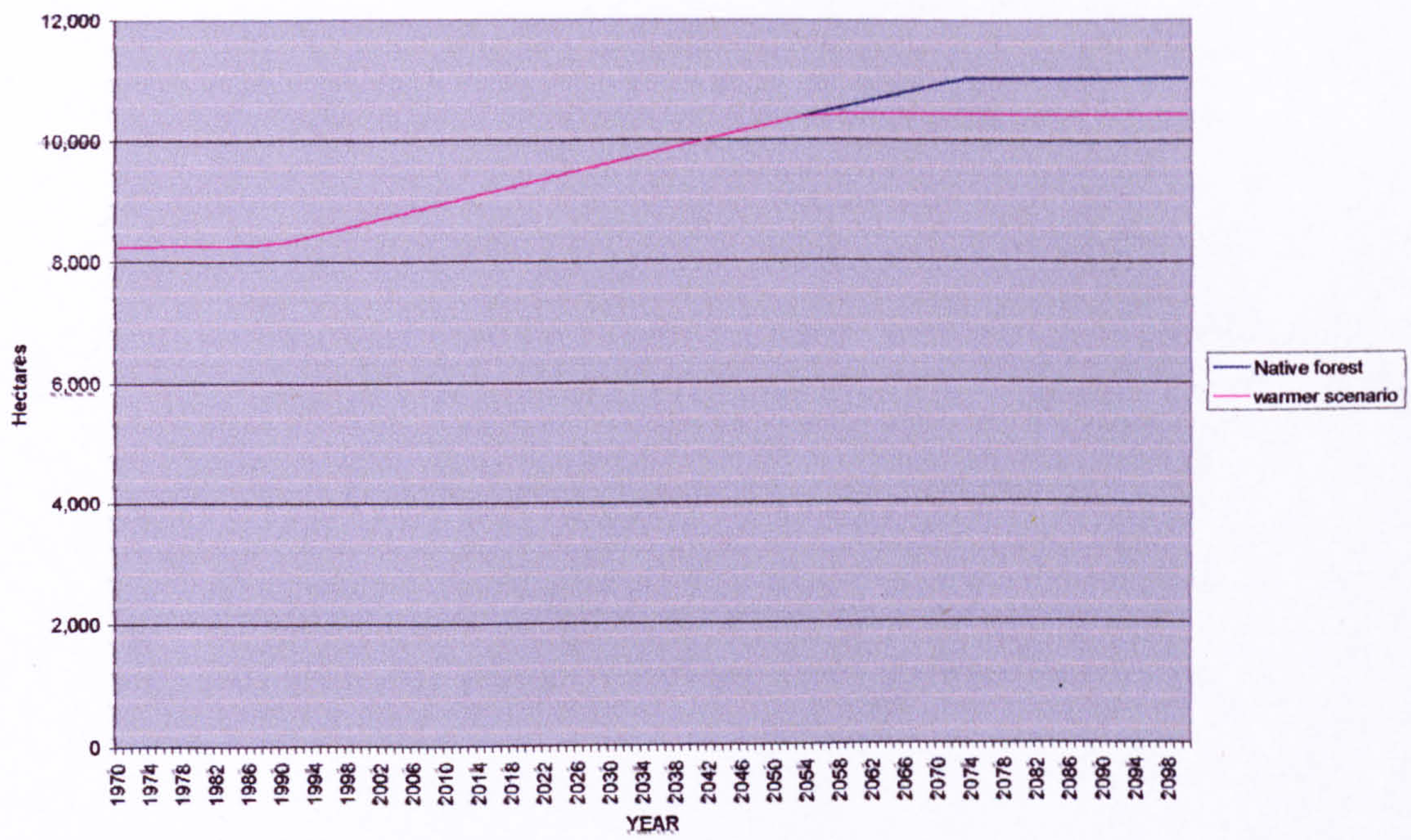


Figure 10.33 Area of broadleaved and native species, Fife.

10.6. Housing sector

Argyll has seen a growth in it's housing stock during a period of population decline. Stirling and Fife, however, have seen housing stocks increase in a manner which correlates with population increase. The difference between these is largely explained by reference to the number of houses in Argyll which are second homes or holiday lets.

In addition to housing the present and projected populations, there is the question of household size to be considered. Recent years have seen a steady decrease in the average household size, with far more people of all ages living alone, and a reduction in the number of households with children. This trend is set to continue, according to the Registrar General of Scotland (General Registrar of Scotland 2000) with a resultant increase in demand for housing even where the population remains constant or even falls.

The housing sector takes projected populations, projected mean household size and the existing and projected housing stock to see if there is likely to be a housing shortage in any of the regions. The accuracy of these forecasts has to be considered. Shortages are likely to alter the rate at which new homes are built, as the homeless would either stimulate the building of new homes by creating demand in the market, or would simply move out of the region to a location where housing was available. The shortage/surplus graph cannot be seen as a predictor of actual shortages, but rather as indicating the existence of potential shortages. The scale of this potential shortfall in housing provision differs from region to region, and, as such, the graphs are useful in that they indicate the regions in which housing action is most important.

Demand graphs indicate the rate at which new building should be undertaken, simply by combining the population projections with the household size forecasts. This is independent of any policy initiatives designed to alter the rate of new buildings, and simply gives a forecast of likely demand. Figure 10.34, Figure 10.35 and Figure 10.36 show the demand curves for the three regions. Only Argyll shows sensitivity to climatic factors, with the higher rate of change of temperatures inducing a greater demand for housing in this region. This occurs through the increase in labour demand leading to an increase in population.

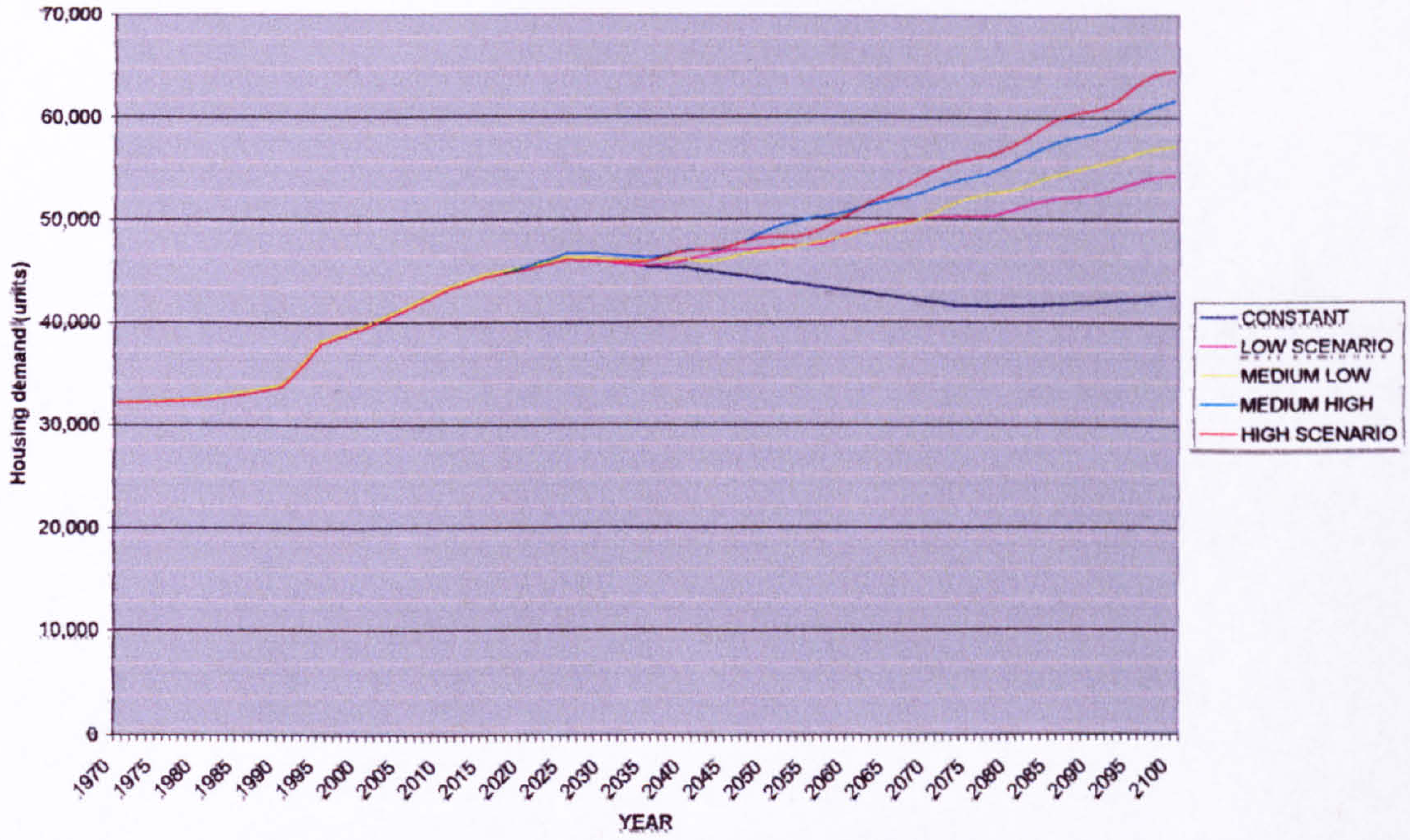


Figure 10.34 Projected housing demand, Argyll.

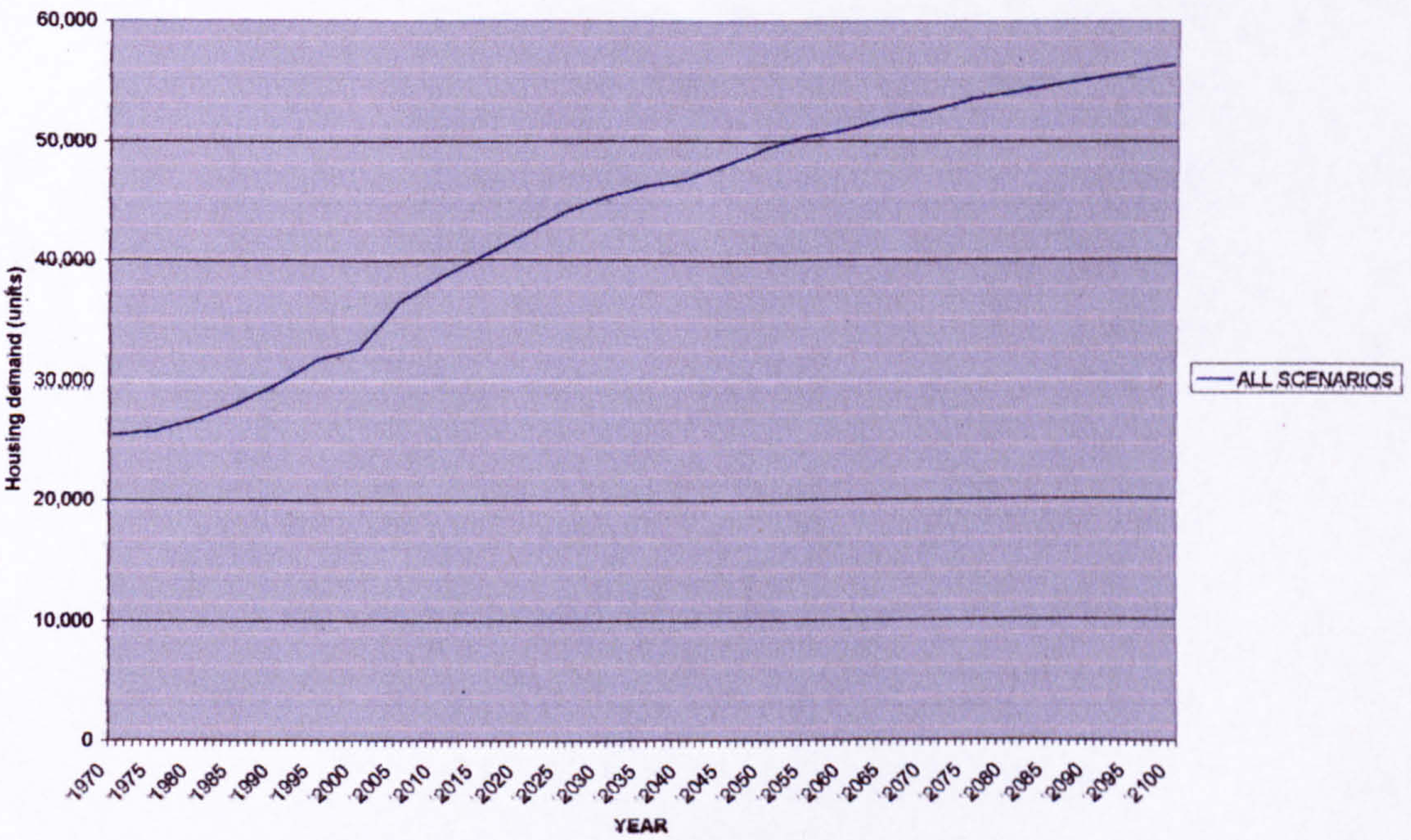


Figure 10.35 Projected housing demand, Stirling.

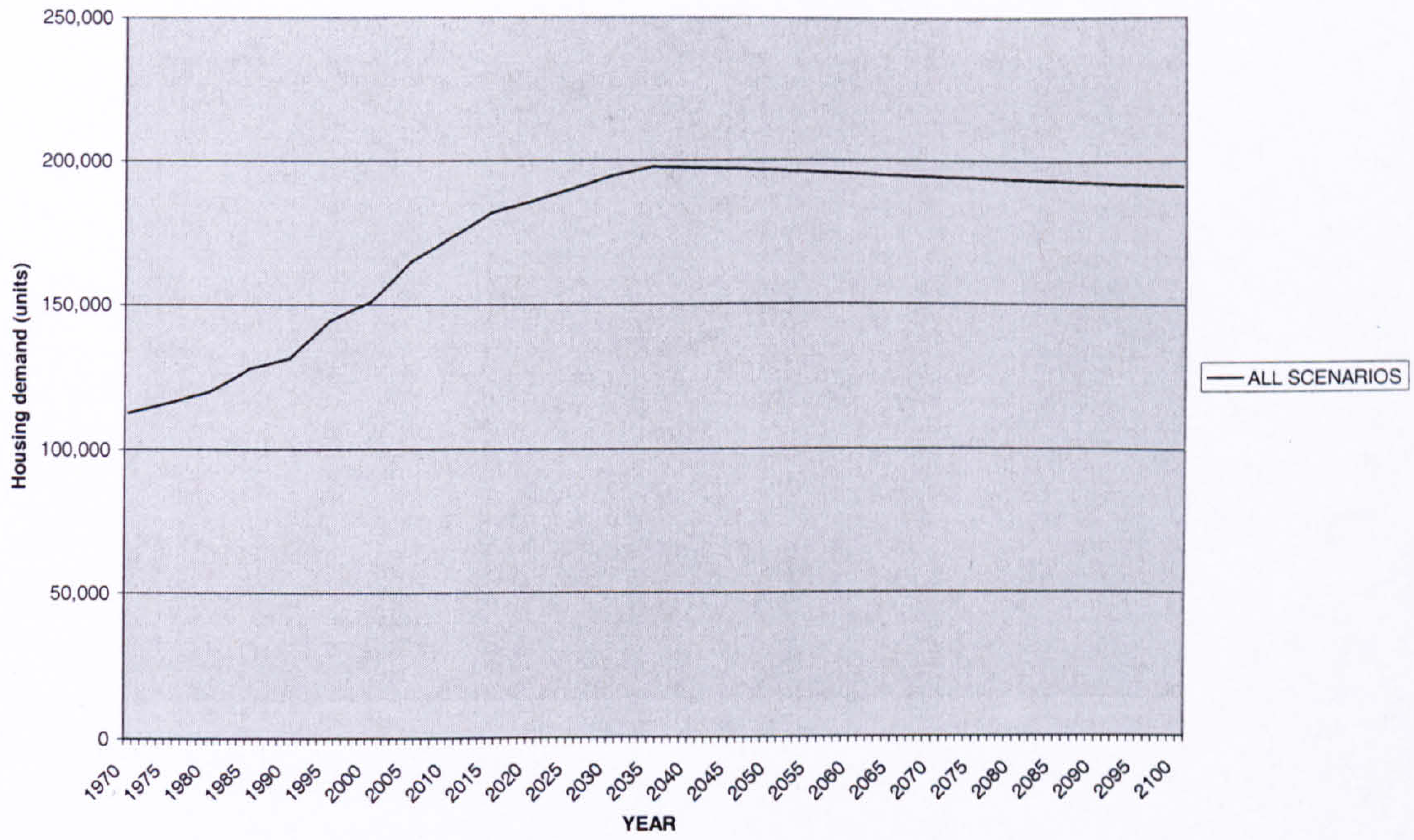


Figure 10.36 Projected housing demand, Fife.

Without climate change, the demand for housing in Argyll resembles that of Fife, with a gradual decline in the latter part of the century when the population is declining. With climate change scenarios, the demand in Argyll resembles that of Stirling where a steady increase due to a rising population, and smaller mean occupancy rates, leads to a rising demand throughout the century.

If present rates of building are continued, then the potential shortages of housing would be as indicated in Figure 10.34, Figure 10.35 and Figure 10.36. This, as mentioned above, simply highlights the regions in which the potential for housing shortages are greatest, and where long term planning of housing provision needs to be concentrated.

10.7. Population sector

This section investigates the effects that simulated temperature change has, through socio-economic feedback loops, on the projected populations of the three regions. In addition, it examines how these changes, driven by climate change, affect the population structure in terms of the different age groups used in the model. Perhaps the most significant result in this section is the different impact on population that climate change has on the different regions. Neither the population of Stirling or Fife are affected by the different climate change scenarios. In both cases, any increase in employment generated by the agricultural, forestry or tourist sectors is readily absorbed by the existing population, these sectors contributing slightly more than 10% of total employment in these two regions. Argyll on the other hand shows a sensitivity to climate change, and the more extreme the climate change scenario, the greater is the impact on the population dynamics. This is due to a far higher percentage (~25%) of Argyll's working population being employed in the climate sensitive sectors. As illustrated in the employment sector, the simulated demand for labour outstrips supply towards the end of this century. The resultant in-migration, which is assumed in the model, accounts for the changes to the population of Argyll.

Projected populations for Stirling and Fife are independent of the climate scenario and are therefore presented as single line graphs. For Argyll, the contrast between a constant temperature regime and the four climate change scenarios is illustrated on each of the figures relating to that region.

10.7.1. Results for Argyll

Figure 10.37, Figure 10.38 and Figure 10.39 show the projected populations for the young, middle and older age cohorts, with lines representing the impacts of the different climate change scenarios. In addition, there is the figure representing the total population (Figure 10.40).

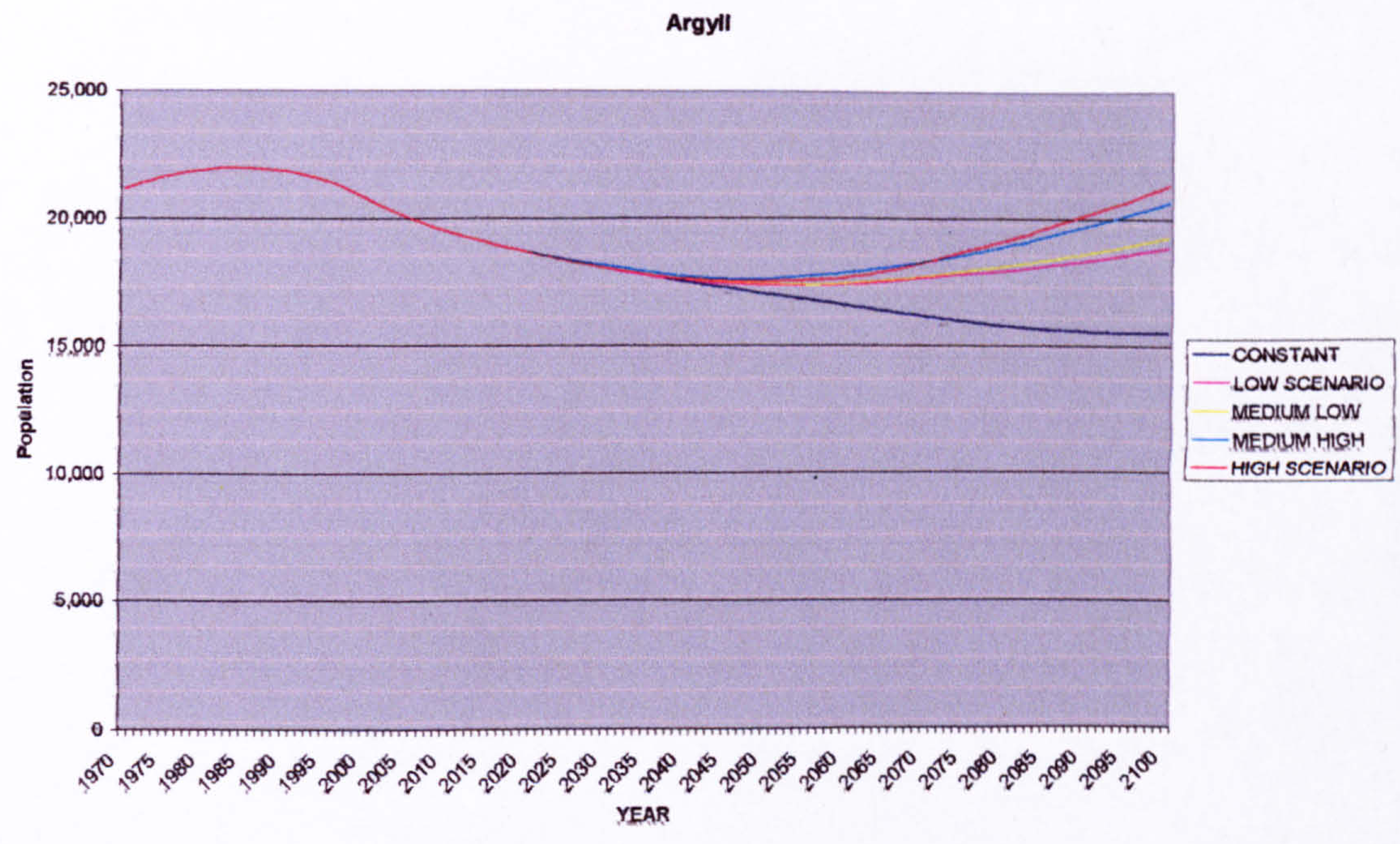


Figure 10.37 Projected numbers of Young age group, Argyll.

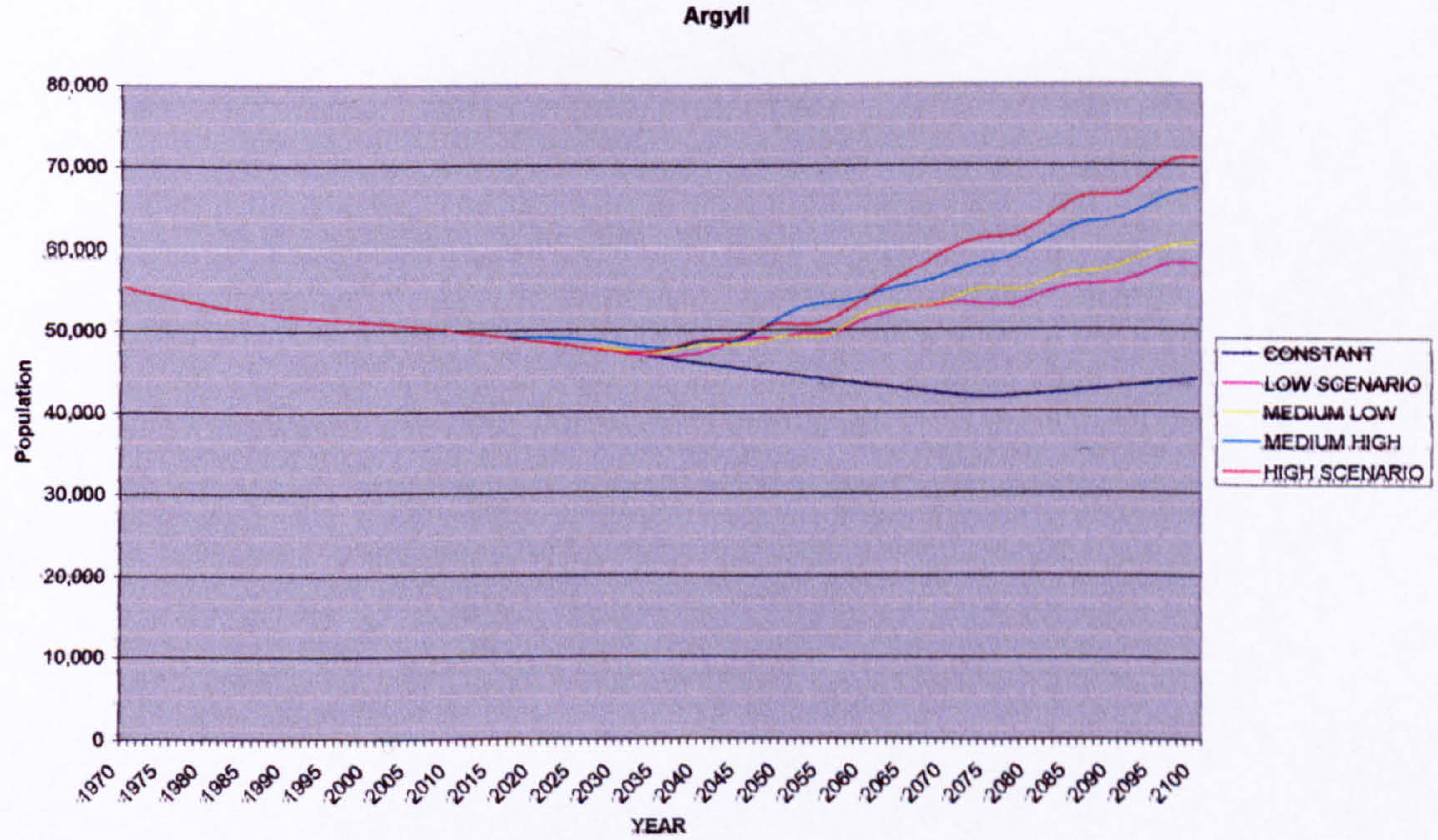


Figure 10.38 Projected numbers of middle age group, Argyll

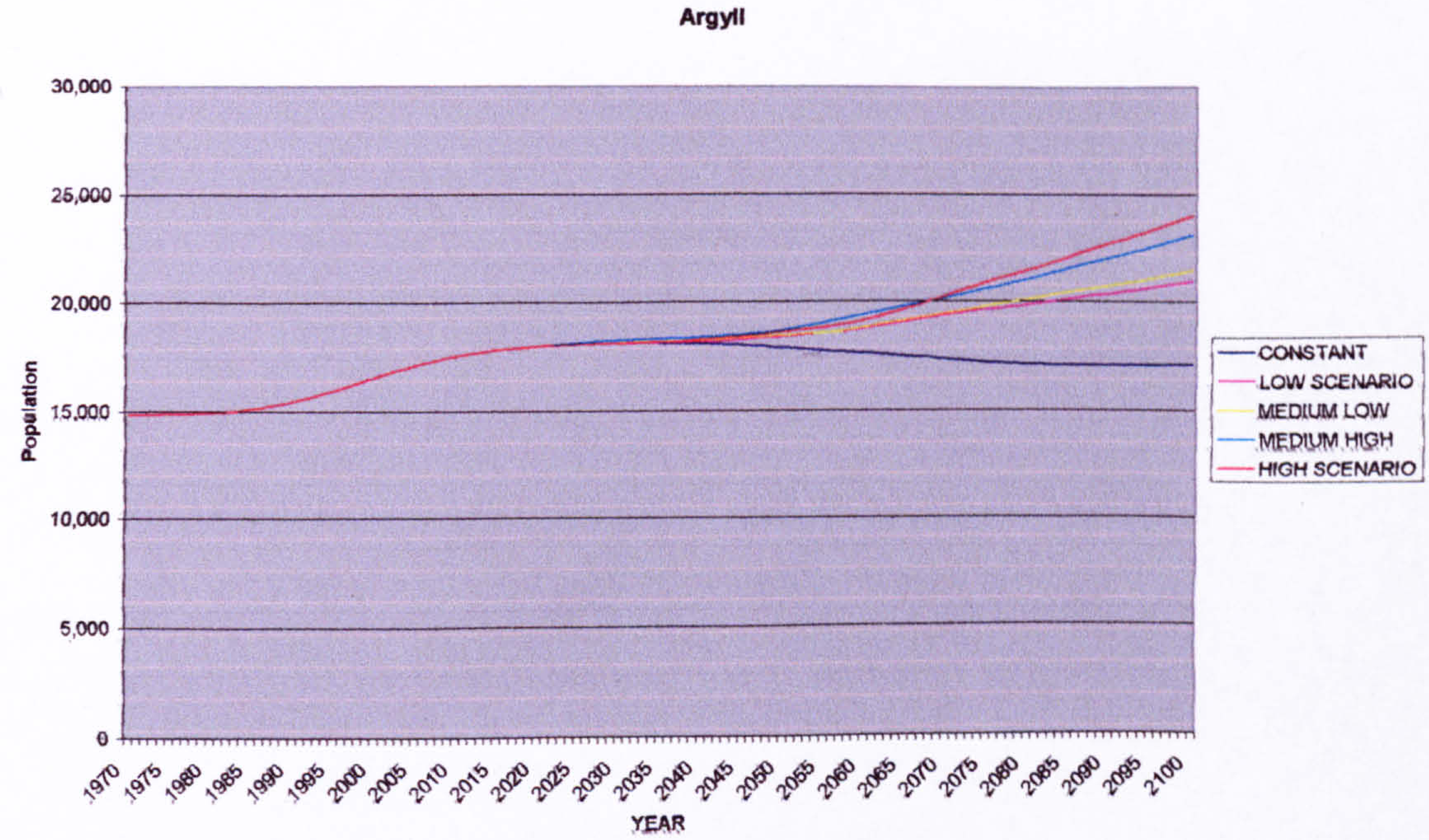


Figure 10.39 Projected numbers of older age group, Argyll.

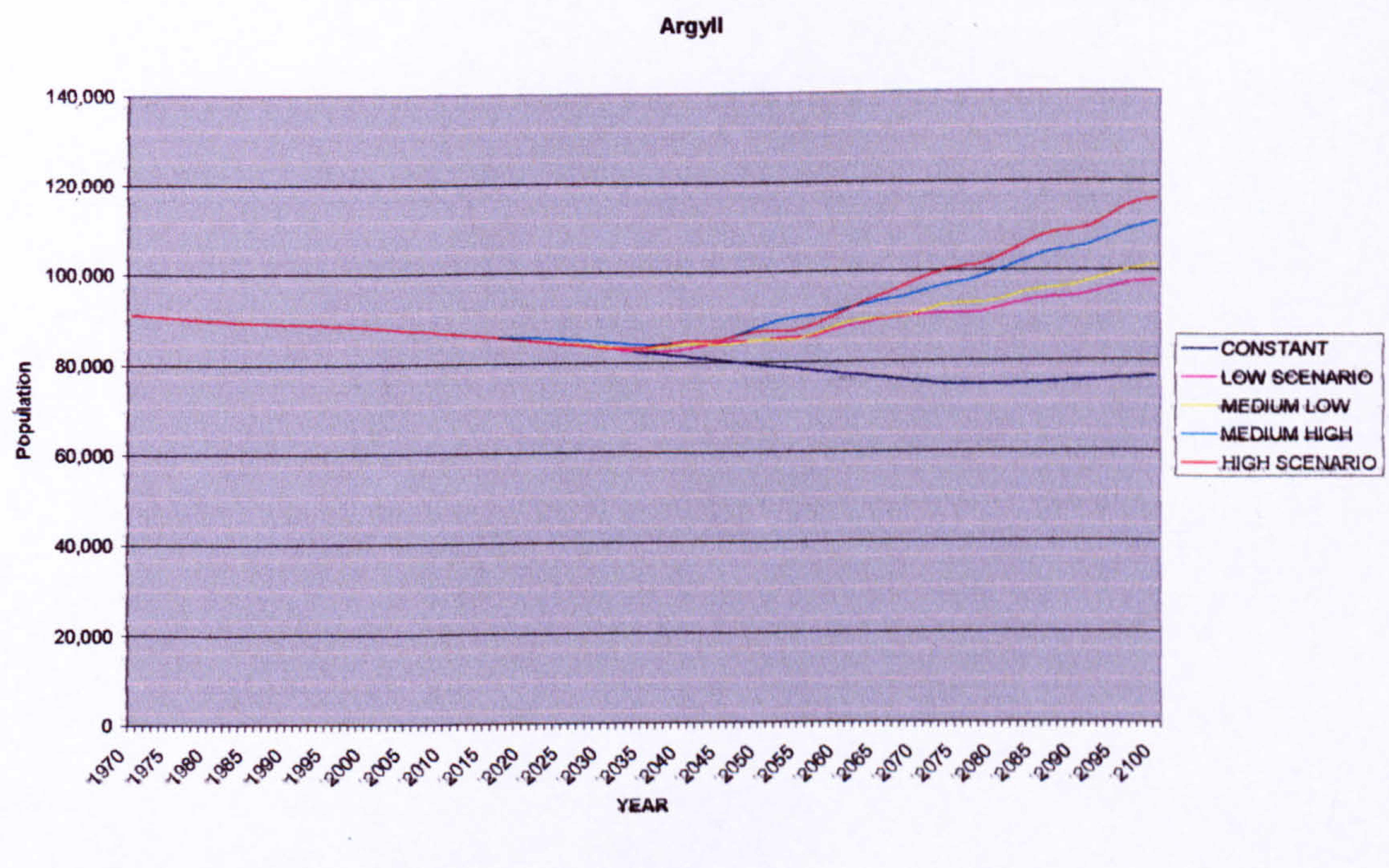


Figure 10.40 Projected numbers for total population, Argyll.

In each case, it can be seen that the projected decline in population, which is evident for all age groups and for the total population, is reversed under the conditions of climate change, with the more extreme climate change scenarios generating a greater increase in population.

One effect of this increase in population is to alter the percentage of the population above retirement age. The injection of immigrants of working (and reproductive) age changes the percentage of the population which is above 65. Figure 10.41 illustrates this effect by showing the percentage of Argyll's population which is over 65 under the different climate change scenarios.

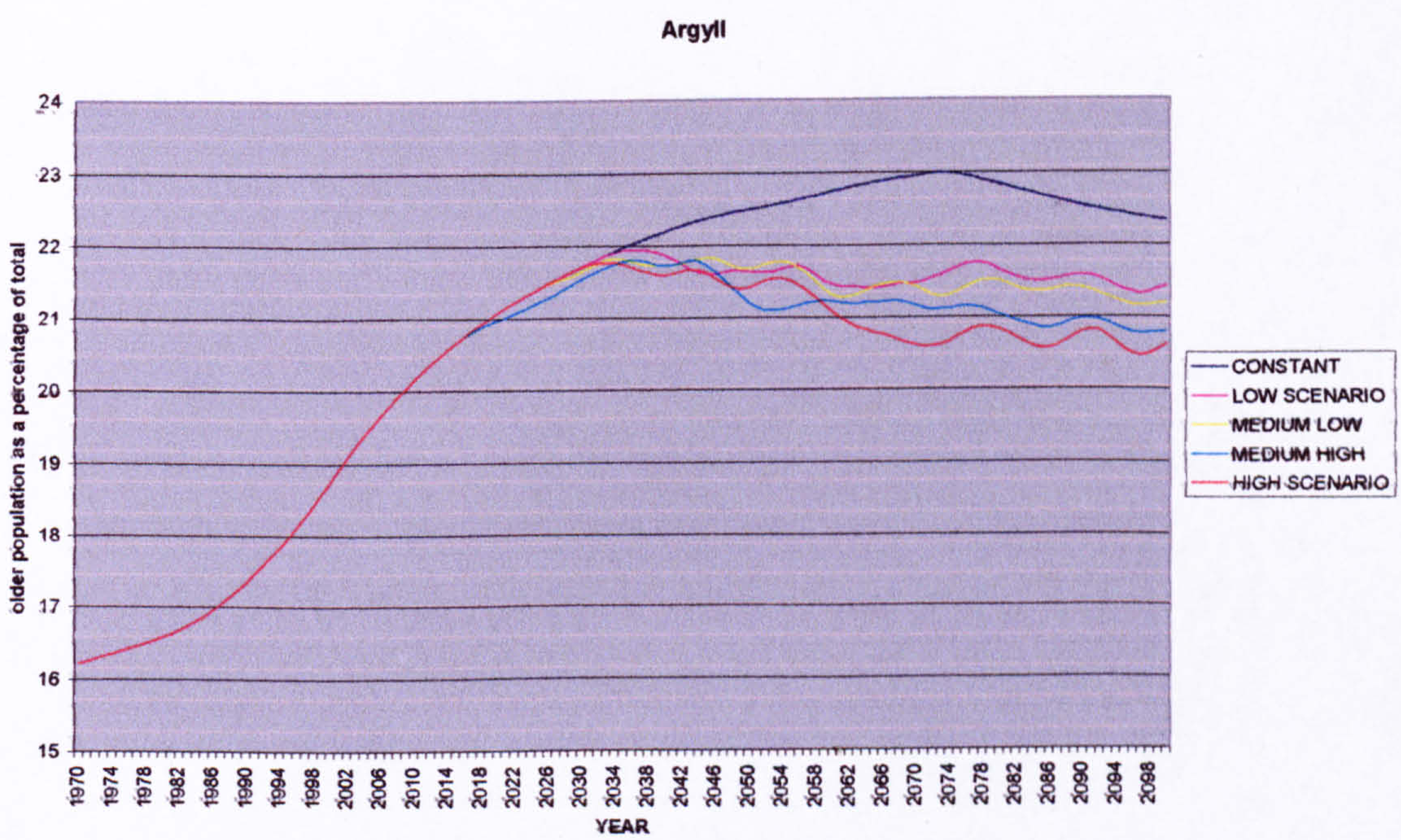


Figure 10.41 Older as percentage of total population, Argyll.

10.7.2. Results for Stirling

The results for Stirling (Figure 10.42, Figure 10.43, Figure 10.44 and Figure 10.45) show no difference between the various scenarios. Consequently, the following figures are much simpler than those for Argyll. All age cohorts eventually increase in size as a result of the marginally higher birth rate projected for this region.

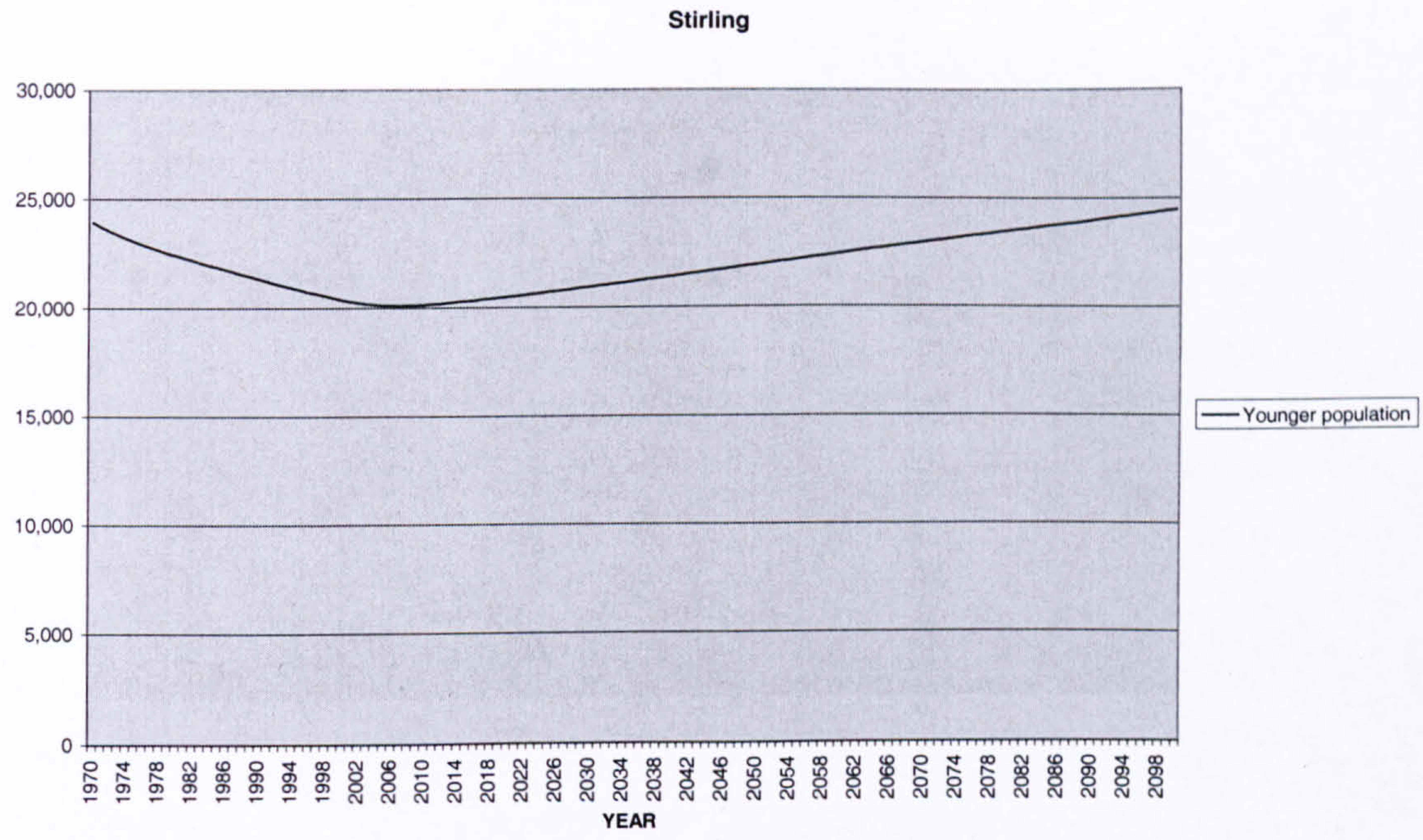


Figure 10.42 Projected numbers of young age group, Stirling

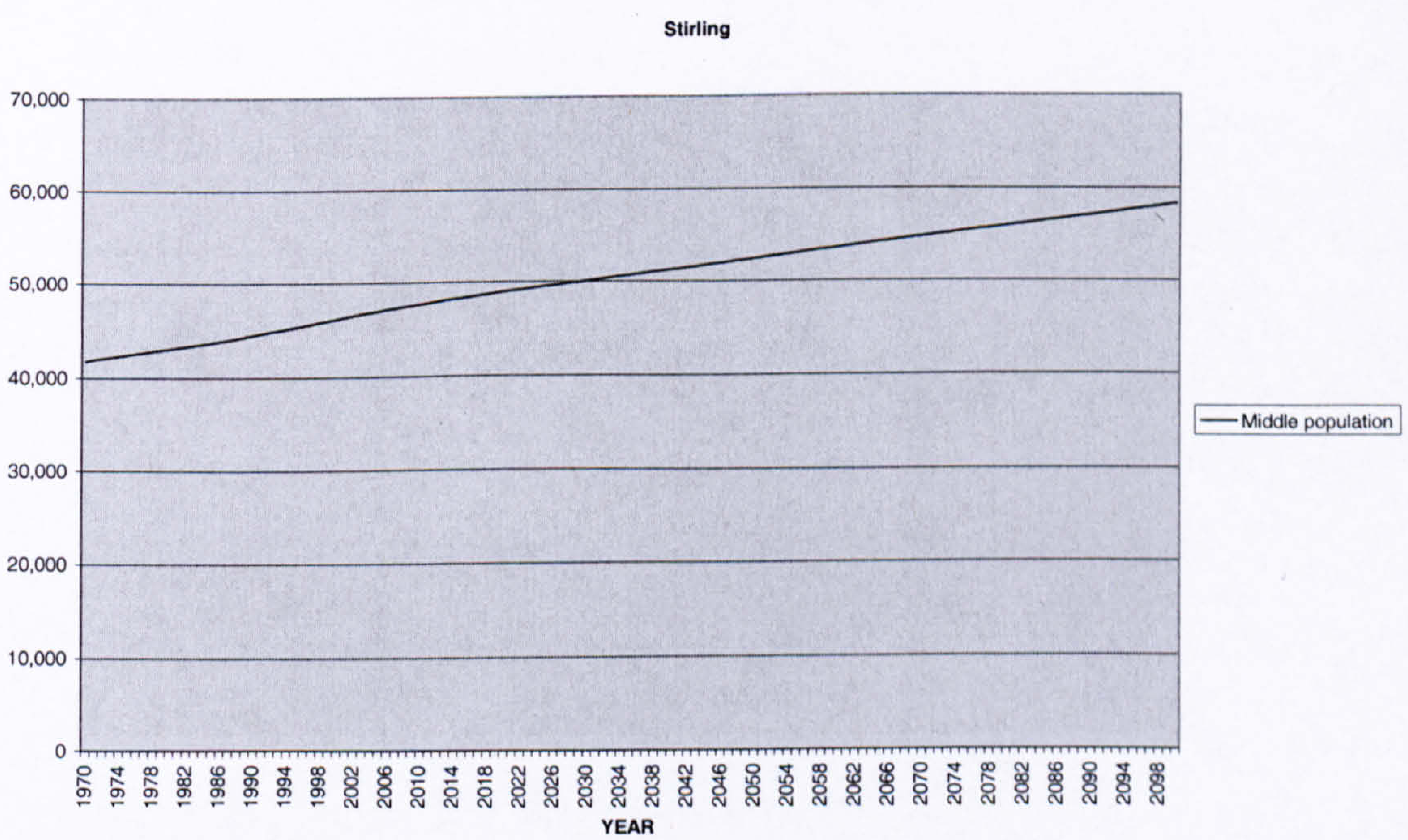


Figure 10.43 Projected numbers of middle age group, Stirling.

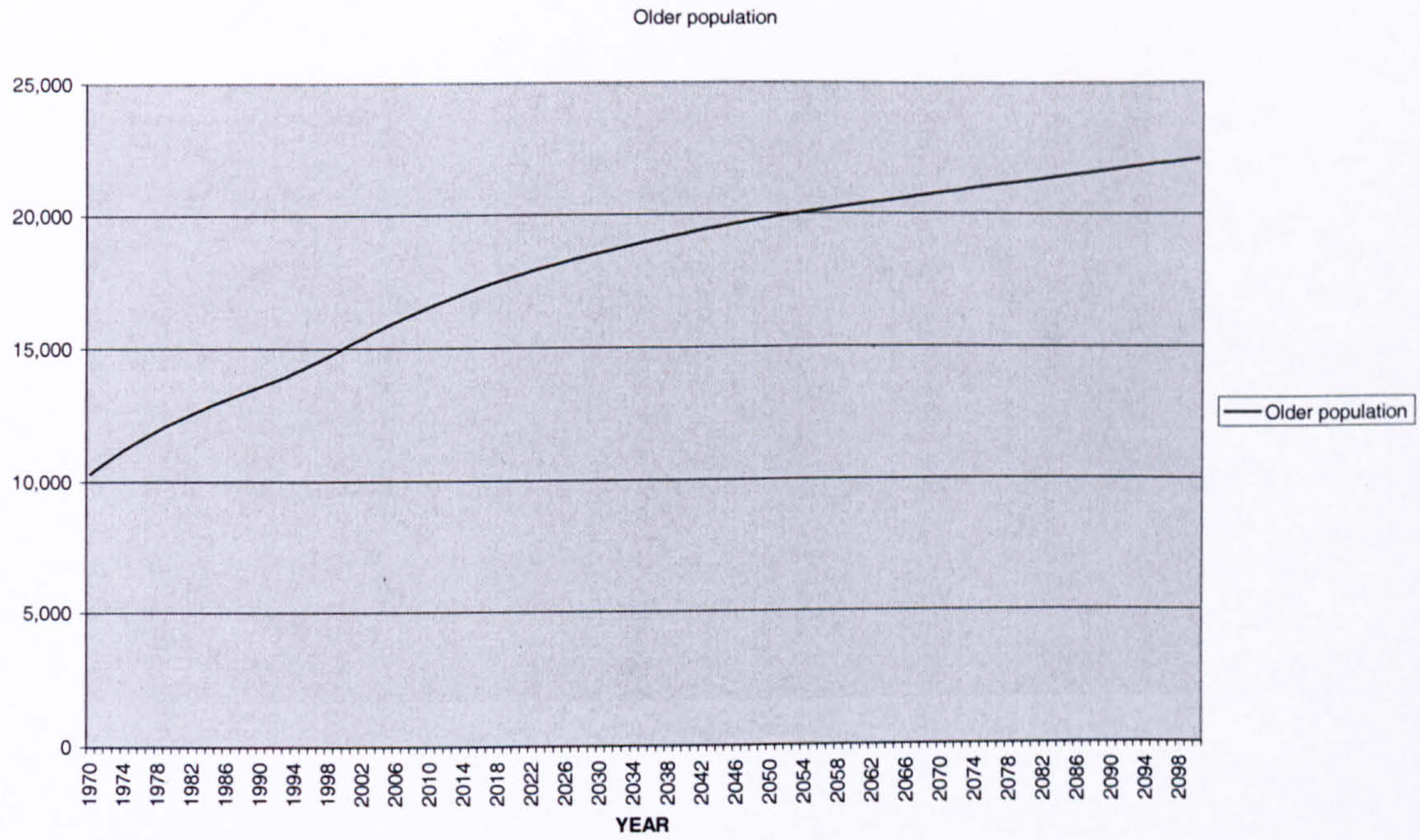


Figure 10.44 Projected numbers of older age group, Stirling.

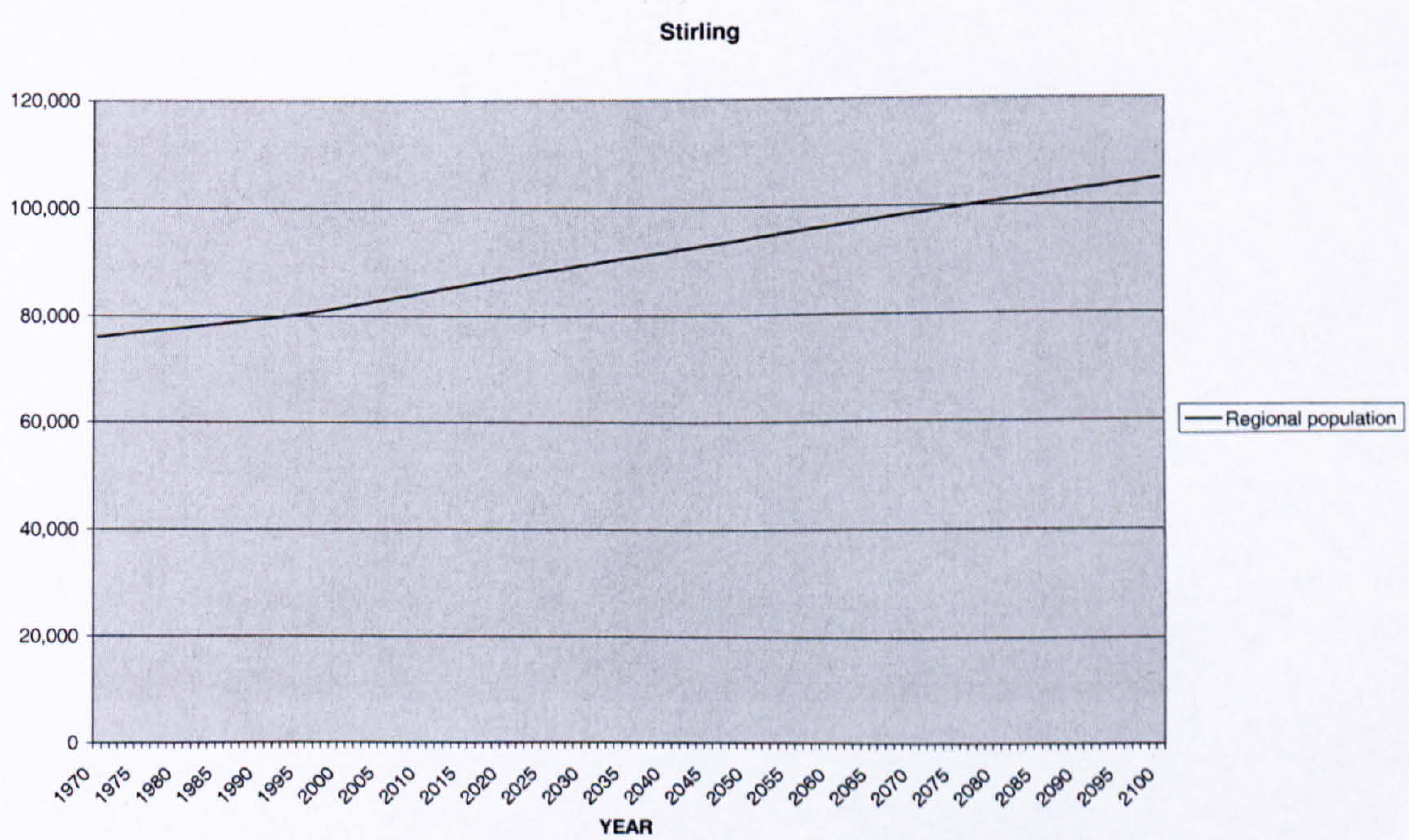


Figure 10.45 Projected numbers for total population, Stirling.

The relative percentages of the total population for each of the age groups is illustrated below in Figure 10.46, with the young group remaining more numerous than the older age group although the gap narrows through time.

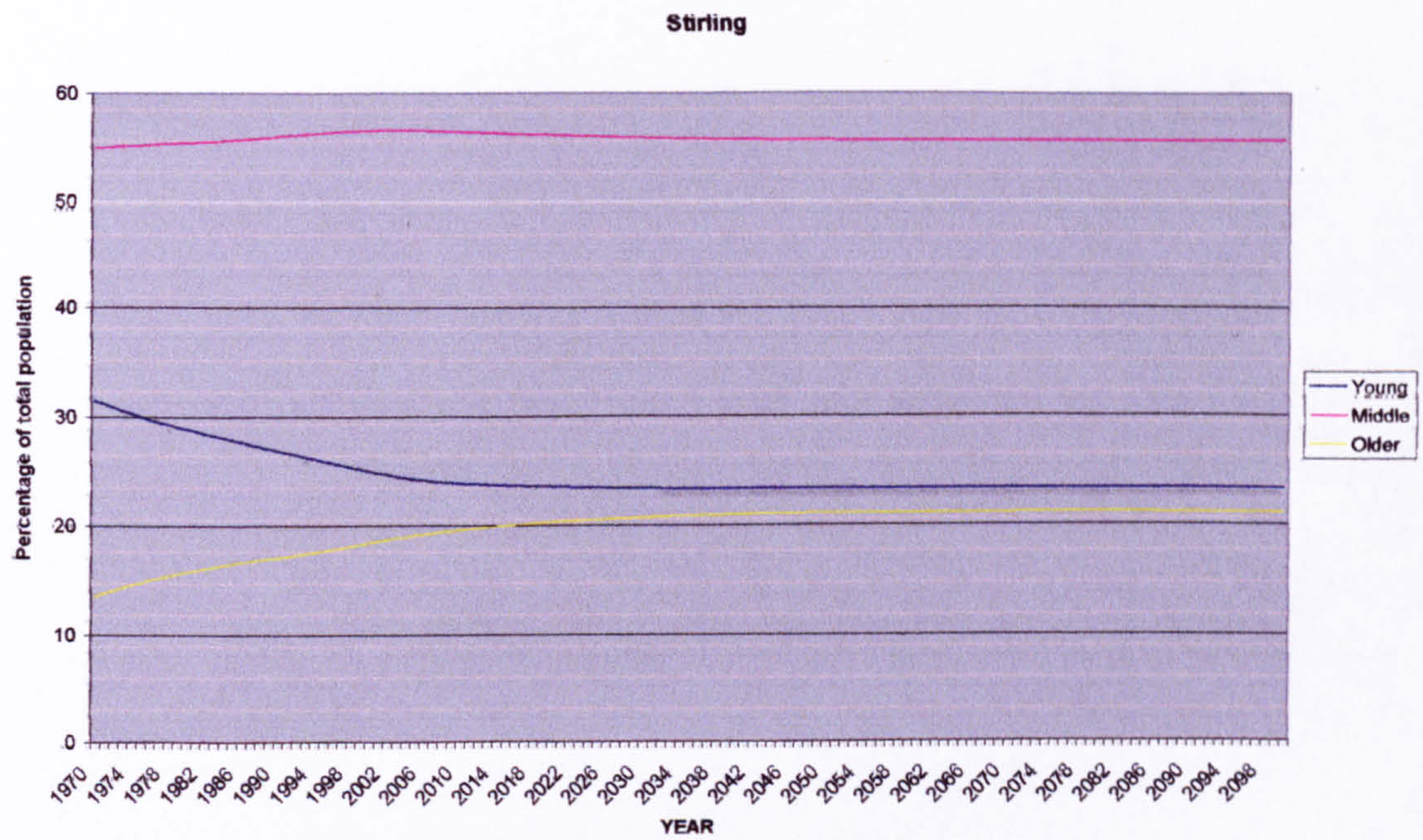


Figure 10.46 Relative percentages of total population, Stirling.

10.7.3. Results for Fife

The lower birth rate projected for Fife results in a declining overall population, with only the older age group remaining relatively constant throughout the next century. The results are illustrated in Figure 10.47, Figure 10.48, Figure 10.49 and Figure 10.50. The relative percentages of the different age groups is illustrated in Figure 10.51.

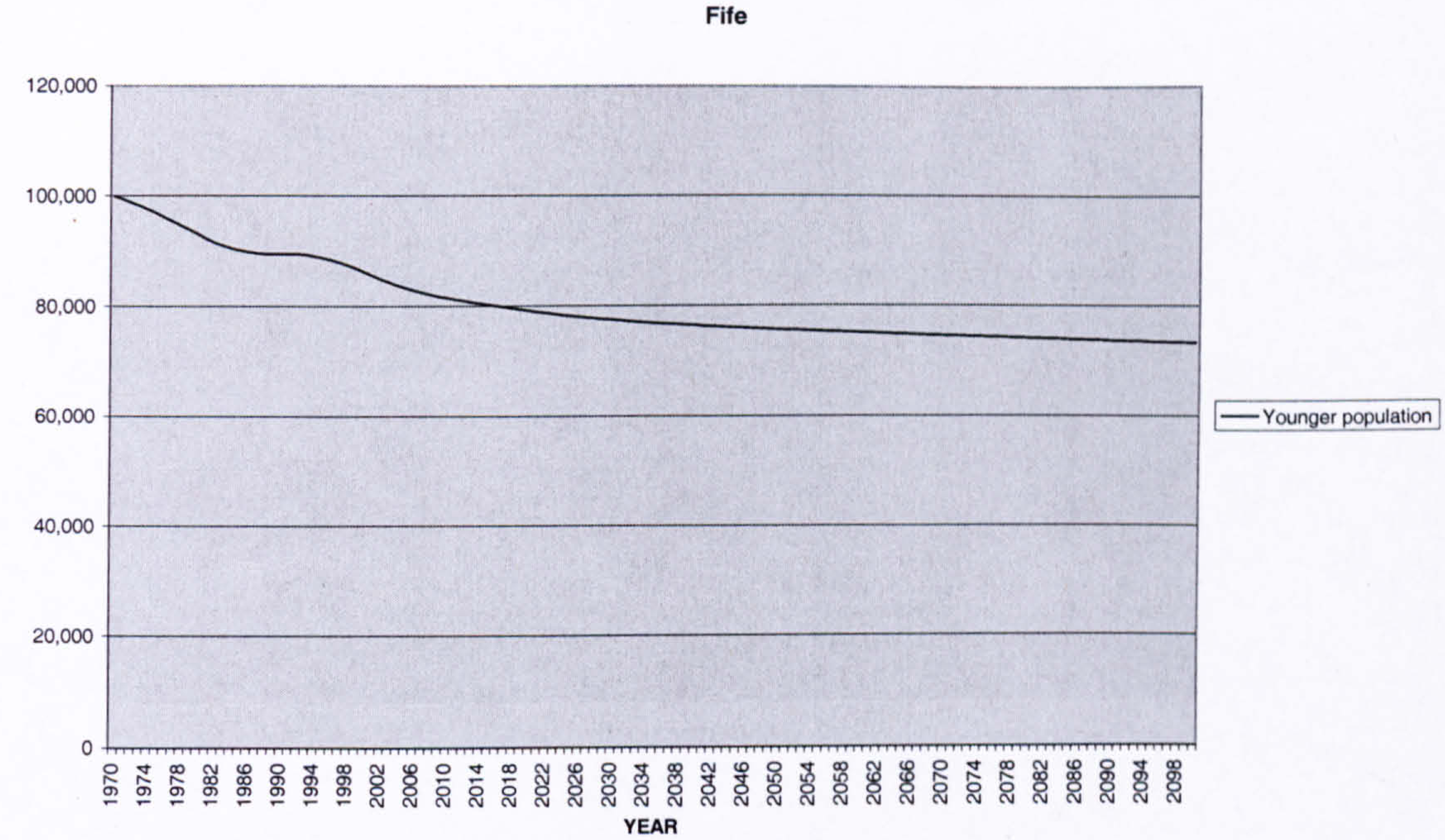


Figure 10.47 Number of young age group, Fife.

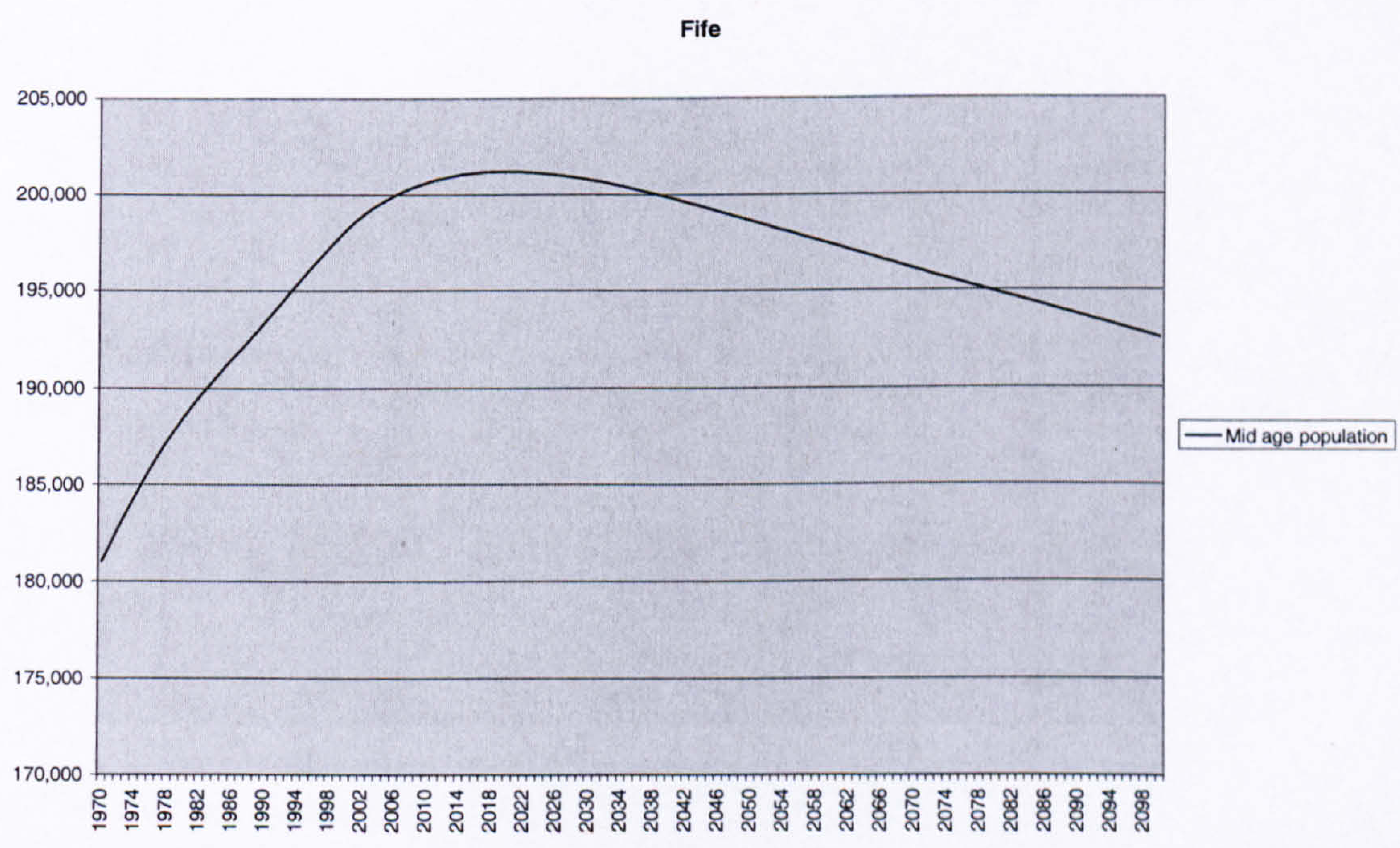


Figure 10.48 Numbers of Middle age group, Fife.

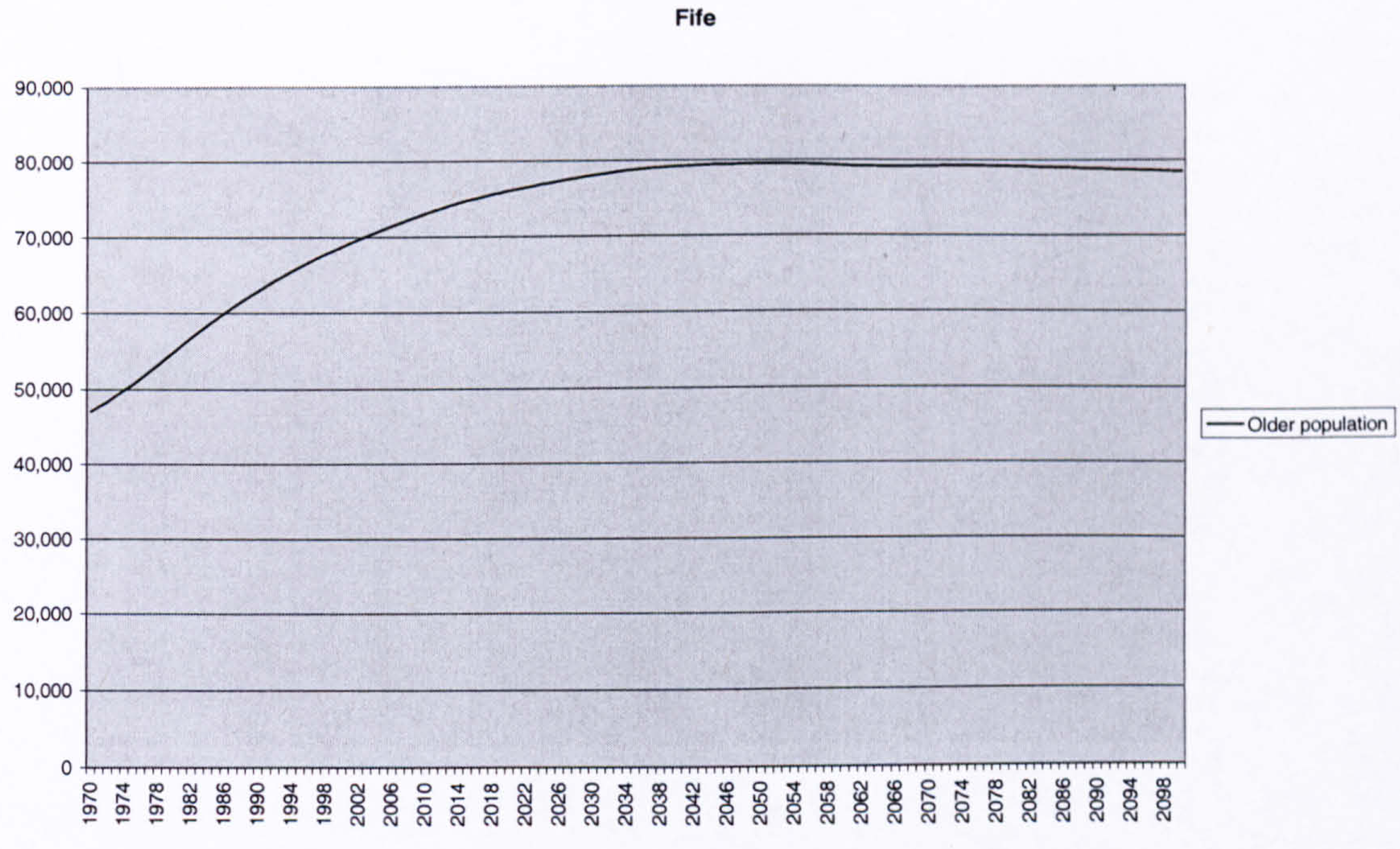


Figure 10.49 Numbers of Older age group, Fife.

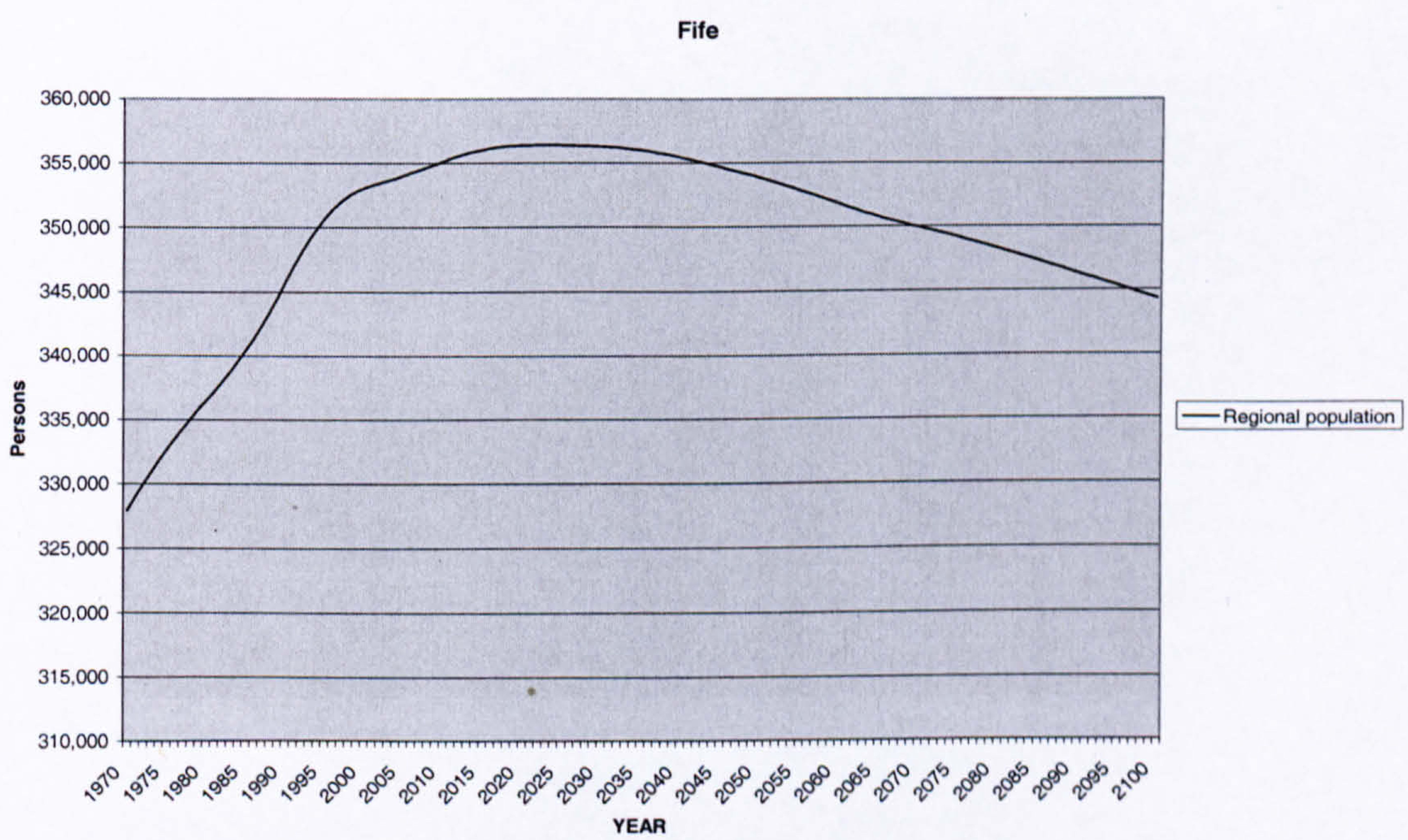


Figure 10.50 Total population , Fife.

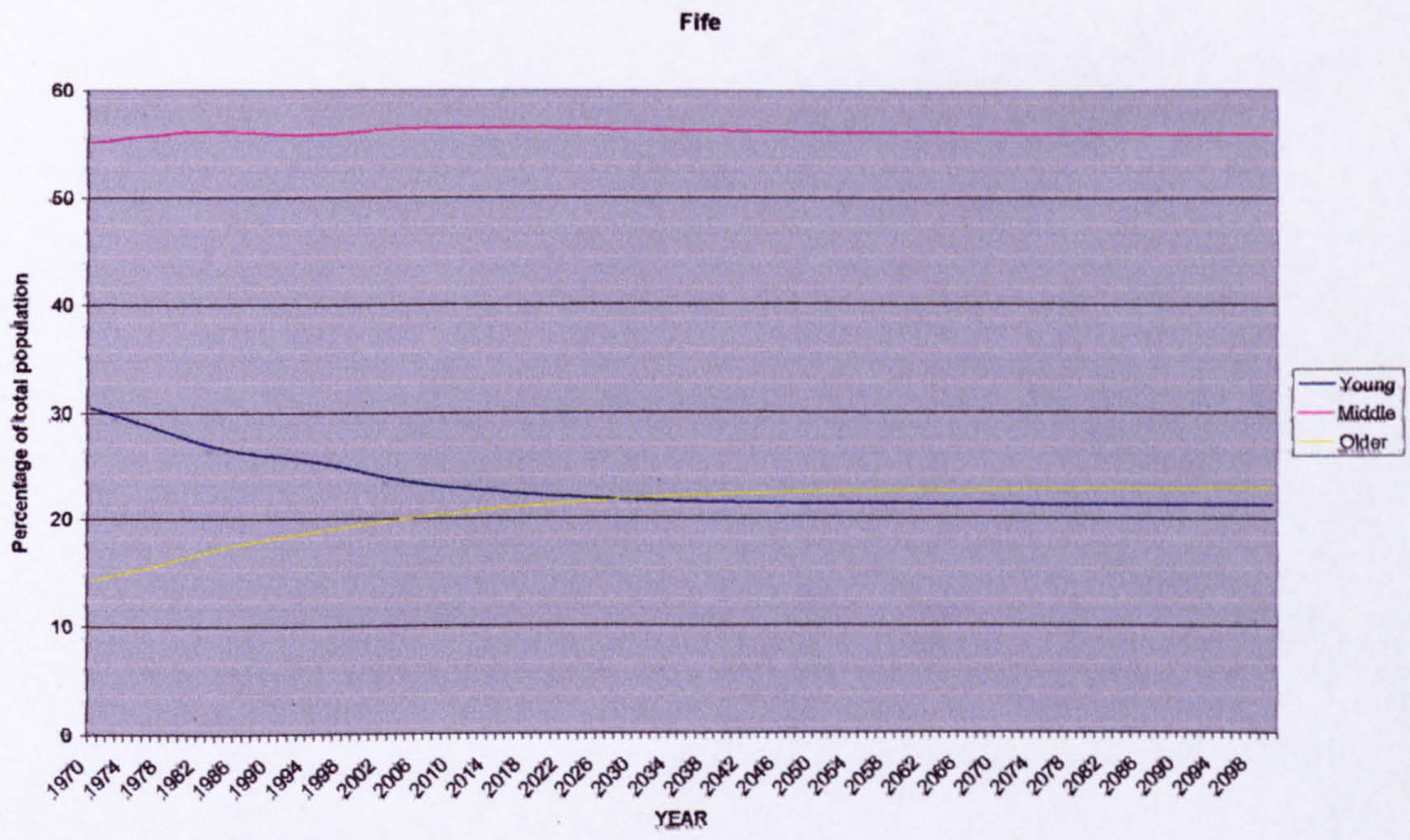


Figure 10.51 Relative percentages of total population, Fife.

In Fife, the projection is for the number of individuals in the older age group to exceed the number in the young age group by the middle of this century and remain so until the end of the simulation. The percentage of the population of working age remains fairly constant throughout.

Chapter 11 Discussion

11.1. Climate section

The analysis of the empirical data reveals evidence of changes occurring in the climate of central Scotland. There is evidence of increased temperatures, mainly in the late winter and early spring, and regional variations in the rate of increase. In addition, there is evidence of increased precipitation, largely in the winter months, and evidence of an increase in the intensity of extreme precipitation. Changes in the pattern of rainfall seem to be confined to the west of the country.

The main factors implicated in these trends are variability of atmospheric circulation patterns and increasing levels of CO_2 and other greenhouse gasses in the atmosphere. Both of these can be measured directly and a time series of values can be produced. It is logical to use these measured variables in analysis of the global and local climate. Such analyses make one important assumption, namely, that solar output varies so little that it can be reasonably assumed to be constant. However, if solar output does vary considerably on different time scales, then this would add a new dimension to the modelling of climate. The major problem with respect to this is that no reliable measurements of solar output have been made on a long time scale (Barry and Phillips 2003). The inclusion of variability in the solar output in the model, which uses a formula derived from empirical observations, generates fluctuations in the simulated temperature. Longer term variability on the scale of decades or centuries could have a major impact on the global climate, and on the modelling of global climate, depending on the scale of these fluctuations. Earth based observations are subject to interference from the atmosphere, so satellites have been equipped with instruments designed to make accurate measurements free from this interference. This has provided a relatively short time series of observations, with the added complication that different satellite based devices record different values for the incoming solar radiation. Reading from five such platforms during 2001-2002 differed by approximately 1.5wm^{-2}, which amounts to almost 0.5 of 1% of solar output, or almost half of the variability assumed to occur during a typical 11 year sunspot cycle. There have been a number of studies of the influence of solar variability on a range of climatic variables, but all suffer from a lack of accurate long-term data series. These studies have used various methods to provide a measure of solar activity, including numbers of sunspots, the length of solar cycles, the ratio of sunspot umbra to penumbra, variations in the equatorial diameter of the sun and disturbances to the sun's rotation caused by gravitational effects within the solar system. Unreliable data or inappropriate methodology has seen many of these studies strongly criticised (for example see Laut (Laut 2003)). There do, however, remain some intriguing studies, which point to a clear influence of variability in solar activity on meteorological parameters, and renewed interest in the topic has developed. These studies tend not to attempt to provide an alternative explanation to the enhanced greenhouse effect, but seek to supplement and add precision to our understanding of climatic variability. In addition, such studies are important as a means of allowing more detailed climate models to be developed (Tsiropoula 2003). The inclusion in the simple climate model of a periodic variation in the flow of energy from the sun is designed to give recognition to this as an important feature in the short term modelling of climate. Longer term cycles, such as those which have been proposed with periods of 80-90 years (Gleissberg cycle) or 180-200 years (de Vries cycle), are not included, but could be seen as an important aspect of climate models. Understanding the role of solar variability in the global and local climate would allow more accurate models to be constructed. Solar induced climate change could then be quantified and the true impact of anthropogenic factors more clearly understood (Hoyt and Shatten 1997).

There is also some debate in the literature as to whether the quasi periodic variability in the different circulation patterns are caused by factors internal or external to the climate system. The long term trends in the indices for patterns such as the NAO or EAJ have been presented as variability resulting from the internal chaotic nature of the troposphere (Visbeck et al. 2001). This view has been prevalent amongst climatologists in the past, and certainly there appear to be no connections between the various patterns themselves. Examining the data using for correlation revealed no significant relationships between any of the circulation patterns described in Chapter 2 and used for analysis in Chapter 5.

Within the climate sector of the model, the indices of circulation patterns are represented by randomly generated numbers with mean zero and standard deviation of one. This, in effect, accepts that there is no method by which forecasts or predictions of the future nature of these patterns can be made. Since these circulation patterns have a definite and marked effect on the weather, and can become locked into a particular phase for years or even decades and hence affect the climate of a region, understanding their dynamics would be a valuable addition to climate models. At present the Hadley centre HAD2 AGCM, when run forward under conditions of increased atmospheric greenhouse gasses, suggests that, with global warming, the North Atlantic Oscillation will become locked into a strongly positive phase. This is a common feature of many of the AGCMs currently in use (Visbeck et al. 2001).

Other mechanisms which influence atmospheric circulation include the variability of sea surface temperatures and the strength of the stratospheric polar vortex. Both these phenomena have been linked to variability in solar output (Tsiropoula 2003).

At present there is no consensus as to the mechanisms driving the variations in circulation patterns, which means that no predictive model can be developed, and a great deal of uncertainty surrounds future patterns of atmospheric circulation. Given the importance of especially the NAO to the climate of North West Europe, and Scotland in particular, this leaves some uncertainty as to the nature of a changing climate under greenhouse gas forcing. The implications for any modelling exercise of a resolution of this debate would be significant.

Measurements which have indicated a decline in the deep water formation under Arctic ice, and a consequent weakening of the North Atlantic Drift give rise for concern regarding a collapse of this system (Houghton 1996). In a world with rising temperatures the collapse of the Atlantic conveyor system could lead to Western Europe being plunged into a period of cool summers and very cold winters. This is seen as a high impact, low probability event, but as such the risk associated cannot be discounted. Such events would reverse many of the trends identified in this study, and would have impacts which contrast with the effects of rising mean surface temperature.

11.2. Modelling Section

Building a model of some real world phenomenon necessarily entails a selective procedure, by which those factors considered relevant to the problem being addressed are included and the irrelevant (or less relevant) are excluded. Any model is therefore built using certain assumptions and cannot be presented as recreating reality. It simply examines a subset of the factors which combine to generate the reality which is being studied.

In this section each of the sectors is critically examined with a view to identifying its strengths and weaknesses, along with an appraisal of the results presented in Chapter 10. The implications are discussed for each of the sectors and their relevance to the decision making process assessed. A final section discusses the overall picture of socio-economic change in Scotland resulting from climate change.

11.2.1. Climate sector

The climate sector is based on a thermodynamically sound model of the planet Earth. Certain simplifications have been made in order to create a model which retains the thermodynamic structure, but which runs with limited computing power and time.

The definition of the planet's atmosphere as a single stock of energy with inflows and outflows is s convenient simplification, based on the fact that the vast majority of the mass of the atmosphere is found in the troposphere which extends to approximately 10,000 metres above the Earth's surface. The turbulence within the troposphere is such that there is rapid mixing of gases. Temperatures are not evened out, and a strong temperature gradient exists. The surface temperature is not the mean temperature of the atmosphere. It is the maximum obtained within the whole system. Thus the model is representing a structure (the atmosphere) which is complex, by use of a single homogenous stock of energy. Similarly there is no differentiation between land and ocean surface in the stock representing the Earth. The contrast between the heat capacity of the oceans and of land masses is not taken into account in the basic model, which relies on an average figure for the planet as a whole.

Introducing a more complex atmosphere and a planet surface which has continents and oceans with currents, would present a more accurate representation of the Earth, but the overall exchanges of energy would remain the same. The introduced complexities would be to the internal workings of the two stocks, the net inflows and outflows would remain the same. The heat capacity of the oceans surrounding Scotland is simulated by use of an additional input of energy to the local system, in the form of "ocean warmth".

The treatment of albedo as a constant is a simplification. Climate change is likely to alter the reflectance of the earth's surface by reducing the extent of the cryosphere, and altering the distribution of temperature and moisture, and hence plant growth, across the continents. Changing patterns of land use have an impact on albedo, for example, the clearance of large areas of tropical forest. Reflectance could also be altered by a changing pattern of cloud cover resulting from changing temperatures and atmospheric circulation.

All of these factors can result in positive or negative feedback loops. The combined effect could be dramatic, in which case the model is deficient, or they could cancel out, in which case the model is accurate. The precise nature of the response of albedo to climate change is not known, and is still a matter of debate. Should clear evidence emerge, especially with respect to the role of cloud cover in the dynamics of climate change, then this could be incorporated into the model at a later date.

The broad agreement between the simple model and the output from the Hadley Centre would suggest that the inclusion of additional feedback loops has a minor effect on the overall functioning of the model, the trapping of heat by the CO_2 enriched atmosphere being by far the most significant driver for climate change.

The output from the climate model has been compared to the empirical trends and the output from the Hadley Centre UKCIP02 model. There is some broad agreements between them, and some differences. The reason for undertaking this comparison was not to verify the model. The simulation of future climates cannot be treated as being correct or otherwise. It was to illustrate that models using the same underlying principles based on our scientific understanding of the climate system produce similar results. The degree of complexity may vary, but there exists a broad agreement in the future trends.

11.2.2. Population sector

At one extreme of simplicity, the entire population could be represented by a single stock, with births and migration flowing in and deaths flowing out. At the other extreme, age groups based on a single year could be constructed, with the surviving total transferring on one stage with each simulated year. The former has the advantage of simplicity and readily available data for calibration. The latter would have the advantage of having great detail and could track the effect of varying birth-rates and mortality through the entire system. This would be complex to construct and would require data which is not readily available.

To generate a population model which could be calibrated against real data, but which was detailed enough to provide more than just a simulation of the total population, a compromise was struck between lack of detail and lack of data. Splitting the population into 3 age bands means that the changing scale of the needs of the young, (nurseries, education, and specific health care) the elderly, (housing, home helps, specific health care) and the rest of the population can be assessed throughout the length of the simulation.

This sector was shown to be sensitive to changes in the birth rate, GROS provides future projections for this until around 2016, and this has been incorporated and the trend continued for the length of the simulation. With a birth rate below a certain level the population goes into decline, but, more importantly, the decline is most noticeable at the lower end of the age structure. This means that if the birth rate picks up in subsequent years, there are fewer individuals of reproductive age in the population to generate this increase. The longer the period before an increase in birth rate, then the bigger the change in individual lifestyles that is required in order to make any impact on total population. This would require younger individuals to have larger families than has been customary for some time.

With a lower birth rate the population would decline over time, eventually to stabilise at some new lower level. For the period of decline there would be an increase in the proportion of elderly people who tend to make greater demands on a range of social and health services than younger people do. The declining labour supply could possibly be insufficient to meet the needs of this ageing population as well as continue with the wealth generating activities in a region.

The model indicates that Argyll is likely to require net in-migration to avoid an overall labour shortage during the next century. In Fife the declining population is still able to absorb new jobs in growth areas, but this shift to an ageing population could mean the emergence of skills shortages. Long-term strategies are required to deal with problems associated with changes to the structure of the population, and if, as the model suggests, climate change adds to these problems, then this would have to be included in these strategies.

11.2.3. Land use sector

The land use sector has five stocks, urban, crops and grass, rough grazing, plantation forestry and native/broadleaved forestry. This classification accounts for the majority of the land in use but excludes several other minor use categories. Perhaps the most extensive of the other types of land use would be recreational, golf courses and shooting estates being examples of extensive areas used for this purpose. Not all of these categories are mutually exclusive, rough grazing land can often have a significant tree cover, as can golf courses. Areas which are grazed in the summer months can be used for sporting purposes in the winter, again blurring the distinction between the land use categories.

The model looks at all land which is at present classified according to these categories. Other areas with different primary uses are not included. The expansion of crops and grass with warmer temperatures takes place at the expense of rough grazing land only. It does not utilise any land which is presently under a different classification.

This sector of the model includes certain assumptions as to the availability of suitable land for more intensive agriculture. Although in Argyll only ~18% of the potentially improveable land is actually transformed, this makes assumptions about the soils being suitable, access being possible and there being financial incentives to make such a course of action feasible.

The land use changes represented by the flows between these land use categories are largely driven by grants and subsidies from national government or via the common agricultural policy. The model would have to recognise shifts in policy as having consequences for the long-term pattern of land use. One such shift has already happened. Since the construction of this sector was completed, the forest grants scheme has been changed quite dramatically. The future projections of plantation and native/broadleaved forest cover showed a steady increase at the expense of much of the open land currently used for rough grazing. This was shown to lead to a complete loss of rough grazing in some areas by the end of this century. The changes in policy (Forestry Commission 2003) appear to be designed in part to halt this process, with the maintenance of existing woodlands for environmental and social goals being the new paradigm. This will undoubtedly alter the rate of change of land use categories. Exactly how these changes will manifest themselves will only become apparent after a few years of operation. The model can be adjusted to take account of such changes and new projections generated. It could also be used to assess the probable consequences of changes to existing legislation in terms of altering the land use patterns.

The major weakness of this sector is the fact that it relies on broad figures for land use rather than a more detailed assessment. This would be possible with the use of remotely sensed data combined with a suitable Geographical Information System (GIS).

By linking the GIS maps to a climate change model, land use changes could be more accurately projected on a scale which would have relevance to individual farmers and landowners. Actual features of the landscape, such as aspect, accessibility, soil types and hydrology could be included to present maps of areas of potential land use under conditions of climate change. This would allow individual projects to be assessed in terms of the costs and benefits to the owner. Considerations for the landscape in general could be included.

11.2.4. Employment sector

The employment sector draws together the numbers of employees from the different areas of the local economy. Those areas, where climate change and land use change are significant in determining the numbers employed, are treated separately from the "non-climatic employment". In Argyll, the proportion of the workforce employed in agriculture, forestry and tourism is the greatest of the three regions. The impact of climate induced changes is therefore greatest in this region.

Tourism related employment is generated directly by the simulated numbers of tourists. The number of tourists is modelled, using analysis of historical data, as a function of summer temperature. This relationship holds for the period that data is available and suggests that around 80% of the variability in tourist numbers can be explained in this way. The model assumes that this relationship will continue, and warmer summer temperatures will lead to increases in the number of visitors.

At present over 90% of visitors arrive by car, a fact which justifies their inclusion in the emissions sector as contributors to the regions' carbon output. If numbers increase significantly over the course of the next few decades then this leads to increased congestion as well as increased emissions. Policies aimed at providing alternative modes of transport, which are reliable and suited to the leisure activities of the visitors to the regions, could make a contribution to reducing greenhouse gas emissions as well as enhancing the quality of the visitors experiences. Already initiatives such as the Green Tourism Business Scheme run on behalf of VisitScotland by Green Business UK Ltd (Green Business UK Ltd. 2002) are recognising that there exists a growing market for holidays which follow certain principles of sustainability. If tourist numbers continue to grow as suggested by the model then the wild open landscape which attracts visitors, particularly to the AILLST tourist area, could loose some of its appeal as a result of road congestion and parking problems.

Employment in agriculture is projected to increase in response to an increase in the area of suitable land available. This has little impact in the regions of Stirling and Fife, where agricultural employment is a very small proportion of overall employment. The impact is felt more in Argyll, where a significant part of the working population is involved in agriculture. Increased mechanisation has led to a decline in the agricultural workforce over the last few decades. The results of the model, which suggest an increase, runs contrary to this trend. The number of employees is seen as a function of the area of land being used for different purposes. It is conceivable that the present workforce could work a larger area without the need for any increase in employment, and, as a result, generate a larger income. This in itself would have a positive impact on the local economy and on the long-term future of rural communities.

In the eastern districts covered by the study there is a less dramatic change to the areas of land used for crops and grass. This leads to a very limited increase in the agricultural workforce. Warmer temperatures would provide the opportunity to diversify the range of crops under cultivation, perhaps replacing relatively expensive imported goods with local produce.

All other employment is classed together as "non climatic" and is set at a certain proportion of the total population. This assumes no changes in the proportion of women classed as economically active and assumes that the extent of employment opportunities remains steady for the length of the simulation. The structure of employment in Fife, for example, has changed dramatically during the latter half of the 20th century and such changes are quite possible in the future. In this respect the accuracy of the employment sector can be seen to decline, the further from the present the model goes in simulated time.

11.2.5. Water resource sector

Water resources are calculated by subtracting runoff, human use and evapo-transpiration from the total incoming precipitation for each region. Total precipitation from the climate sector is based on the records from an array of meteorological stations, all of which are situated at relatively low altitude. It can be assumed that the actual average precipitation for each region is greater than the figures generated by the model as a result of the effect of relief on the intensity and frequency of rainfall. Similarly, runoff cannot be accurately represented by one single figure for a region, when topography, soils, land use and vegetation will all play a part in determining local values.

Precipitation and runoff are included in the model as average figures for each region, despite the spatial variability in both. This sector of the model is therefore used to assess the overall probability of summer drought, but cannot provide any information as to the location of areas which may be affected. With reasonably accurate maps used with GIS, such as were discussed in the land use sector, areas particularly prone to drought within the regions could be identified. The results from this sector suggest that water management will become a more serious issue in the drier east of the country, with the increasing frequency of agricultural drought resulting from serious soil moisture deficiencies. No deficiencies exist at other times of the year, so the provision of reservoirs, coupled with waste minimisation strategies would be necessary to prevent serious harm being done to the agricultural sector of the local economy.

Flooding, unlike drought, can be the result of short term intense events. Rainfall landing on a parched surface can lead to flooding of the same intensity as rainfall landing on a saturated surface. It is the intensity of the event which is of most importance. There is evidence from Chapter 4 that the intensity of precipitation events has been increasing in the west of the country. No such evidence was found for the east of the country, suggesting that the risks of flood events have not increased. However, the expansion of urban areas has led to more buildings being erected in vulnerable areas, suggesting that the hazard has indeed increased.

11.2.6. Housing sector

Housing demand results from two main factors. The size of the regional population is important, as is the mean size of individual households. In all regions there has been a definite trend towards smaller average household sizes, and this trend is forecast to continue. This puts increasing strain on housing provision, even in the regions where population is projected to decline in the coming decades.

The rate at which new housing is built depends on a number of factors. The demise of the local authority housing sector has meant that "market forces" have tended to dominate the provision of new housing in recent years. Argyll, despite a steady growth in the housing stock, is one area in which affordable housing is in short supply, many of the new builds being holiday rents as is a large number of previously council owned property. The provision of housing for the local population must be a priority if this growing tourist market is to be serviced. There is an adequate stock of housing in Argyll based on the size of the population, but this is a region with a shortage of affordable housing. The structure plan for the region (Chief Executive Argyll and Bute Council 2002) recognises this, and makes provision for land to be made available for housing.

In both Stirling and Fife the rate of new house building is closely correlated with the rate of increase in the population, and there has been a steady decline in the number of dwellings classified as below tolerable standard. Argyll on the other hand has seen virtually no reduction in the number of houses with this classification. In Argyll this represents around 25% of the housing stock. The definition of a dwelling which is of tolerable standard includes several factors (Watchman 1991) of which the provision of an "adequate piped supply of wholesome water available within the house" is one. This may be the problem for a large number of rural dwellings which have no connection to a mains water supply but rely on unfiltered or untreated water from a local source.

11.2.7. Emissions sector

With a constant figure for per capita carbon emissions, Argyll and Fife, with declining populations, show a medium to long term decline in output of carbon. This decline can be hastened by an increase in tree cover if the assimilation rate for forestry is considered. In Argyll, with a low population density, this is an effective method of reducing the regions' carbon output. The more populous regions of Stirling, and particularly Fife, would require a massive increase in forest cover to offset the emissions from human activities. Reducing per capita emissions figures will have to take into account the differences between the sources within each region. Inhabitants of rural areas are more dependent on personal transport to perform basic daily tasks. The distances covered tend to be greater, whether this is for shopping, travelling to work or other social and domestic purposes. Public transport in rural areas tends also to be far less well developed than in more densely populated areas, and these factors make car ownership and use more important to the inhabitants of a region such as Argyll. Nationally, approximately one quarter of CO_2 emissions come from transport, and it is reasonable to assume that individuals living in rural areas contribute somewhat more than the national average. Efforts to reduce the dependence on cars by increasing fuel tax may be suitable in areas where an efficient and inexpensive public transport system already exists and individuals have a realistic choice, but this is seen as a tax on a necessity by those living in scattered rural communities. A financial disincentive to car use can only work where there is a viable and realistic alternative available.

Energy consumption in the home accounts for a further quarter of all emissions. Although heating bills may well fall with milder winters, the trend towards hotter summers may well counter this with an increased demand for air conditioning in homes and offices. It would be interesting to do a comparison of the costs and benefits of a national campaign to better insulate housing stock and business premises, when compared with the energy demand from existing buildings. The technology exists for new buildings to be constructed in such a way as to cut energy demands dramatically, and this does not necessarily involve increased construction costs. Examples can be seen at the Sustainable Communities Initiatives website (SCI 2002) or the Hockerton project (Hockerton Housing Project 1998).

As stated earlier, the population of Scotland is approximately 0.01% of the world's population, and even though per capita emissions are well above the global average, Scotland's contribution to global carbon emissions is relatively small. However, it is a global solution to emissions of carbon to the atmosphere which is required and this requires action by all, especially in the more developed nations, where emissions tend to be higher.

11.2.8. General discussion

The empirical evidence points to regional differences in the way in which global climate change manifests itself. The results of the model indicate that the socio-economic impacts of future changes will also have a distinct regional character. The region with the lowest population density, Argyll seems to be more sensitive to the climatic changes forecast in the model. The impacts on land use are more dramatic, and the simulated growth in tourism, coupled with an enhanced agricultural sector, has a greater impact on employment and the general population than in the other regions. In contrast, the landscape and general population of Fife seems relatively unchanged by the impacts of climate change, the exception being the availability of water resources during the summer months. It is the areas defined as both rural and, in terms of agriculture, as Less Favourable Areas, that the model identifies as being most significantly affected by changes in climate.

The Scottish Executive recently published its Rural Development Plan for Scotland (Scottish Executive website 2 2002) which makes a wide appraisal of all factors affecting rural areas in terms of employment, land use and conservation. A significant proportion of this document relates to efforts to enhance the prospects of farmers in "less favourable areas". This classification relies on a geographical definition, with most of the Highlands and Islands belonging to the area covered by the term. However, within this area farms are classified on an individual basis. Thus neighbouring farms can be classified differently, and be eligible for different levels of grants and subsidies, based on an assessment of their agricultural potential. The rural development plan is not designed as a long-term plan. It presents forecasts for the period up to 2006, and deals with current issues and problems in rural areas.

If the long-term picture as defined by the model is considered, then it is possible that the problems to be addressed may alter through time. In particular, the classification of land according to agricultural potential could well be influenced by climate change. Decisions taken now and which have long-term consequences, for example to alter land use in response to lack of productivity by planting with forestry, may reduce the options at a later date. A long term view, which takes into consideration the effects of climate change, may need to be built into such development plans as they are produced, rather than reacting to change as it occurs.

Given that the nature of the changes in climate are likely to be different at the local level and that responses and adaptations will similarly require a distinct local character, the notion of national policies to deal with the impacts of climate change seems inappropriate. Water resources are unlikely to be a major issue in Argyll or Stirling, but Fife would appear to require a considered long-term strategy to deal with potential water shortages in the latter part of this century. If the more rural west is to make use of the potential for increased agricultural productivity then consideration will have to be given to the provision of infrastructure to support this. In general, it is at the local level that decisions concerning the management of change will be required, with the benefits and costs being weighed up on a local level, rather than blanket policies for Scotland as a whole.

The changes to the potential for agriculture, particularly significant in the west, are particularly significant. If such changes are forecast for a period of anthropogenic climate change, it would suggest that past climate change should have had a marked impact on the predominantly agrarian societies inhabiting this region in the past. The Medieval warm period and the transition to the cooler climate of the "Little Ice Age" ought to be associated with different fortunes for the peoples of the west of Scotland to a greater extent than those of the inhabitants of the eastern parts. An archaeological and historical study would be interesting, and could be of use in providing evidence to shed light on this subject.

11.3. Further work

Two main areas emerge for further work relating to this project. Firstly there is the need to improve the resolution and accuracy of the model. Secondly there is the need to extend the scope of the model, to cover in particular the rural areas of Scotland, but ideally to extend it to cover Scotland as a whole.

11.3.1. Accuracy of the model

Both the land use sector and the water resources sectors would be greatly enhanced by greater resolution of their spatial dimensions. The application of GIS would allow more accurate mapping of land use, using satellite imagery to define accurately the distribution of different land use categories. This, combined with climate data, geological maps and digital terrain models would allow the land use changes associated with climate change to be assessed. This could be achieved with a resolution which would identify the location and extent of areas suitable for different purposes. Protection of designated areas, and the quality of the landscape in general, could be included, avoiding change which reduces the attractiveness of the regions, a major factor in drawing tourists to rural Scotland. This would allow a more accurate assessment of the potential for increased agricultural activity and give spatial detail of suitable areas.

Similarly, the use of GIS to map water resources would avoid the situation where average figures for each region are used. By combining data sets relating to topography, vegetation cover and land use, and generating precipitation maps which take into account aspect and altitude, the areas most prone to drought or flooding could be identified. The hydrology of a region would be an important input to the land use sector and would help in the definition of areas suitable for agricultural change.

In addition, the mean surface temperature used in the climate model refers to areas at, or close to, sea level. The effect of altitude on temperature has in effect been ignored when generating the regional mean temperatures. It would be possible to generate a temperature map, with isotherms defining areas with similar altitudes for each of the regions, again using GIS. Runs of the climate model could then be used to illustrate the changing bands of temperature, as well as providing a mean surface temperature for each region which included the altitude effect of mountainous regions (especially in Argyll). This would give an average temperature based effectively on the average altitude of each region, and would be useful for comparing such variables as overall agricultural productivity.

11.3.2. Extent of the study

Extending the scope of the study to include all local authority areas in Scotland would be possible, and would provide a spatially explicit understanding of the scope of the socio-economic changes likely to result from climatic changes. A national assessment of costs and benefits would be invaluable in planning resource allocation, and the targeting of particular areas which are forecast to experience particular problems would then be possible. A single model, with each region treated as an element in an array, would allow the impacts of climate change to be assessed for each individual local authority. It would also allow national figures to be produced, by summing across the arrayed results. In this way, costs and benefits could be assessed on a national basis, allowing for prioritisation at this level, but the needs of individual regions would not be ignored where impacts are restricted to particular local areas. For example, it may be that the national picture for water resources is healthy and shows no problem with respect to delivering supplies for domestic consumption and industrial and agricultural use. However, a disaggregated model could illustrate that within this healthy national picture there are areas, such as Fife, where problems are likely to arise and would require the direction financial resources to safeguard summer supplies.

As discussed in Chapter 3, the System Dynamics method has drawbacks in terms of the lack of detail for short term analysis and the necessary omission of factors, the impact of which cannot be predicted in advance. The results of the model hold as an "all other things being equal" analysis, but cannot take into account the effects of factors as the CAP on agriculture, world oil prices on carbon emissions or world timber prices on forestry. The characterisation of the economy into climate sensitive and non-sensitive areas is a simplification which fails to capture the interaction and interdependence of all sectors of the local economy.

These are however necessary if a long term model run is to be undertaken, and so long as the limitations in terms of the accuracy of the model are understood the results are nevertheless interesting comparisons between the different climate change scenarios. Future work could involve running the model with a simulated deterioration in the climate, resulting from a "switching off" of the Atlantic conveyor system, or higher rates of increase in CO_2 levels in the atmosphere resulting from feedback effects from the biosphere or oceans.

Chapter 12 Conclusion

12.1. General conclusions

This study has investigated the empirical evidence for local effects of global climate change in three local authority areas of Scotland. The choice of regions, Argyll in the west, Stirling centrally located and Fife on the east coast, provides a transect across Scotland. Analysis of meteorological data indicates that there is evidence of changes to the climate of these three regions in the period 1970-2000.

Mean surface temperature has increased for all three regions, though the rate of change has been different for each site. Central areas show more overall warming than coastal sites and whereas spring shows the strongest warming trend of any season, central areas have experienced more warming than coastal sites during the Autumn. There is therefore evidence that warming is not uniform but shows spatial variation. This is similar in nature to the output from the UKCIP02 regional climate model (UKCIP 2002).

There is evidence from Argyll of a trend towards greater rainfall totals during the winter months, though no such trend exists in the data from sites in Fife. Stirling shows some evidence of a slight increase in winter rainfall, but this trend is not statistically significant. There is evidence of an increase in the intensity of precipitation events in Argyll, but this trend does not extend eastwards towards Stirling and Fife.

Very little change to either mean or maximum wind speeds was found at either of the two sites studied, which lie at the western and eastern extremities of the study area. A slight increase in mean wind speed in the west was matched by a slight decrease in mean wind speed in the east. No significant changes to maximum speeds were found.

Analysis of the meteorological data suggests that the main factor explaining these climatic changes has been alterations in atmospheric circulation patterns, most significantly the North Atlantic Oscillation. The significance of this pattern in determining features of the weather declines with distance from the west coast. Precipitation in Fife is influenced mainly by the Scandinavian pattern, whereas precipitation in Argyll and Stirling is influenced largely by the NAO.

Temperature across Scotland shows the influence of the NAO, but winter temperatures are shown to be influenced by the conditions which prevailed in the Pacific, as measured by the Southern Oscillation Index, during the previous autumn.

Levels of CO_2 in the atmosphere are included in the regression equations for summer temperatures in all three regions. This covers the period when incoming solar radiation, and hence the absorption of long wave radiation from the earth's surface, is at its greatest.

Levels of CO_2 in the atmosphere are included in the regression equations for precipitation in Argyll during winter and spring, in Stirling during the winter but not at all in Fife. Warming caused by increased levels of greenhouse gasses appears to affect precipitation towards the west of the country during the coldest part of the year. This suggests that increased temperatures, brought on by increased CO_2 levels, influence the evaporation of water vapour from the Atlantic.

A simple climate model was constructed based on thermodynamic properties of the Earth's atmosphere. This allows simulated temperature and precipitation on a seasonal basis to be generated for the three regions under conditions of enhanced atmospheric CO_2. When run forward in simulated time to 2100, the output from this model shows considerable similarities with the recently published output from the UKCIP02 model from the Hadley Centre. The simple climate model was used to generate temperature and precipitation as an input to different sectors of the socio-economic model.

The socio-economic sectors, population, land use, employment, water resources, housing and emissions, were constructed using data for each of the three regions where possible, and national figures where necessary. Evidence of climatic influences on aspects of the economy and land use were sought, and where clear relationships were found, were included in the model. The model was calibrated using data for the period from 1970 to 2000.

A large number of feedback loops were identified, the greatest number being associated with the population sector of the model. Sensitivity testing indicated that the model was sensitive to few of the parameters, with the exception of the birth rate (and death rate) where small changes led to considerably different population dynamics over time.

Four versions of the combined model were produced, each one corresponding to a different climate change scenario as defined by the IPCC Special Report on Emissions Scenarios. This allowed for four sets of results to be generated and a comparison of the impacts of different rates of growth in atmospheric CO_2 to be produced. A run of the model with the climate sector switched off, and therefore generating constant values, was also included so the impact of the different scenarios could be assessed against the output from the model without climate change.

The results indicate that it is possible to broadly describe socio-economic effects of climate change on local areas of Scotland. The different regions of the study show different responses to increased temperatures and changes to the pattern of precipitation. The scale of the effects on the population is greatest in Argyll, this being a region which, according to this model, could potentially experience certain benefits from climate change. Stirling and Fife are less affected though, here too, some benefits in terms of increased employment in certain sectors are possible. Studies of the impact of climate change on agriculture (European Environment Agency 2004), (Holden et al. 2003), (Richer and Semenov 2004), tend to point to similar trends including the potential for a wider range of crops being grown. They also point to increased yields but also an increase in the variability of yields due to potential drought and extreme weather events.

The main cost associated with climate change seems to be concentrated in the East of the country, where water resources during the summer months are set to decline. This could have a major impact on the agricultural sector, with a dramatic increase in the frequency of summer droughts and the corresponding impacts on crops. Irrigation of certain crops could become the norm and it may become uneconomic to grow others in the areas worst affected by summer soil moisture deficits (Holden et al. 2003)

The costs and benefits of climate change in the coming decades are not evenly distributed throughout the three regions of the study, and this needs to be considered when policy decisions are made with respect to the management of change.

In some cases the model represents a continuation of current trends, for example in the continuing expansion of forestry. In other areas the effect of climate change can be to reverse current trends. Agricultural employment has been in decline for several decades, but the model indicates a potential for growth of employment in this sector. Another major change is in the population of Argyll, which the model forecasts as reversing it's downward trend. This does not occur from increased births, but from in-migration resulting from a labour shortage by the middle of this century.

In general, the scale of the costs and benefits increases with more rapid accumulation of greenhouse gasses in the atmosphere.

All results must be viewed within the limitations of the model which was developed. Long term simulations rely by necessity on the selection of features which can be assumed to remain reasonably close to constant over the period of the simulation.

Other factors which may have a profound impact, such as the Common Agricultural Policy or Forestry Grants scheme, cannot be included as their future effects cannot be predicted. The model is therefore constructed "all other things being equal" and the results hold true if this condition holds true. The model does however demonstrate the areas in which impacts could be experienced, and illustrates the knock on effects of these changes through the socio-economic structures of the regions.

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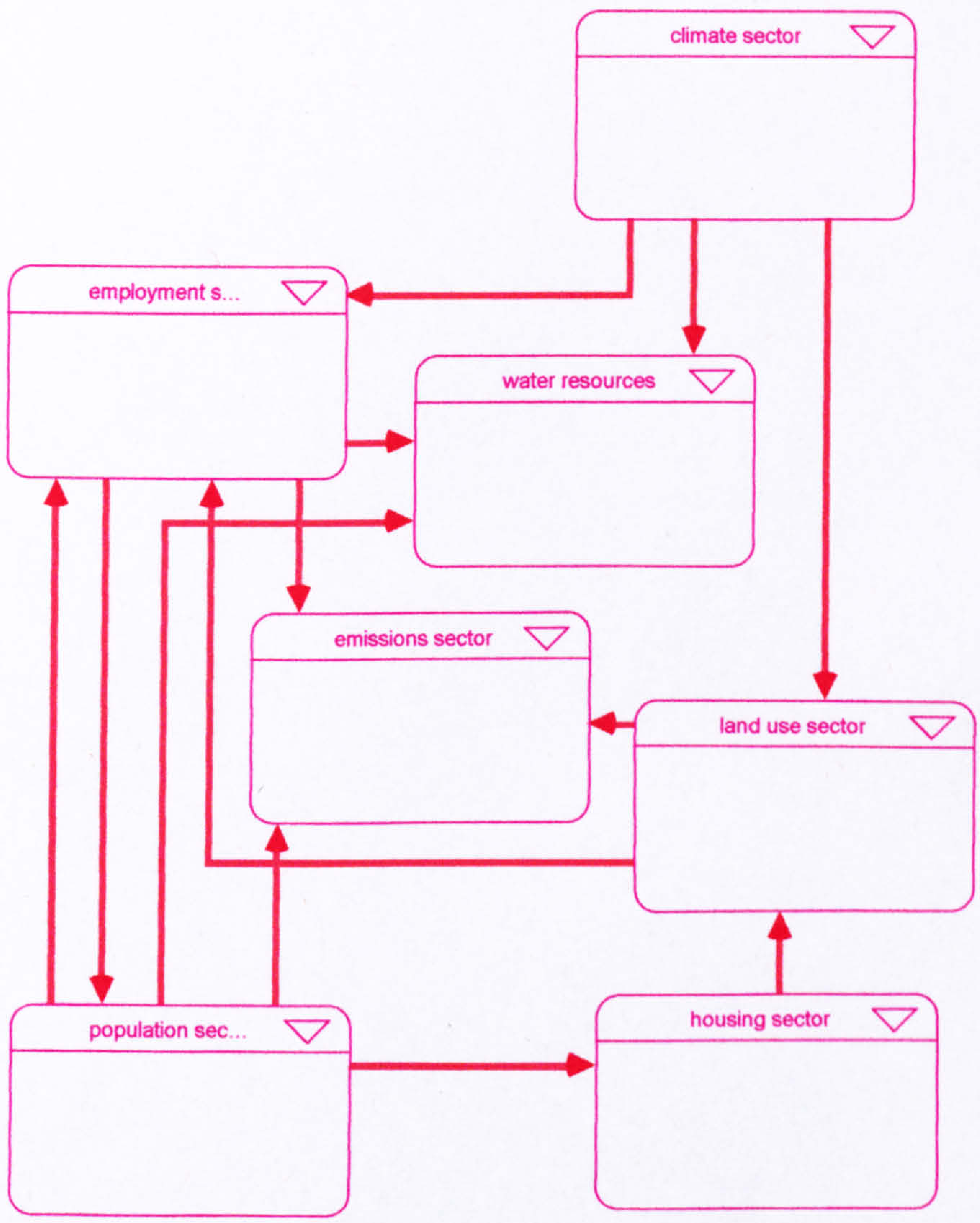
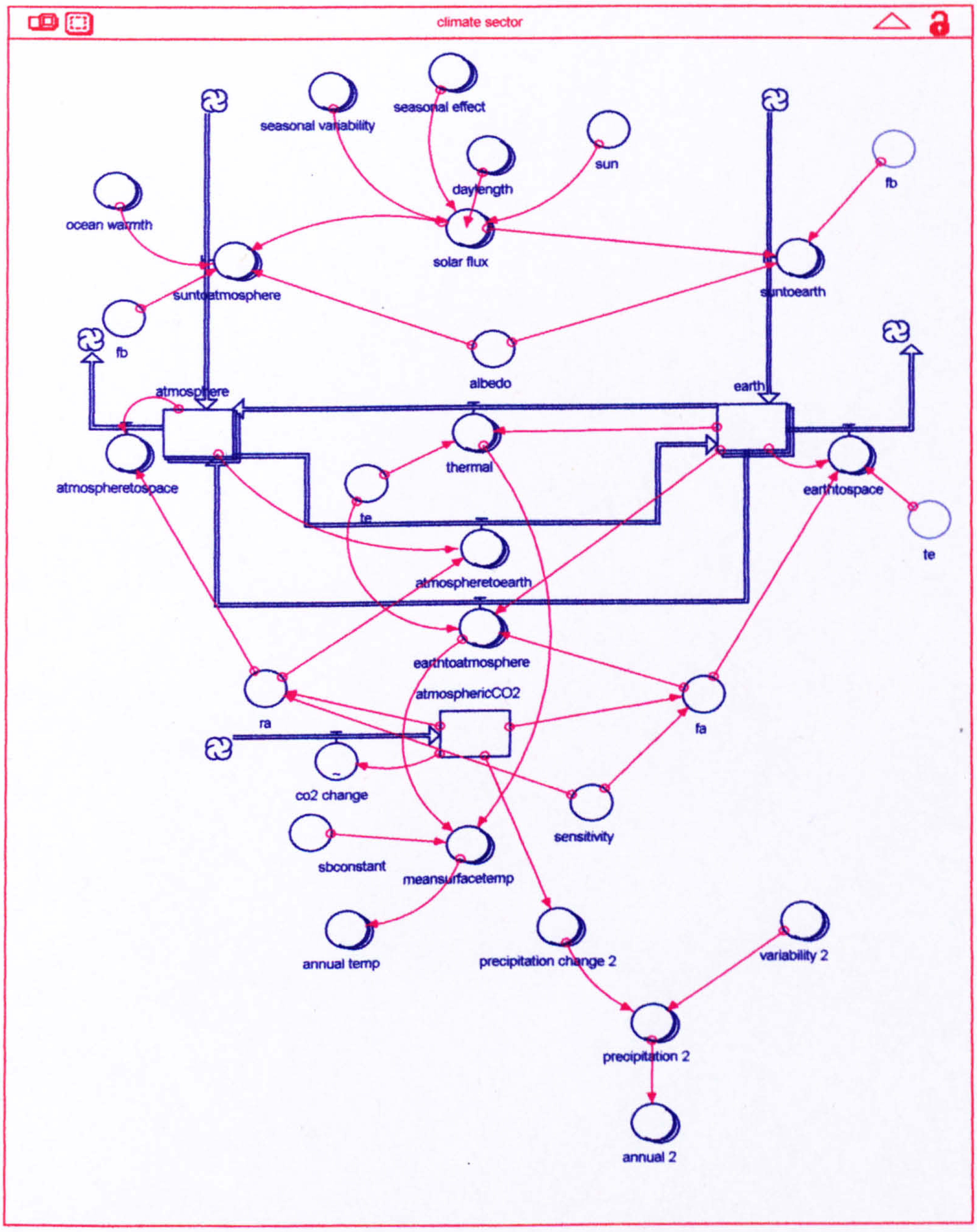
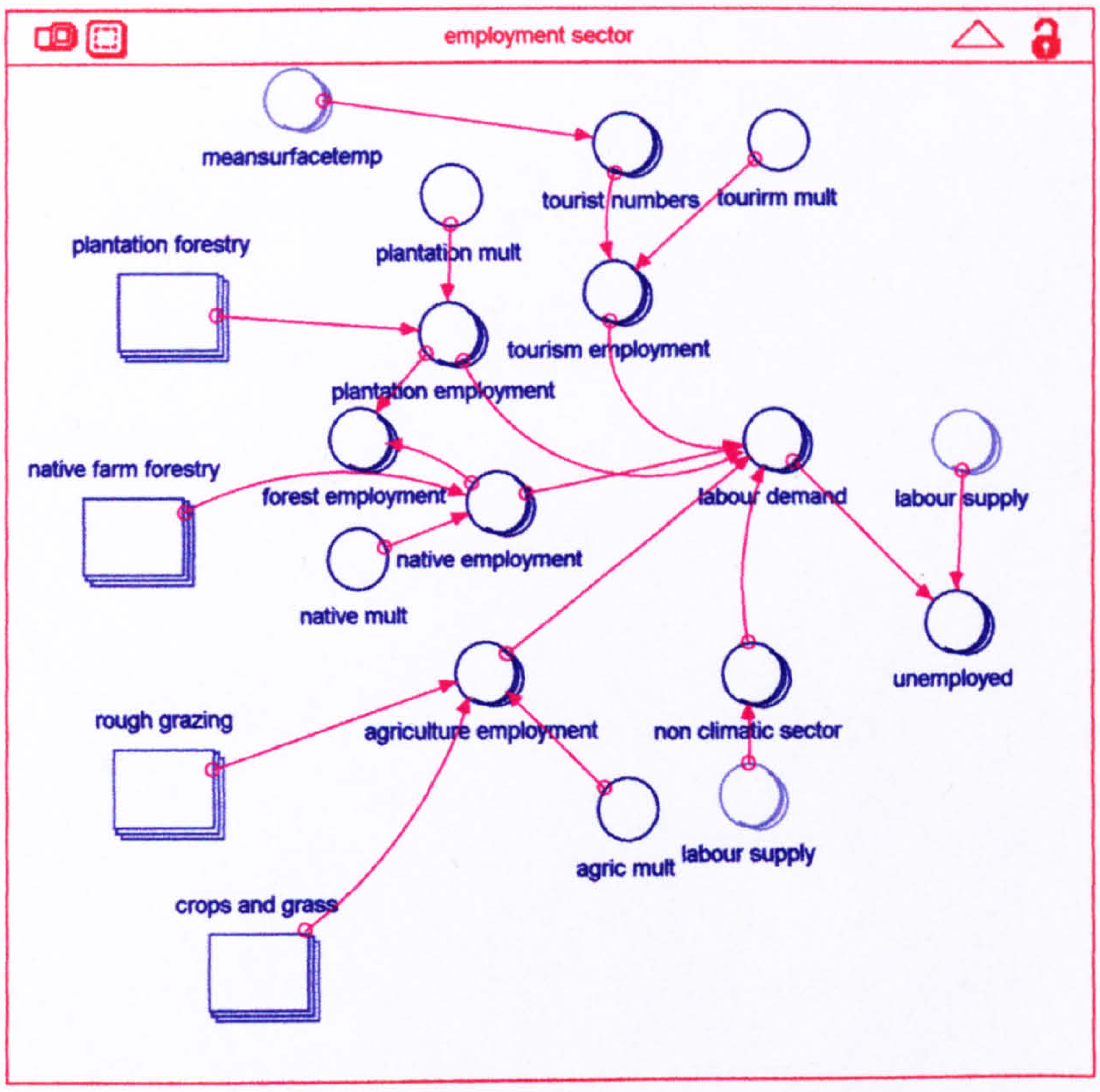
Appendix A

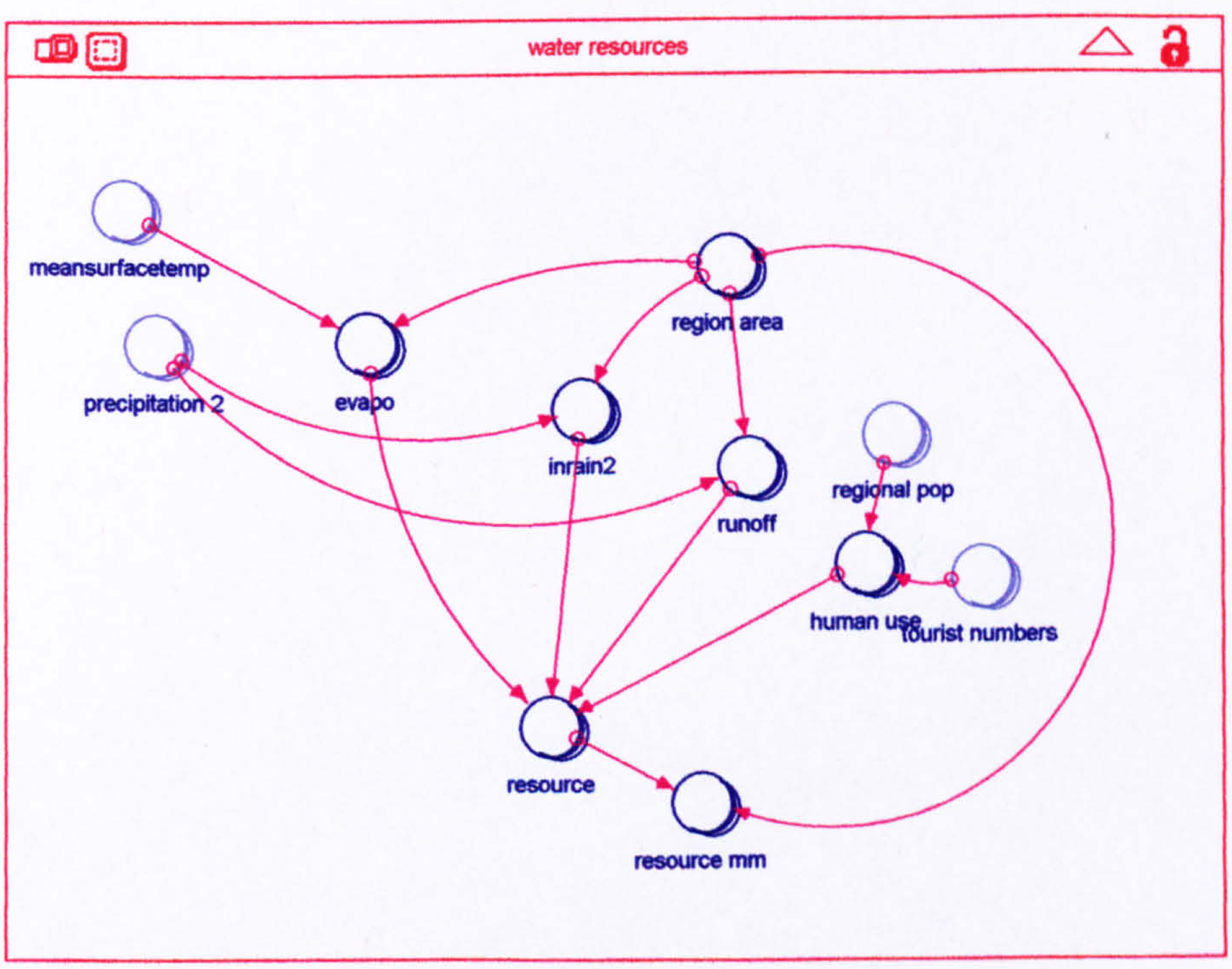
A.1 The Stella model. Upper level.

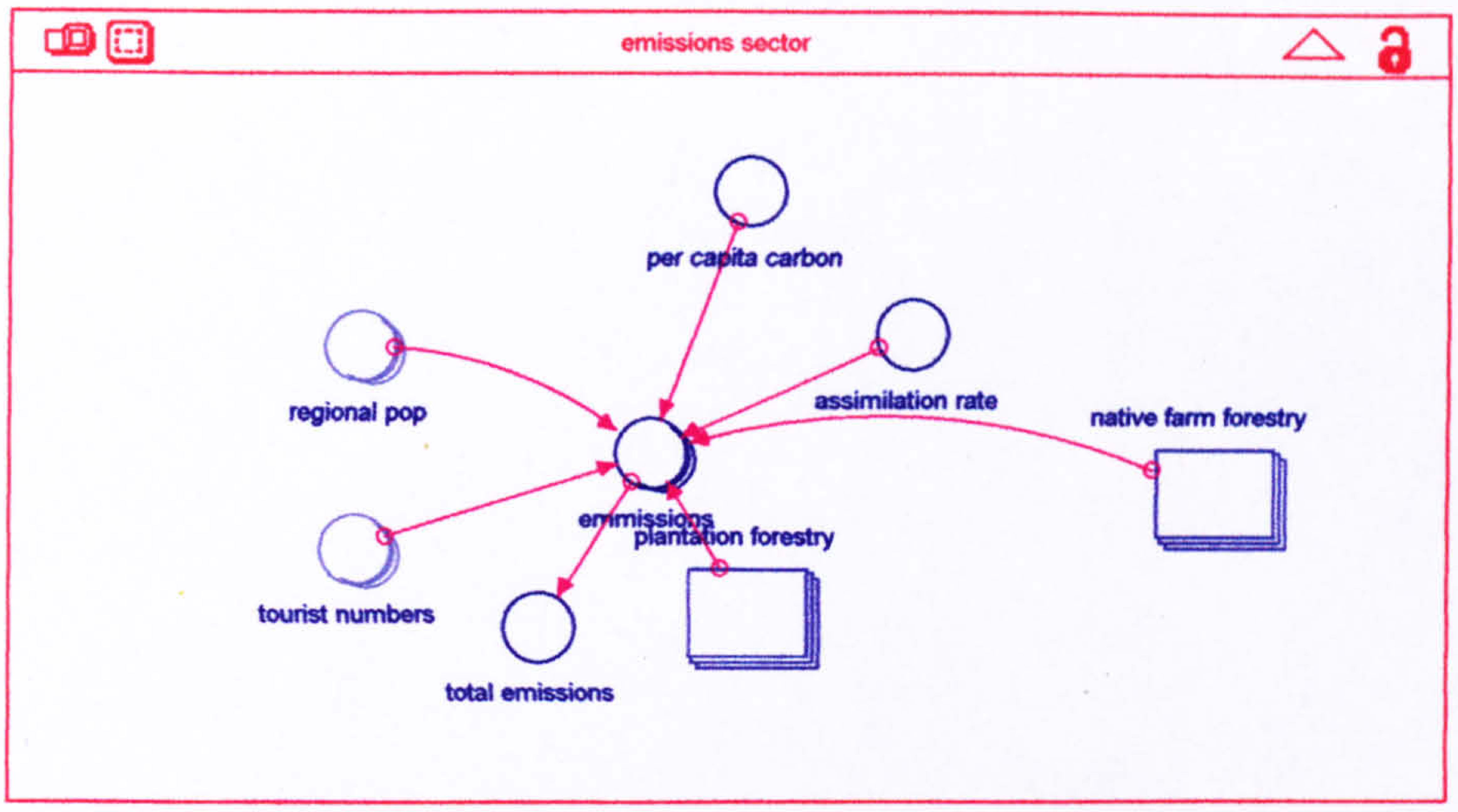


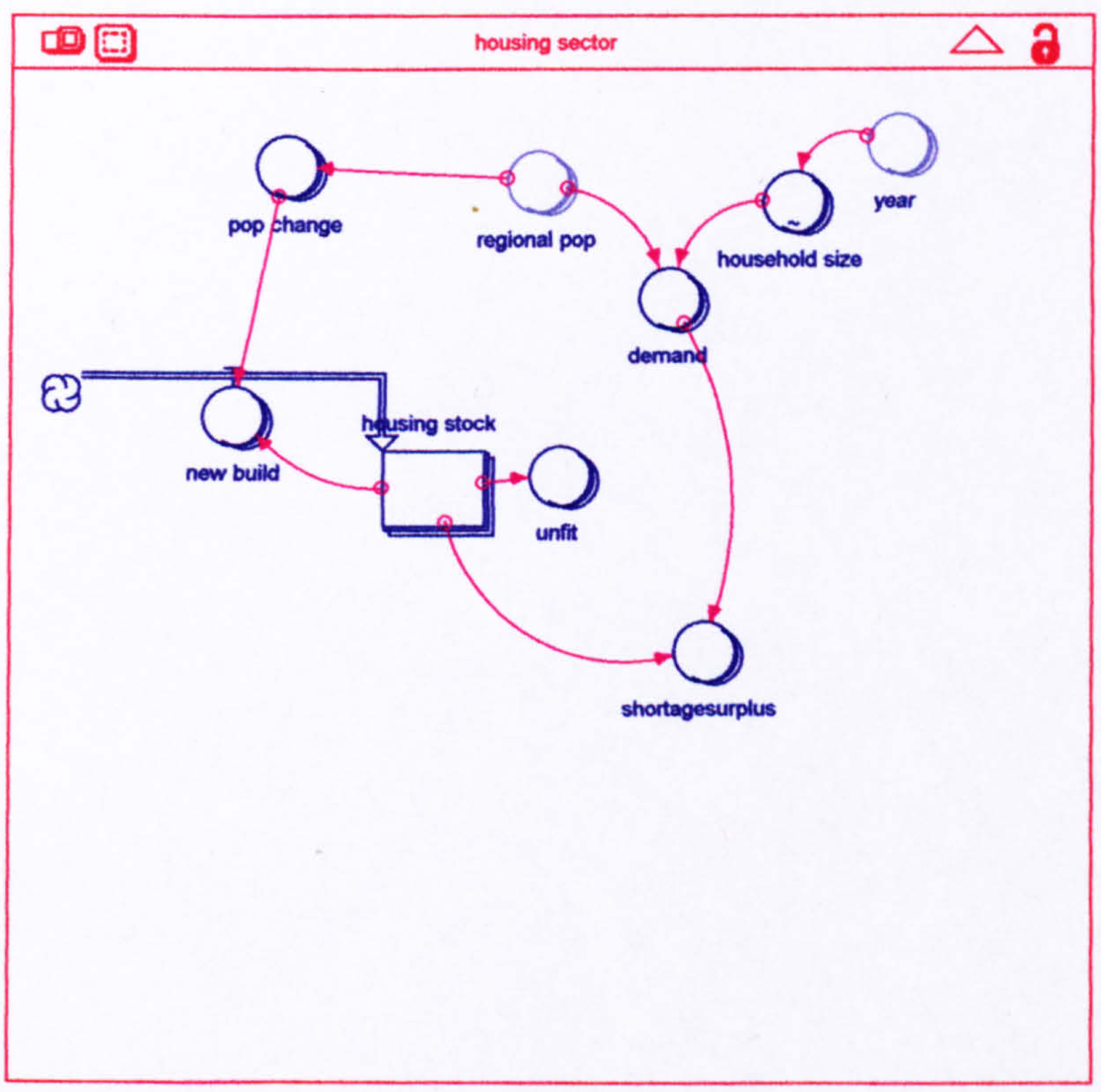
A.2 The Stella model. Diagram layer.

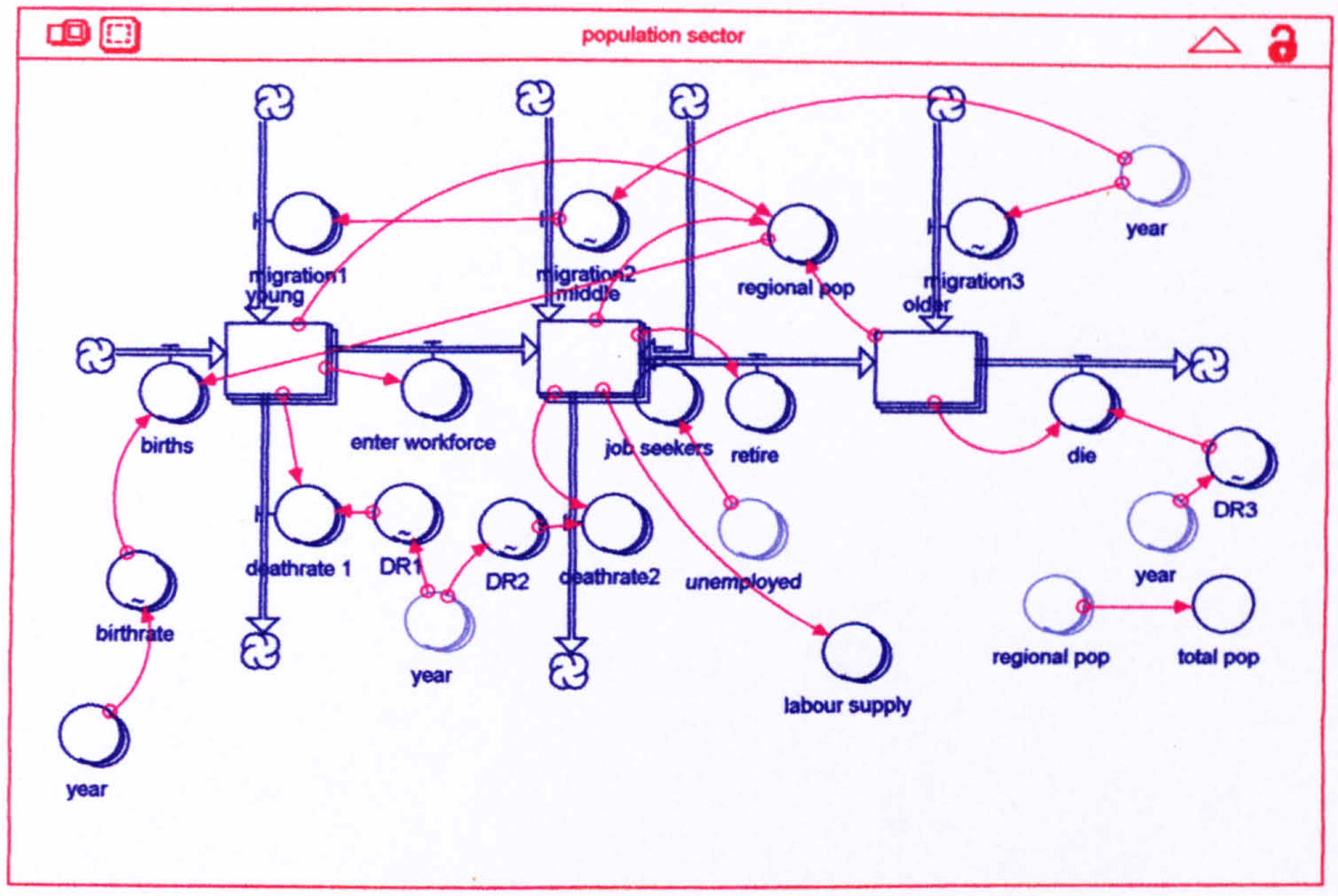


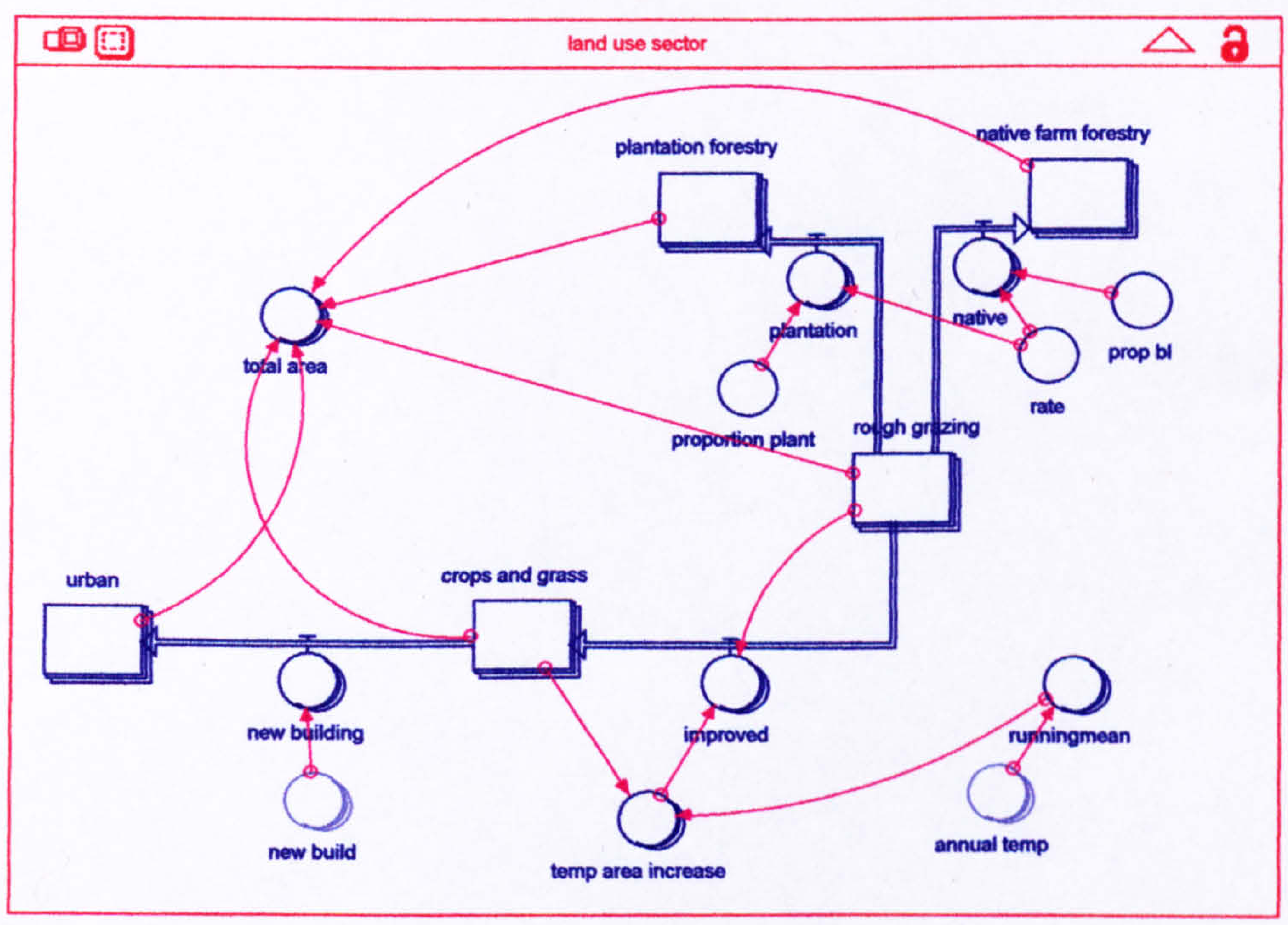

employment sector
meansurfacetemp
tourist numbers
tourirn mult
plantation mult
plantation forestry
tourism employment
plantation employment
native farm forestry
forest employment
labour demand
labour supply
native employment
native mult
unemployed
rough grazing
agriculture employment
non climatic sector
labour supply
agric mult
crops and grass


water resources
meansurfacetemp
region area
precipitation 2
evapo
inrain2
runoff
regional pop
human use
tourist numbers
resource
resource mm


emissions sector
per capita carbon
regional pop
assimilation rate
native farm forestry
emmissions
plantation forestry
tourist numbers
total emissions


housing sector
pop change
regional pop
year
household size
demand
housing stock
new build
unfit
shortagesurplus


population sector
migration1
young
migration2
middle
regional pop
migration3
older
year
births
enter workforce
job seekers
retire
die
deathrate 1
DR1
DR2
deathrate2
unemployed
DR3
year
birthrate
year
labour supply
regional pop
total pop
year


land use sector
plantation forestry
native farm forestry
total area
plantation
native
prop bl
rate
proportion plant
rough grazing
urban
crops and grass
new building
improved
runningmean
new build
temp area increase
annual temp

A.3 Stella model Equations

Climate sector

atmosphere[argyll,spring](t) = atmosphere[argyll,spring](t - dt) + (suntoatmosphere[argyll,spring] + thermal[argyll,spring] + earthtoatmosphere[argyll,spring] - atmospheretoearth[argyll,spring] - atmospheretospace[argyll,spring]) * dt

INIT atmosphere[argyll,spring] = 4.258e+009

DOCUMENT: The store of energy in the atmosphere.

atmosphere[argyll,summer](t) = atmosphere[argyll,summer](t - dt) + (suntoatmosphere[argyll,summer] + thermal[argyll,summer] + earthtoatmosphere[argyll,summer] - atmospheretoearth[argyll,summer] - atmospheretospace[argyll,summer]) * dt

INIT atmosphere[argyll,summer] = 4.7e+009
atmosphere[argyll,autumn](t) = atmosphere[argyll,autumn](t - dt) + (suntoatmosphere[argyll,autumn] + thermal[argyll,autumn] + earthtoatmosphere[argyll,autumn] - atmospheretoearth[argyll,autumn] - atmospheretospace[argyll,autumn]) * dt

INIT atmosphere[argyll,autumn] = 4.51e+009
atmosphere[argyll,winter](t) = atmosphere[argyll,winter](t - dt) + (suntoatmosphere[argyll,winter] + thermal[argyll,winter] + earthtoatmosphere[argyll,winter] - atmospheretoearth[argyll,winter] - atmospheretospace[argyll,winter]) * dt

INIT atmosphere[argyll,winter] = 4.124e+009
atmosphere[stirling,spring](t) = atmosphere[stirling,spring](t - dt) + (suntoatmosphere[stirling,spring] + thermal[stirling,spring] + earthtoatmosphere[stirling,spring] - atmospheretoearth[stirling,spring] - atmospheretospace[stirling,spring]) * dt

INIT atmosphere[stirling,spring] = 4.245e+009
atmosphere[stirling,summer](t) = atmosphere[stirling,summer](t - dt) + (suntoatmosphere[stirling,summer] + thermal[stirling,summer] + earthtoatmosphere[stirling,summer] - atmospheretoearth[stirling,summer] - atmospheretospace[stirling,summer]) * dt

INIT atmosphere[stirling,summer] = 4.747e+009
atmosphere[stirling,autumn](t) = atmosphere[stirling,autumn](t - dt) + (suntoatmosphere[stirling,autumn] + thermal[stirling,autumn] + earthtoatmosphere[stirling,autumn] - atmospheretoearth[stirling,autumn] - atmospheretospace[stirling,autumn]) * dt

INIT atmosphere[stirling,autumn] = 4.480e+009
atmosphere[stirling,winter](t) = atmosphere[stirling,winter](t - dt) + (suntoatmosphere[stirling,winter] + thermal[stirling,winter] + earthtoatmosphere[stirling,winter] - atmospheretoearth[stirling,winter] - atmospheretospace[stirling,winter]) * dt

INIT atmosphere[stirling,winter] = 4.069e+009
atmosphere[fife,spring](t) = atmosphere[fife,spring](t - dt) + (suntoatmosphere[fife,spring] + thermal[fife,spring] + earthtoatmosphere[fife,spring] - atmospheretoearth[fife,spring] - atmospheretospace[fife,spring]) * dt

INIT atmosphere[fife,spring] = 4.214e+009
atmosphere[fife,summer](t) = atmosphere[fife,summer](t - dt) + (suntoatmosphere[fife,summer] + thermal[fife,summer] + earthtoatmosphere[fife,summer] - atmospheretoearth[fife,summer] - atmospheretospace[fife,summer]) * dt

INIT atmosphere[fife,summer] = 4.723e+009 atmosphere[fife,autumn](t) = atmosphere[fife,autumn](t - dt) + (suntoatmosphere[fife,autumn] + thermal[fife,autumn] + earthtoatmosphere[fife,autumn] - atmospheretoearth[fife,autumn] - atmospheretospace[fife,autumn]) * dt

INIT atmosphere[fife,autumn] = 4.452e+009
atmosphere[fife,winter](t) = atmosphere[fife,winter](t - dt) + (suntoatmosphere[fife,winter] + thermal[fife,winter] + earthtoatmosphere[fife,winter] - atmospheretoearth[fife,winter] - atmospheretospace[fife,winter]) * dt

INIT atmosphere[fife,winter] = 4.035e+009
suntoatmosphere[region,Season] = solar_flux(Harrison and Harrison 1988)*fb*(1-albedo)+ocean_warmth[region,Season]

DOCUMENT: The proportion of solar radiation which is absorbed by the atmosphere.

thermal[region,Season] = earth[region,Season]*te

DOCUMENT: Thermal transfer of energy from the Earth to the atmosphere. This includes latent heat transfer.

earthtoatmosphere[region,Season] = (1-te)*fa*earth[region,Season]

DOCUMENT: Long wave radiation flow from Earth to atmosphere.

atmospheretoearth[region,Season] = atmosphere[region,Season]*ra

DOCUMENT: The flow from the atmosphere to the earth, as long wave radiation.

atmospheretospace[region,Season] = (1-ra)*atmosphere[region,Season]

DOCUMENT: The energy radiated by the atmosphere which is lost to space.

atmosphericCO2(t) = atmosphericCO2(t - dt) + (co2_change) * dt

INIT atmosphericCO2 = 326

DOCUMENT: The level of atmospheric carbon dioxide

co2_change = GRAPH(atmosphericCO2)
(270, 0.275), (323, 0.725), (376, 2.13), (429, 2.43), (482, 2.30), (535, 0.35), (588, 0.35), (641, 0.375), (694, 0.325), (747, 0.3), (800, 0.35)

DOCUMENT: The rate of change of atmospheric carbon dioxide concentrations.

earth[argyll,spring](t) = earth[argyll,spring](t - dt) + (atmospheretoearth[argyll,spring] + suntoearth[argyll,spring] - thermal[argyll,spring] - earthtoatmosphere[argyll,spring] - earthtospace[argyll,spring]) * dt

INIT earth[argyll,spring] = 3.042e+009

DOCUMENT: The store of energy at the Earth's surface, including the oceans.

earth[argyll,summer](t) = earth[argyll,summer](t - dt) + (atmospheretoearth[argyll,summer] + suntoearth[argyll,summer] - thermal[argyll,summer] - earthtoatmosphere[argyll,summer] - earthtospace[argyll,summer]) * dt

INIT earth[argyll,summer] = 3.268e+009
earth[argyll,autumn](t) = earth[argyll,autumn](t - dt) + (atmospheretoearth[argyll,autumn] + suntoearth[argyll,autumn] - thermal[argyll,autumn] - earthtoatmosphere[argyll,autumn] - earthtospace[argyll,autumn]) * dt

INIT earth[argyll,autumn] = 3.135e+009
earth[argyll,winter](t) = earth[argyll,winter](t - dt) + (atmospheretoearth[argyll,winter] + suntoearth[argyll,winter] - thermal[argyll,winter] - earthtoatmosphere[argyll,winter] - earthtospace[argyll,winter]) * dt

INIT earth[argyll,winter] = 2.924e+009
earth[stirling,spring](t) = earth[stirling,spring](t - dt) + (atmospheretoearth[stirling,spring] + suntoearth[stirling,spring] - thermal[stirling,spring] - earthtoatmosphere[stirling,spring] - earthtospace[stirling,spring]) * dt

INIT earth[stirling,spring] = 3.033e+009
earth[stirling,summer](t) = earth[stirling,summer](t - dt) + (atmospheretoearth[stirling,summer] + suntoearth[stirling,summer] - thermal[stirling,summer] - earthtoatmosphere[stirling,summer] - earthtospace[stirling,summer]) * dt

INIT earth[stirling,summer] = 3.301e+009
earth[stirling,autumn](t) = earth[stirling,autumn](t - dt) + (atmospheretoearth[stirling,autumn] + suntoearth[stirling,autumn] - thermal[stirling,autumn] - earthtoatmosphere[stirling,autumn] - earthtospace[stirling,autumn]) * dt

INIT earth[stirling,autumn] = 3.105e+009
earth[stirling,winter](t) = earth[stirling,winter](t - dt) + (atmospheretoearth[stirling,winter] + suntoearth[stirling,winter] - thermal[stirling,winter] - earthtoatmosphere[stirling,winter] - earthtospace[stirling,winter]) * dt

INIT earth[stirling,winter] = 2.887e+009
earth[fife,spring](t) = earth[fife,spring](t - dt) + (atmospheretoearth[fife,spring] + suntoearth[fife,spring] - thermal[fife,spring] - earthtoatmosphere[fife,spring] - earthtospace[fife,spring]) * dt

INIT earth[fife,spring] = 3.012e+009
earth[fife,summer](t) = earth[fife,summer](t - dt) + (atmospheretoearth[fife,summer] + suntoearth[fife,summer] - thermal[fife,summer] - earthtoatmosphere[fife,summer] - earthtospace[fife,summer]) * dt

INIT earth[fife,summer] = 3.284e+009
earth[fife,autumn](t) = earth[fife,autumn](t - dt) + (atmospheretoearth[fife,autumn] + suntoearth[fife,autumn] - thermal[fife,autumn] - earthtoatmosphere[fife,autumn] - earthtospace[fife,autumn]) * dt

INIT earth[fife,autumn] = 3.086e+009
earth[fife,winter](t) = earth[fife,winter](t - dt) + (atmospheretoearth[fife,winter] + suntoearth[fife,winter] - thermal[fife,winter] - earthtoatmosphere[fife,winter] - earthtospace[fife,winter]) * dt

INIT earth[fife,winter] = 2.8863e+009
suntoearth[region,Season] = (solar_flux(Harrison and Harrison 1988))*(1-albedo)*(1-fb)

DOCUMENT: The proportion of incoming solar radiation which reaches the earth's surface.

atmospheretoearth[region,Season] = atmosphere[region,Season]*ra

DOCUMENT: The flow from the atmosphere to the earth, as long wave radiation.

thermal[region,Season] = earth[region,Season]*te

DOCUMENT: Thermal transfer of energy from the Earth to the atmosphere. This includes latent heat transfer.

earthtoatmosphere[region,Season] = (1-te)*fa*earth[region,Season]

DOCUMENT: Long wave radiation flow from Earth to atmosphere.

earthtospace[region,Season] = (1-fa)*earth[region,Season]*(1-te)

DOCUMENT: Energy radiated from the Earth which is lost directly to space.

albedo = 0.313

DOCUMENT: The average reflectance of the earth and atmosphere.

annual_2[argyll] = ARRAYSUM(precipitation_2[argyll,*])

DOCUMENT: Arraysum to give each regions annual rainfall.

annual_2[stirling] = ARRAYSUM(precipitation_2[stirling,*])
annual_2[fife] = ARRAYSUM(precipitation_2[fife,*])
annual_temp[argyll] = ARRAYMEAN(meansurfacetemp[argyll,*])
annual_temp[stirling] = ARRAYMEAN(meansurfacetemp[stirling,*])
annual_temp[fife] = ARRAYMEAN(meansurfacetemp[fife,*])

DOCUMENT: This uses the Arraymean function to generate an annual mean surface temperature from the seasonal figures calculated by the model.

daylength(Carson 1963) = 14.2
daylength[summer] = 16.8
daylength[autumn] = 9.5
daylength(Harrison, Winterbotom, and Johnson 2001) = 7
DOCUMENT: The mean length of day for each of the seasons, a measure of the intensity of solar radiation.

fa = 0.815+sensitivity*LOGN(atmosphericCO2)

DOCUMENT: This controls the rate of flow between Earth and atmosphere.

fb = 0.9285
meansurfacetemp[region,Season] =
((((earthtoatmosphere[region,Season]+thermal[region,Season])/sbconstant)^0.25)-(273.15))

DOCUMENT: The temperature at the surface of the Earth.

ocean_warmth[argyll,spring] = (343*60*60*24*91.25)*0.279

DOCUMENT: The contribution to the energy in the atmosphere which originates as latent and sensible heat transfer from the oceans.

ocean_warmth[argyll,summer] = (343*60*60*24*91.25)*0.218
ocean_warmth[argyll,autumn] = (343*60*60*24*91.25)*0.461
ocean_warmth[argyll,winter] = (343*60*60*24*91.25)*0.487
ocean_warmth[stirling,spring] = (343*60*60*24*91.25)*0.2795
ocean_warmth[stirling,summer] = (343*60*60*24*91.25)*0.226
ocean_warmth[stirling,autumn] = (343*60*60*24*91.25)*0.457
ocean_warmth[stirling,winter] = (343*60*60*24*91.25)*0.478
ocean_warmth[fife,spring] = (343*60*60*24*91.25)*0.273
ocean_warmth[fife,summer] = (343*60*60*24*91.25)*0.22
ocean_warmth[fife,autumn] = (343*60*60*24*91.25)*0.452
ocean_warmth[fife,winter] = (343*60*60*24*91.25)*0.474
precipitation_2[argyll,spring] = (IF(variability_2[argyll,spring]>0.5
)THEN((311.6*variability_2[argyll,spring])+311.6*precipitation_change_2[argyll,spring])ELSE(311.6*0.5+311.6*precipitation_change_2[argyll,spring]))*1.2
precipitation_2[argyll,summer] =
(IF(variability_2[argyll,summer]>0.4)then(302*variability_2[argyll,summer])+302*precipitation_change_2[argyll,summer] else (302*0.4+302*precipitation_change_2[argyll,summer]))*1.53
precipitation_2[argyll,autumn] = (if(variability_2[argyll,autumn])>0.5 then
(533*variability_2[argyll,autumn])+533*precipitation_change_2[argyll,autumn] else
(533*0.5+533*precipitation_change_2[argyll,autumn]))*1.53
precipitation_2[argyll,winter] = (if(variability_2[argyll,winter]>0.5)
then((513.6*variability_2[argyll,winter])+513.6*precipitation_change_2[argyll,winter]) else
((513.6*0.5+513.6*precipitation_change_2[argyll,winter])))*1.62
precipitation_2[stirling,spring] = (if(variability_2[stirling,spring]>0.5)
then((222.2*variability_2[stirling,spring])+222.2*precipitation_change_2[stirling,spring]) else
((222.2*0.5+222.2*precipitation_change_2[stirling,spring])))*1.46
precipitation_2[stirling,summer] = (if variability_2[stirling,summer]>0.3 then
((216.1*variability_2[stirling,summer])+216.1*precipitation_change_2[stirling,summer]) else
((216.1*0.3+216.1*precipitation_change_2[stirling,summer])))*1.37
precipitation_2[stirling,autumn] = (if variability_2[stirling,autumn]>0.5
then((340.4*variability_2[stirling,autumn])+340.4*precipitation_change_2[stirling,autumn]) else
((340.4*0.5+340.4*precipitation_change_2[stirling,autumn])))*1.6
precipitation_2[stirling,winter] = (if variability_2[stirling,winter]>0.4 then
(323.1*variability_2[stirling,winter]+323.1*precipitation_change_2[stirling,winter]) else
(323.1*0.4+323.1*precipitation_change_2[stirling,winter]))*1.5
precipitation_2[fife,spring] = (if variability_2[fife,spring]>0.5 then
(163.5*variability_2[fife,spring]+163.5*precipitation_change_2[fife,spring]) else
(163.5*0.5+163.5*precipitation_change_2[fife,spring]))*1.55
precipitation_2[fife,summer] = (if variability_2[fife,summer]>0.4
then(170.9*variability_2[fife,summer]+170.9*precipitation_change_2[fife,summer]) else
(170.9*0.4+170.9*precipitation_change_2[fife,summer]))*1.55
precipitation_2[fife,autumn] = (if variability_2[fife,autumn]>0.4
then(222.4*variability_2[fife,autumn]+222.4*precipitation_change_2[fife,autumn]) else
(222.4*0.4+222.4*precipitation_change_2[fife,autumn]))*1.6

DOCUMENT: The simulated precipitation for each region for each season.

precipitation_2[fife,winter] = (if variability_2[fife,winter]>0.4
then(204.7*variability_2[fife,winter]+204.7*precipitation_change_2[fife,winter]) else
(204.7*0.4+204.7*precipitation_change_2[fife,winter]))*1.69
precipitation_change_2[argyll,spring] = 0.026*(atmosphericCO2-270)/100

DOCUMENT: Precipitation change by region and by season based on CO2 concentrations. (Relationships derived from the UKCIP02 model)

precipitation_change_2[argyll,summer] = -0.087*(atmosphericCO2-270)/100
precipitation_change_2[argyll,autumn] = 0*atmosphericCO2
precipitation_change_2[argyll,winter] = 0.061*(atmosphericCO2-270)/100
precipitation_change_2[stirling,spring] = 0*(atmosphericCO2-270)/100
precipitation_change_2[stirling,summer] = -0.069*(atmosphericCO2-270)/100
precipitation_change_2[stirling,autumn] = 0*(atmosphericCO2-270)/100
precipitation_change_2[stirling,winter] = 0.064*(atmosphericCO2-270)/100
precipitation_change_2[fife,spring] = 0*(atmosphericCO2-270)/100
precipitation_change_2[fife,summer] = -0.077*(atmosphericCO2-270)/100
precipitation_change_2[fife,autumn] = 0*(atmosphericCO2-270)/100
precipitation_change_2[fife,winter] = 0.059*(atmosphericCO2-270)/100
ra = 0.615+sensitivity*LOGN(atmosphericCO2)

DOCUMENT: This controls the rate of flow betwen atmosphere and Earth

sbconstant = 60*60*24*91.25*5.67*10^-8

DOCUMENT: The Stefan -Boltzman constant, used to convert energy radiation to surface temperature.

seasonal_effect(Carson 1963) = 0.84

DOCUMENT: Derived from the angle of incidence of solar radiation, taken as the value at the mid point of the season.

seasonal_effect[summer] = 0.94
seasonal_effect[autumn] = 0.67
seasonal_effect(Harrison, Winterbotom, and Johnson 2001) = 0.58
seasonal_variability(Carson 1963) = 1.6
DOCUMENT: Scales the amplitude of the variability, in accordance with the empirical evidence, for each season.

seasonal_variability[summer] = 1.7
seasonal_variability[autumn] = 1.7
seasonal_variability(Harrison, Winterbotom, and Johnson 2001) = 3
sensitivity = 0.0103

DOCUMENT: This affects the flows between earth and atmosphere of long wave radiation, by altering the absorbtion of radiation in the atmosphere. It scales the value of the logarithm of CO2 concentration.

solar_flux(Carson 1963) = 343*60*60*91.25*daylength(Carson 1963)*sun*seasonal_effect(Carson 1963)+(343*60*60*24*91.25)*((NORMAL(0,1)+NORMAL(0,1))*0.011)*seasonal_variability(Carson 1963)

DOCUMENT: The incidence of solar radiation at the edge of the atmosphere, treated as a constant.

solar_flux[summer] =
343*60*60*91.25*daylength[summer]*sun*seasonal_effect[summer]+(343*60*60*24*91.25)*((NORMAL(0,1)+NORMAL(0,1))*0.011)*seasonal_variability[summer]
solar_flux[autumn] =
343*60*60*91.25*daylength[autumn]*sun*seasonal_effect[autumn]+(343*60*60*24*91.25)*((NORMAL(0,1)+NORMAL(0,1))*0.011)*seasonal_variability[autumn]
solar_flux[Harrison, Winterbotom, et al. 2001 #1940] = 343*60*60*91.25*daylength[Harrison, Winterbotom, et al. 2001 #1940]*sun*seasonal_effect[Harrison, Winterbotom, et al. 2001

#1940]+(343*60*60*24*91.25)*((NORMAL(0,1)+NORMAL(0,1))*0.011)*seasonal_variability[Harrison, Winterbotom, et al. 2001 #1940]
sun = (1+(SINWAVE(0.01,11.6)))

DOCUMENT: This introduces variability to the flow, as suggested by studies of solar output which indicate that there is a periodic variation based on the 11 year solar cycle.

te = 0.34

DOCUMENT: The proportion of energy from the Earth to the atmosphere by thermal transfer

variability_2[argyll,spring] = NORMAL(1,0.274)

DOCUMENT: A region by season scaling factor for the precipitation output, calibrated against empirical data.

variability_2[argyll,summer] = NORMAL(1,0.295)
variability_2[argyll,autumn] = NORMAL(1,0.218)
variability_2[argyll,winter] = NORMAL(1,0.258)
variability_2[stirling,spring] = NORMAL(1,0.281)
variability_2[stirling,summer] = NORMAL(1,0.35)
variability_2[stirling,autumn] = NORMAL(1,0.253)
variability_2[stirling,winter] = NORMAL(1,0.311)
variability_2[fife,spring] = NORMAL(1,0.273)
variability_2[fife,summer] = NORMAL(1,0.334)
variability_2[fife,autumn] = NORMAL(1,0.317)
variability_2[fife,winter] = NORMAL(1,0.298)

Emissions sector

assimilation_rate = 6.2

DOCUMENT: Tons of carbon uptake per hectare of forest per year.

emmissions[argyll] =
((regional_pop[argyll]+((ARRAYSUM(tourist_numbers[argyll,*])/365)))*per_capita_carbon)-((native_farm_forestry[argyll]+plantation_forestry[argyll])*assimilation_rate)

DOCUMENT: Difference between carbon emitted and carbon assimilated for each region in a year.

emmissions[stirling] =
((regional_pop[stirling]+(ARRAYSUM(tourist_numbers[stirling,*]))/365)*per_capita_carbon)-((native_farm_forestry[stirling]+plantation_forestry[stirling])*assimilation_rate)
emmissions[fife] =
((regional_pop[fife]+((ARRAYSUM(tourist_numbers[fife,*]))/365))*per_capita_carbon)-((native_farm_forestry[fife]+plantation_forestry[fife])*assimilation_rate)
per_capita_carbon = 3.33

DOCUMENT: Tons of carbon per person per year.

total_emissions = ARRAYSUM(emmissions[*])
agriculture_employment[region] =
((crops_and_grass[region]*0.016285)+(rough_grazing[region]*0.00102834))*agric_mult

DOCUMENT: The combined figures for employment relating to rough grazing and intensive agriculture, calculated from the respective areas of each.

Employment sector

agric_mult = 2.43

DOCUMENT: The multiplier effect due to increases in agricultural employment.

forest_employment[region] = native_employment[region]+plantation_employment[region]
labour_demand[region] =
(agriculture_employment[region]+plantation_employment[region]+non_climatic_sector[region]+tourism_employment[region]+native_employment[region])

DOCUMENT: The sum of all forms of employment in each region.

native_employment[region] = (native_farm_forestry[region]/120)*native_mult

DOCUMENT: Employment in forestry relating to broadleaves and native species.

native_mult = 1.999

DOCUMENT: The multiplier effect of Native and broadleaved forestry employment.

non_climatic_sector[argyll] = labour_supply[argyll]-(0.47*labour_supply[argyll])

DOCUMENT: The employment in each region not considered to be climate sensitive.

non_climatic_sector[stirling] = labour_supply[stirling]-(0.28*labour_supply[stirling])
non_climatic_sector[fife] = labour_supply[fife]-0.19*labour_supply[fife]
plantation_employment[argyll] = ((plantation_forestry[argyll])/120)*plantation_mult

DOCUMENT: The number of employees depends on the area of plantation forestry.

plantation_employment[stirling] = (plantation_forestry[stirling]/120)*plantation_mult
plantation_employment[fife] = (plantation_forestry[fife]/120)*plantation_mult
plantation_mult = 1.722

DOCUMENT: The knock on effect of increases in plantation forestry employment.

tourirm_mult = 1

DOCUMENT: Set at 1, assuming employment figures include tourism related jobs.

tourism_employment[argyll] =
((((ARRAYSUM(tourist_numbers[argyll,*])+(DELAY(ARRAYSUM(tourist_numbers[argyll,*]),1))+(DELAY(ARRAYSUM(tourist_numbers[argyll,*]),2))+(DELAY(ARRAYSUM(tourist_numbers[argyll,*]),3))+(DELAY(ARRAYSUM(tourist_numbers[argyll,*]),4))))/5)/601)*tourirm_mult

DOCUMENT: This converts tourist numbers into employment in the tourist related industries, different rates reflect the different tourist market in the regions.

tourism_employment[stirling] =
(((ARRAYSUM(tourist_numbers[stirling,*])+(DELAY(ARRAYSUM(tourist_numbers[stirling,*]),1))+(DELAY(ARRAYSUM(tourist_numbers[stirling,*]),2))+(DELAY(ARRAYSUM(tourist_numbers[stirling,*]),3))+(DELAY(ARRAYSUM(tourist_numbers[stirling,*]),4)))/5)/601)*tourirm_mult
tourism_employment[fife] =
((((ARRAYSUM(tourist_numbers[fife,*])+(DELAY(ARRAYSUM(tourist_numbers[fife,*]),1))+(DELAY(ARRAYSUM(tourist_numbers[fife,*]),2))+(DELAY(ARRAYSUM(tourist_numbers[fife,*]),3))+(DELAY(ARRAYSUM(tourist_numbers[fife,*]),4)))/5)/358))*tourirm_mult
tourist_numbers[argyll,spring] = (0.3*(0.67*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000

DOCUMENT: Tourist numbers are calculated as a function of summer temperature.

tourist_numbers[argyll,summer] = (0.33*(0.67*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[argyll,autumn] = (0.22*(0.67*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[argyll,winter] = (0.15*(0.67*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[stirling,spring] = (0.3*(0.33*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[stirling,summer] = (0.33*(0.33*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[stirling,autumn] = (0.22*(0.33*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[stirling,winter] = (0.15*(0.33*(-18.356+0.911*meansurfacetemp[argyll,summer]+0.88*delay(meansurfacetemp[argyll,summer],1))))*1000000
tourist_numbers[fife,spring] = (0.22*(-8.695+0.78*delay(meansurfacetemp[fife,summer],1)))*1000000
tourist_numbers[fife,summer] = (0.41*(-8.695+0.78*delay(meansurfacetemp[fife,summer],1)))*1000000
tourist_numbers[fife,autumn] = (0.16*(-8.695+0.78*delay(meansurfacetemp[fife,summer],1)))*1000000
tourist_numbers[fife,winter] = (0.22*(-8.695+0.78*delay(meansurfacetemp[fife,summer],1)))*1000000
unemployed[region] = labour_supply[region]-labour_demand[region]

DOCUMENT: Labour supply minus labour demand for each region gives projected unemployment figures or generates in-migration to vacancies due to a labour shortage.

Housing sector

housing_stock[argyll](t) = housing_stock[argyll](t - dt) + (new_build[argyll]) * dt

INIT housing_stock[argyll] = 21000

DOCUMENT: The total housing stock for each region.

housing_stock[stirling](t) = housing_stock[stirling](t - dt) + (new_build[stirling]) * dt

INIT housing_stock[stirling] = 22400
housing_stock[fife](t) = housing_stock[fife](t - dt) + (new_build[fife]) * dt

INIT housing_stock[fife] = 102000
new_build[argyll] = 0.010*housing_stock[argyll]+pop_change[argyll]*0
new_build[stirling] = if(pop_change[stirling]>0)then
(0*(housing_stock[stirling])+(pop_change[stirling]*0.9)) else (0)
new_build[fife] = if(pop_change[fife]>0) then (pop_change[fife]*1.37) else (0)+housing_stock[fife]*0
demand[region] = regional_pop[region]/household_size[region]

DOCUMENT: The regional population and the mean household size are used to calculate the demand for housing.

household_size[region] = year[region]

DOCUMENT: Mean number of persons per household for each region.

pop_change[argyll] = regional_pop[argyll]-DELAY(regional_pop[argyll],1)
pop_change[stirling] = regional_pop[stirling]-DELAY(regional_pop[stirling],1)
pop_change[fife] = regional_pop[fife]-DELAY(regional_pop[fife],1)
shortagesurplus[region] = housing_stock[region]-demand[region]

DOCUMENT: Housing stock minus demand give a surplus or shortage of housing.

unfit[argyll] = if(time <20) then 0.3*housing_stock[argyll]else (0.3-0.00365*TIME)*housing_stock[argyll]

DOCUMENT: The number of houses considered below tolerable standard in each region.

unfit[stirling] = 0.018*housing_stock[stirling]
unfit[fife] = 0.01*housing_stock[fife]
household_size[region] = year[region]

DOCUMENT: Mean number of persons per household for each region.

Land use sector

crops_and_grass[argyll](t) = crops_and_grass[argyll](t - dt) + (improved[argyll] - new_building[argyll]) * dt

INIT crops_and_grass[argyll] = 31093

DOCUMENT: The area in hectares of crops and grass in each region.

crops_and_grass[stirling](t) = crops_and_grass[stirling](t - dt) + (improved[stirling] - new_building[stirling]) * dt

INIT crops_and_grass[stirling] = 36714
crops_and_grass[fife](t) = crops_and_grass[fife](t - dt) + (improved[fife] - new_building[fife]) * dt

INIT crops_and_grass[fife] = 83863
improved[argyll] = ((-(rough_grazing[argyll]-DELAY(rough_grazing[argyll],1))/15)*0.85)+temp_area_increase[argyll]

improved[stirling] = ((-(rough_grazing[stirling]-
DELAY(rough_grazing[stirling],1))/4)*1)+temp_area_increase[stirling]
improved[fife] = (-(rough_grazing[fife]-DELAY(rough_grazing[fife],1))/4)+temp_area_increase[fife]
new_building[argyll] = new_build[argyll]*0.06
new_building[stirling] = new_build[stirling]*0.06
new_building[fife] = new_build[fife]*0.06
native_farm_forestry[argyll](t) = native_farm_forestry[argyll](t - dt) + (native[argyll]) * dt

INIT native_farm_forestry[argyll] = 17981
native_farm_forestry[stirling](t) = native_farm_forestry[stirling](t - dt) + (native[stirling]) * dt

INIT native_farm_forestry[stirling] = 7458
native_farm_forestry[fife](t) = native_farm_forestry[fife](t - dt) + (native[fife]) * dt

INIT native_farm_forestry[fife] = 8243

DOCUMENT: Hectares devoted to forestry using native and broadleaved species.

native[argyll] = 12000*rate*prop_bl/5
native[stirling] = 500*rate*prop_bl/5
native[fife] = 300*rate*prop_bl/5
plantation_forestry[argyll](t) = plantation_forestry[argyll](t - dt) + (plantation[argyll]) * dt

INIT plantation_forestry[argyll] = 89687
plantation_forestry[stirling](t) = plantation_forestry[stirling](t - dt) + (plantation[stirling]) * dt

INIT plantation_forestry[stirling] = 22375
plantation_forestry[fife](t) = plantation_forestry[fife](t - dt) + (plantation[fife]) * dt

INIT plantation_forestry[fife] = 4573

DOCUMENT: Hectares devoted to plantation forestry in each region.

plantation[argyll] = (12000*rate)*proportion_plant/5
plantation[stirling] = 500*rate*proportion_plant/5
plantation[fife] = 300*rate*proportion_plant/5
rough_grazing[argyll](t) = rough_grazing[argyll](t - dt) + (- improved[argyll] - native[argyll] -
plantation[argyll]) * dt

INIT rough_grazing[argyll] = 658854

DOCUMENT: The area in hectares of rough grazing in each region.

rough_grazing[stirling](t) = rough_grazing[stirling](t - dt) + (- improved[stirling] - native[stirling] -
plantation[stirling]) * dt

INIT rough_grazing[stirling] = 59245
rough_grazing[fife](t) = rough_grazing[fife](t - dt) + (- improved[fife] - native[fife] - plantation[fife]) * dt

INIT rough_grazing[fife] = 12040
improved[argyll] = ((-(rough_grazing[argyll]-
DELAY(rough_grazing[argyll],1))/15)*0.85)+temp_area_increase[argyll]
improved[stirling] = ((-(rough_grazing[stirling]-
DELAY(rough_grazing[stirling],1))/4)*1)+temp_area_increase[stirling]
improved[fife] = (-(rough_grazing[fife]-DELAY(rough_grazing[fife],1))/4)+temp_area_increase[fife]
native[argyll] = 12000*rate*prop_bl/5
native[stirling] = 500*rate*prop_bl/5

native[fife] = 300*rate*prop_bl/5
plantation[argyll] = (12000*rate)*proportion_plant/5
plantation[stirling] = 500*rate*proportion_plant/5
plantation[fife] = 300*rate*proportion_plant/5
urban[argyll](t) = urban[argyll](t - dt) + (new_building[argyll]) * dt

INIT urban[argyll] = 3090

DOCUMENT: Urban areas per region.

urban[stirling](t) = urban[stirling](t - dt) + (new_building[stirling]) * dt

INIT urban[stirling] = 2970
urban[fife](t) = urban[fife](t - dt) + (new_building[fife]) * dt

INIT urban[fife] = 11997
new_building[argyll] = new_build[argyll]*0.06
new_building[stirling] = new_build[stirling]*0.06
new_building[fife] = new_build[fife]*0.06
proportion_plant = IF(TIME<16)then 0.99 else(if(time>15and time <21) then 0.9 else 0.45)

DOCUMENT: The proportion of the land changing use from rough grazing to forestry which ends up as plantation forestry.

prop_bl = IF(TIME<16)then 0.01 else(if(time>15and time <21) then 0.1 else 0.55)

DOCUMENT: The proportion of land changing to forestry which is devoted to native species.

rate = IF(TIME<6)then 3 else(if(time>5and time <21) then 2 else 1)

DOCUMENT: The overall rate of planting of forestry.

runningmean[region] =
MEAN(DELAY(annual_temp[region],10),DELAY(annual_temp[region],9),DELAY(annual_temp[region],
8),DELAY(annual_temp[region],7),DELAY(annual_temp[region],6),DELAY(annual_temp[region],5),DE
LAY(annual_temp[region],4),DELAY(annual_temp[region],3),DELAY(annual_temp[region],2),DELAY(
annual_temp[region],1))

DOCUMENT: The ten year running mean of temperature.

temp_area_increase[argyll] =
(IF(TIME>30)THEN(IF(crops_and_grass[argyll]<39106AND(runningmean[argyll]-
8.92>0.2))THEN(4367)ELSE(IF(crops_and_grass[argyll]<59523AND(runningmean[argyll]-
8.92>0.7))THEN(3481)ELSE(IF(crops_and_grass[argyll]<75797AND(runningmean[argyll]-
8.92>1.2))THEN(1859)ELSE(IF(crops_and_grass[argyll]<86786AND(runningmean[argyll]-
8.92>1.7))THEN(1129)ELSE(IF(crops_and_grass[argyll]<93117AND(runningmean[argyll]-
8.92>2.2))THEN(1000)ELSE(IF(crops_and_grass[argyll]<96190AND(runningmean[argyll]-
8.92>2.7))THEN(840)ELSE(0)))))))ELSE(0))*0.185

DOCUMENT: The increase in the rate of change of land from rough grazing to intensive agriculture as a result of increasing temperatures.

temp_area_increase[stirling] =
(IF(TIME>30)THEN(IF(crops_and_grass[stirling]<49369AND(runningmean[stirling]-
8.8>0.2))THEN(1000)ELSE(IF(crops_and_grass[stirling]<57674AND(runningmean[stirling]-

8.8>0.7))THEN(650)ELSE(IF(crops_and_grass[stirling]<64749AND(runningmean[stirling]-8.8>1.2))THEN(460)ELSE(IF(crops_and_grass[stirling]<70824AND(runningmean[stirling]-8.8>2.2))THEN(480)ELSE(0)))))ELSE(0))*0.505
temp_area_increase[fife] =
(IF(TIME>30)THEN(IF(crops_and_grass[fife]<85361AND(runningmean[fife]-8.25>0.2))THEN(100)ELSE(IF(crops_and_grass[fife]<85608AND(runningmean[fife]-8.25>0.6))THEN(20)ELSE(IF(crops_and_grass[fife]<85635AND(runningmean[fife]-8.25>1.1))THEN(3)ELSE(IF(crops_and_grass[fife]<85637AND(runningmean[fife]-8.25>1.6))THEN(1)ELSE(0)))))ELSE(0))*0.676
total_area[region] =
crops_and_grass[region]+plantation_forestry[region]+rough_grazing[region]+urban[region]+native_farm_forestry[region]

population sector

middle[argyll](t) = middle[argyll](t - dt) + (enter_workforce[argyll] + migration2[argyll] + job_seekers[argyll] - retire[argyll] - deathrate2[argyll]) * dt

INIT middle[argyll] = 55400
middle[stirling](t) = middle[stirling](t - dt) + (enter_workforce[stirling] + migration2[stirling] + job_seekers[stirling] - retire[stirling] - deathrate2[stirling]) * dt

INIT middle[stirling] = 41756
middle[fife](t) = middle[fife](t - dt) + (enter_workforce[fife] + migration2[fife] + job_seekers[fife] - retire[fife] - deathrate2[fife]) * dt

INIT middle[fife] = 181030

DOCUMENT: The working population, those aged between 20 and 65.

enter_workforce[region] = 0.05*young[region]

DOCUMENT: The number of young people each year who enter the middle age group.

migration2[region] = year[region]

DOCUMENT: The average number of migrants per year to each region.

job_seekers[region] = IF(unemployed[region]<0)THEN(-unemployed[region])ELSE(0)

DOCUMENT: Those entering a region because of a labour shortage.

retire[region] = 0.018*middle[region]

DOCUMENT: Those retiring and entering the older age group.

deathrate2[argyll] = DR2[argyll]*middle[argyll]
deathrate2[stirling] = DR2[stirling]*middle[stirling]
deathrate2[fife] = DR2[fife]*middle[fife]
older[argyll](t) = older[argyll](t - dt) + (retire[argyll] + migration3[argyll] - die[argyll]) * dt

INIT older[argyll] = 14820

DOCUMENT: Those over 65 in each region.

older[stirling](t) = older[stirling](t - dt) + (retire[stirling] + migration3[stirling] - die[stirling]) * dt

INIT older[stirling] = 10311
older[fife](t) = older[fife](t - dt) + (retire[fife] + migration3[fife] - die[fife]) * dt

INIT older[fife] = 47043
retire[region] = 0.018*middle[region]

DOCUMENT: Those retiring and entering the older age group.

migration3[region] = year[region]

DOCUMENT: The migration of older persons.

die[argyll] = DR3[argyll]*older[argyll]
die[stirling] = DR3[stirling]*older[stirling]
die[fife] = DR3[fife]*older[fife]
young[argyll](t) = young[argyll](t - dt) + (births[argyll] + migration1[argyll] - enter_workforce[argyll] - deathrate_1[argyll]) * dt

INIT young[argyll] = 21150
young[stirling](t) = young[stirling](t - dt) + (births[stirling] + migration1[stirling] - enter_workforce[stirling] - deathrate_1[stirling]) * dt

INIT young[stirling] = 23934
young[fife](t) = young[fife](t - dt) + (births[fife] + migration1[fife] - enter_workforce[fife] - deathrate_1[fife]) * dt

INIT young[fife] = 99870

DOCUMENT: The young population of each region, including those between 0 and 19 years of age.

births[argyll] = birthrate[argyll]*(regional_pop[argyll])/1000
births[stirling] = birthrate[stirling]*(regional_pop[stirling])/1000
births[fife] = birthrate[fife]*(regional_pop[fife])/1000
migration1[argyll] = 0.43*migration2[argyll]
migration1[stirling] = 0.38*migration2[stirling]
migration1[fife] = 0.43*migration2[fife]
enter_workforce[region] = 0.05*young[region]

DOCUMENT: The number of young people each year who enter the middle age group.

deathrate_1[argyll] = (DR1[argyll]/10)*young[argyll]
deathrate_1[stirling] = (DR1[stirling])*young[stirling]/1000
deathrate_1[fife] = (DR1[fife])*young[fife]/1000
birthrate[region] = year[region]

DOCUMENT: The birth rate for each region, using the projections from the GROS.

DR1[region] = year[argyll]

DOCUMENT: The deathrate in the young age group.

DR2[region] = year[argyll]

DOCUMENT: The rate of deaths in the middle age group.

DR3[region] = year[argyll]

DOCUMENT: The death rate among the older population.

labour_supply[argyll] = middle[argyll]*0.76
labour_supply[stirling] = middle[stirling]*0.916
labour_supply[fife] = middle[fife]*0.786

DOCUMENT: The proportion of the middle age group who are economically active.

regional_pop[region] = middle[region]+older[region]+young[region]

DOCUMENT: The total population of each region.

total_pop = ARRAYSUM(regional_pop[*])
year[region] = TIME
birthrate[region] = year[region]

DOCUMENT: The birth rate for each region, using the projections from the GROS.

DR1[region] = year[argyll]

DOCUMENT: The deathrate in the young age group.

DR2[region] = year[argyll]

DOCUMENT: The rate of deaths in the middle age group.

DR3[region] = year[argyll]

DOCUMENT: The death rate among the older population.

Water resource sector

evapo[argyll,spring] = (151.8+(0.04*(meansurfacetemp[argyll,spring]-7.72))*151.8)*region_area[argyll]*10000

DOCUMENT: Estimated mean rates of evapotranspiration for each region and for each season. This includes an increase of 4% for each degree increase in temperature.

evapo[argyll,summer] = (253+(0.04*(meansurfacetemp[argyll,summer]-13.44))*253)*region_area[argyll]*10000
evapo[argyll,autumn] = (107.5+(0.04*(meansurfacetemp[argyll,autumn]-9.6))*107.5)*region_area[argyll]*10000
evapo[argyll,winter] = ((23+(0.04*(meansurfacetemp[argyll,winter]-4.9))*23)*region_area[argyll]*10000)

evapo[stirling,spring] = (149+(0.04*(meansurfacetemp[stirling,spring]-7.73))*149)*region_area[stirling]*10000
evapo[stirling,summer] = (216+(0.04*(meansurfacetemp[stirling,summer]-14.26))*216)*region_area[stirling]*10000
evapo[stirling,autumn] = (97.2+(0.04*(meansurfacetemp[stirling,autumn]-9.2))*97.2)*region_area[stirling]*10000
evapo[stirling,winter] = (13.8+(0.04*(meansurfacetemp[stirling,winter]-3.95))*13.8)*region_area[stirling]*10000
evapo[fife,spring] = (209.5+(0.04*(meansurfacetemp[fife,spring]-7.1))*209.5)*region_area[fife]*10000
evapo[fife,summer] = (303.6+(0.04*(meansurfacetemp[fife,summer]-13.71))*303.6)*region_area[fife]*10000
evapo[fife,autumn] = (136.6+(0.04*(meansurfacetemp[fife,autumn]-8.72))*136.6)*region_area[fife]*10000
evapo[fife,winter] = (24.8+(0.04*(meansurfacetemp[fife,winter]-3.41))*24.8)*region_area[fife]*10000
human_use[argyll,spring] = (regional_pop[argyll]*92+tourist_numbers[argyll,spring])*479

DOCUMENT: The regional population and the number of tourists multiplied by the average daily consumption of water over each season.

human_use[argyll,summer] = (regional_pop[argyll]*92+tourist_numbers[argyll,summer])*479
human_use[argyll,autumn] = (regional_pop[argyll]*92+tourist_numbers[argyll,autumn])*479
human_use[argyll,winter] = (regional_pop[argyll]*92+tourist_numbers[argyll,winter])*479
human_use[stirling,spring] = (regional_pop[stirling]*92+tourist_numbers[stirling,spring])*479
human_use[stirling,summer] = (regional_pop[stirling]*92+tourist_numbers[stirling,summer])*479
human_use[stirling,autumn] = (regional_pop[stirling]*92+tourist_numbers[stirling,autumn])*479
human_use[stirling,winter] = (regional_pop[stirling]*92+tourist_numbers[stirling,winter])*479
human_use[fife,spring] = (regional_pop[fife]*92+tourist_numbers[fife,spring])*479
human_use[fife,summer] = (regional_pop[fife]*92+tourist_numbers[fife,summer])*479
human_use[fife,autumn] = (regional_pop[fife]*92+tourist_numbers[fife,autumn])*479
human_use[fife,winter] = (regional_pop[fife]*92+tourist_numbers[fife,winter])*479
inrain2[region,Season] = precipitation_2[region,Season]*region_area[region]*10000

DOCUMENT: This takes mean seasonal rainfall over the entire region and calculates the quantity in litres.

region_area[argyll] = 702300
region_area[stirling] = 224320
region_area[fife] = 134045

DOCUMENT: The area in hectares of each region.

resource[region,Season] = inrain2[region,Season]-(human_use[region,Season]+evapo[region,Season]+runoff[region,Season])

DOCUMENT: Litres of water surplus or deficit.

resource_mm[region,Season] = resource[region,Season]/(10000*region_area[region])

DOCUMENT: Converting the resource in litres to a measure of mm of rainfall

runoff[argyll,spring] = 0.62*precipitation_2[argyll,spring]*region_area[argyll]*10000

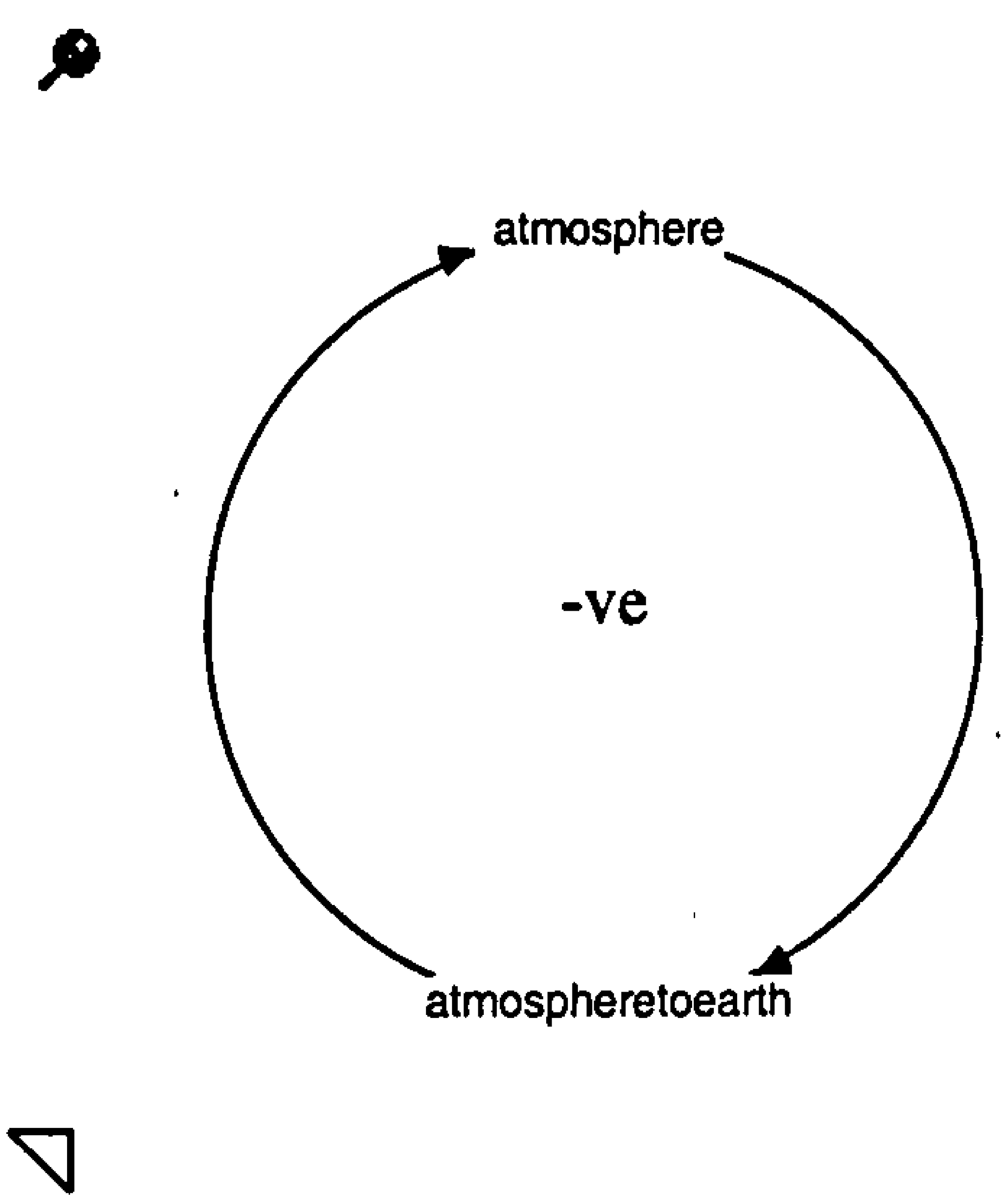
DOCUMENT: For each season and each region this gives a figure for the percentage of precipitation which is lost as runoff.

runoff[argyll,summer] = 0.45*precipitation_2[argyll,summer]*region_area[argyll]*10000
runoff[argyll,autumn] = 0.825*precipitation_2[argyll,autumn]*region_area[argyll]*10000
runoff[argyll,winter] = 0.75*precipitation_2[argyll,winter]*region_area[argyll]*10000
runoff[stirling,spring] = 0.58*precipitation_2[stirling,spring]*region_area[stirling]*10000
runoff[stirling,summer] = 0.425*precipitation_2[stirling,summer]*region_area[stirling]*10000
runoff[stirling,autumn] = 0.79*precipitation_2[stirling,autumn]*region_area[stirling]*10000
runoff[stirling,winter] = 0.911*precipitation_2[stirling,winter]*region_area[stirling]*10000
runoff[fife,spring] = 0.3*precipitation_2[fife,spring]*region_area[fife]*10000
runoff[fife,summer] = 0.21*precipitation_2[fife,summer]*region_area[fife]*10000
runoff[fife,autumn] = 0.7*precipitation_2[fife,autumn]*region_area[fife]*10000
runoff[fife,winter] = 0.757*precipitation_2[fife,winter]*region_area[fife]*10000

A.4 The Structure of the Model

Climate sector

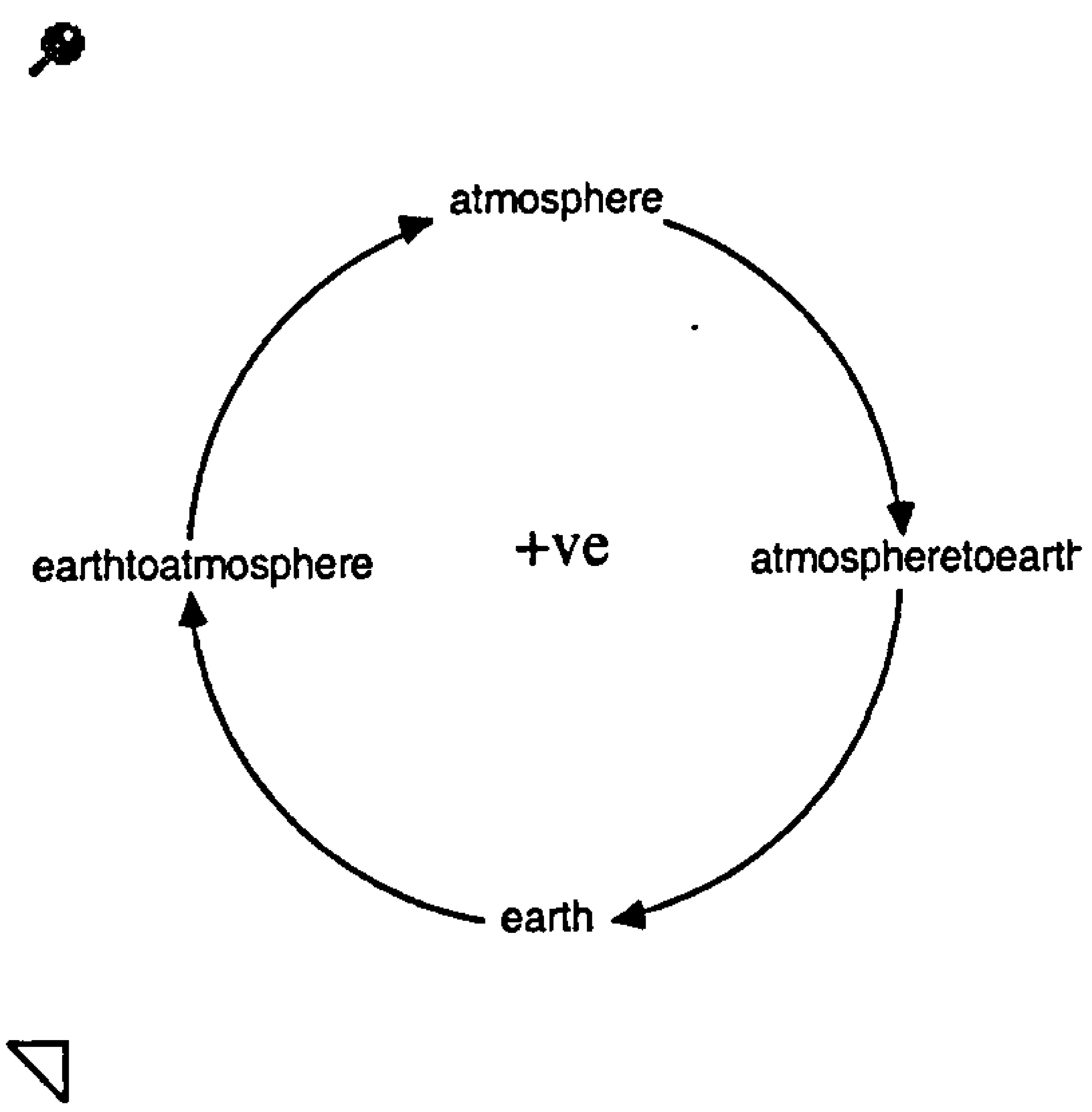
Loop1



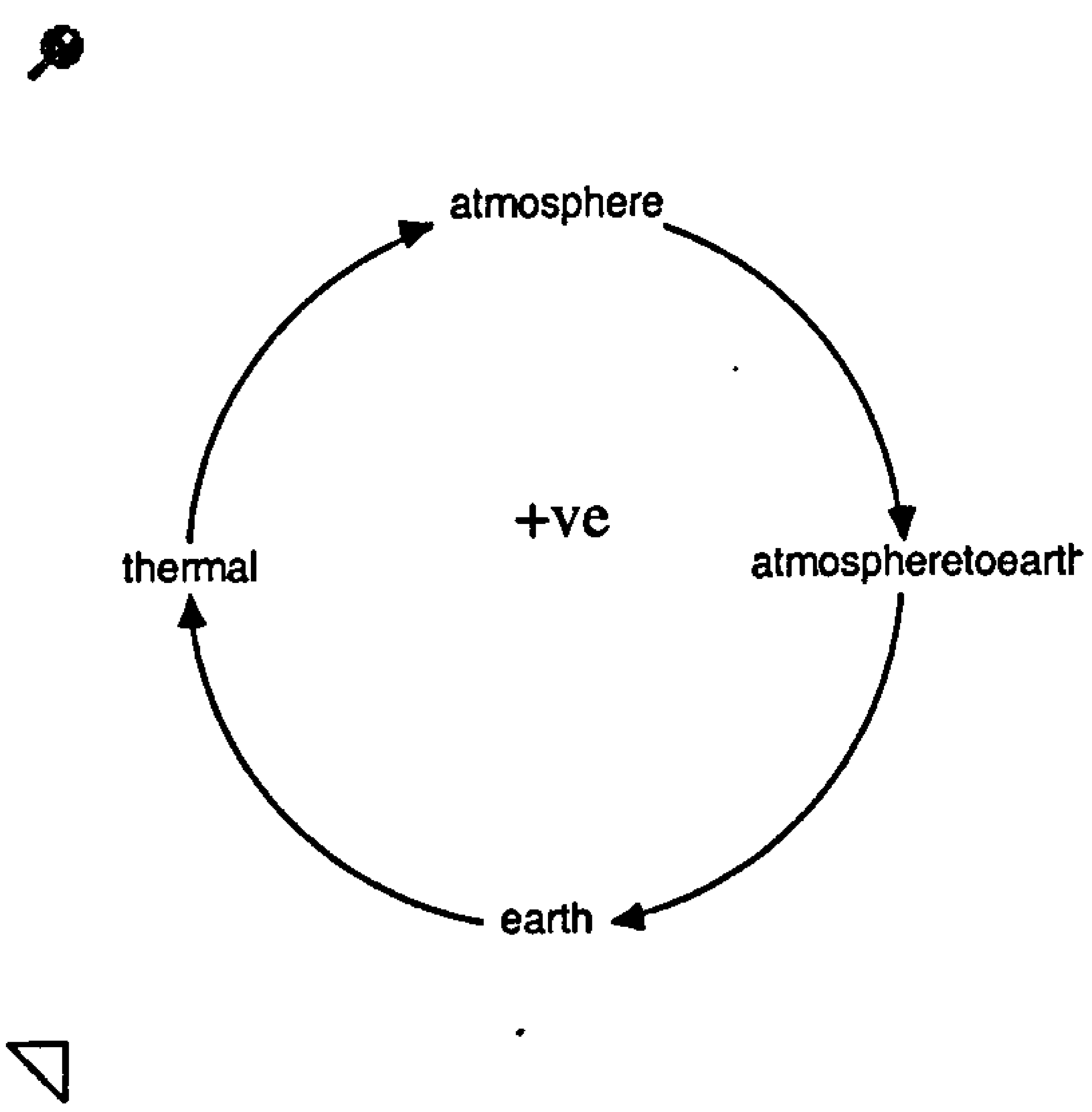
This loop represents the flow of energy from the atmosphere to the Earth which is controlled by the variable "ra", representing the proportion of the radiation stored in the atmosphere which is emitted towards the Earth. This is a negative feedback loop- the more energy held in the atmosphere the more will be emitted and hence the store in the atmosphere will drop. Further examination of the model reveals that this is also part of two other loop structures. Loop 2 shows the feedback through from atmosphere to earth and then back to the atmosphere in the form of long wave radiation, a positive feedback loop. Loop 3 shows the same route, but the energy transfer is in the form of thermal transfer of energy, involving convective heat transfer as well as energy transfer in the form of latent heat of evaporation and condensation.

Loop 2 and Loop 3 are both positive feedback loops

Loop 2

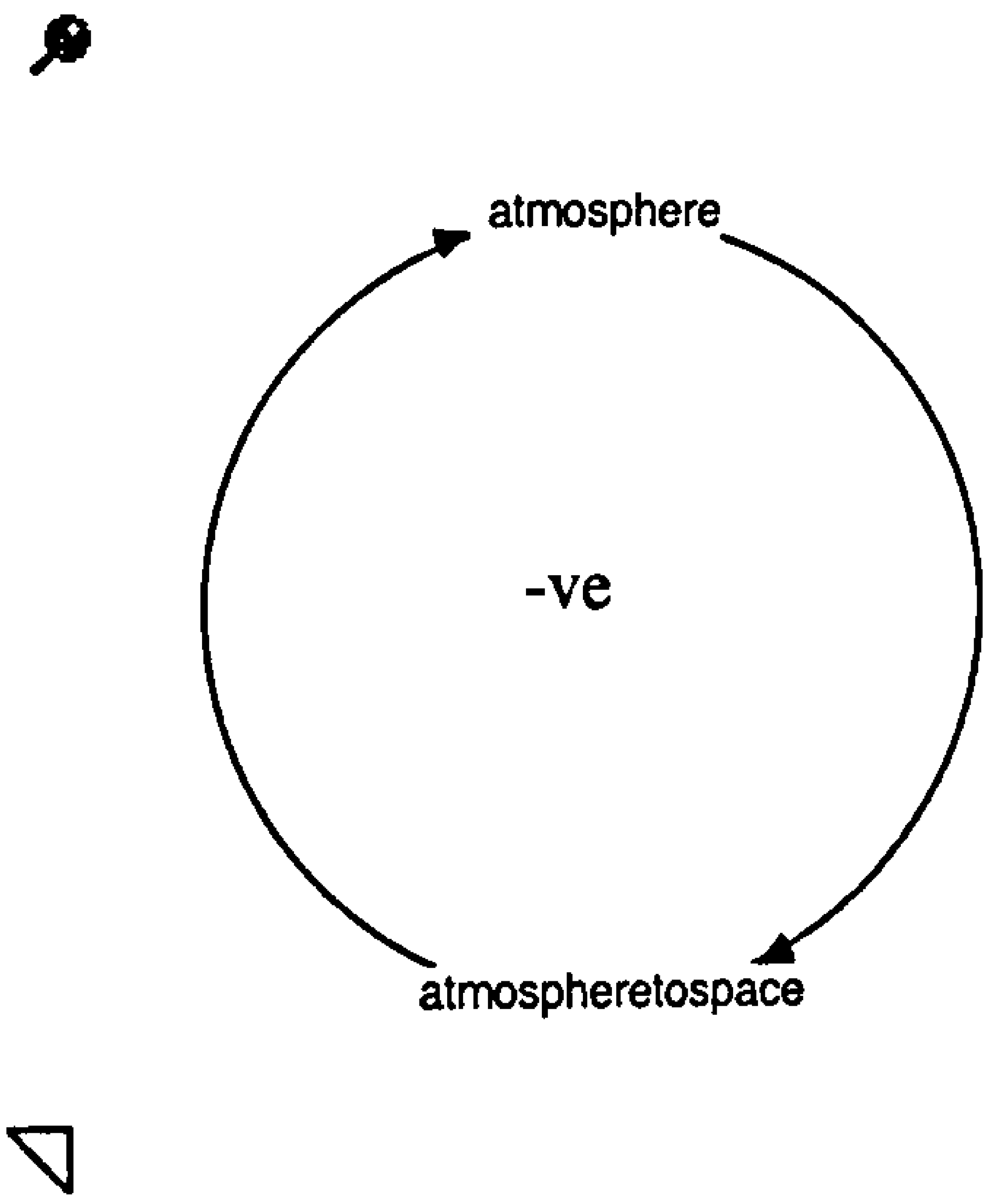


Loop 3



The final loop associated with the store of energy in the atmosphere, Loop 4, is a simple structure which involves the loss of energy to space. Energy in the form of short wave radiation which has been absorbed by the atmosphere is re-emitted as long wave energy, a proportion of which is lost to space. This is a negative feedback loop- as the energy in the atmosphere increases so the rate at which it is lost increases.

Loop 4



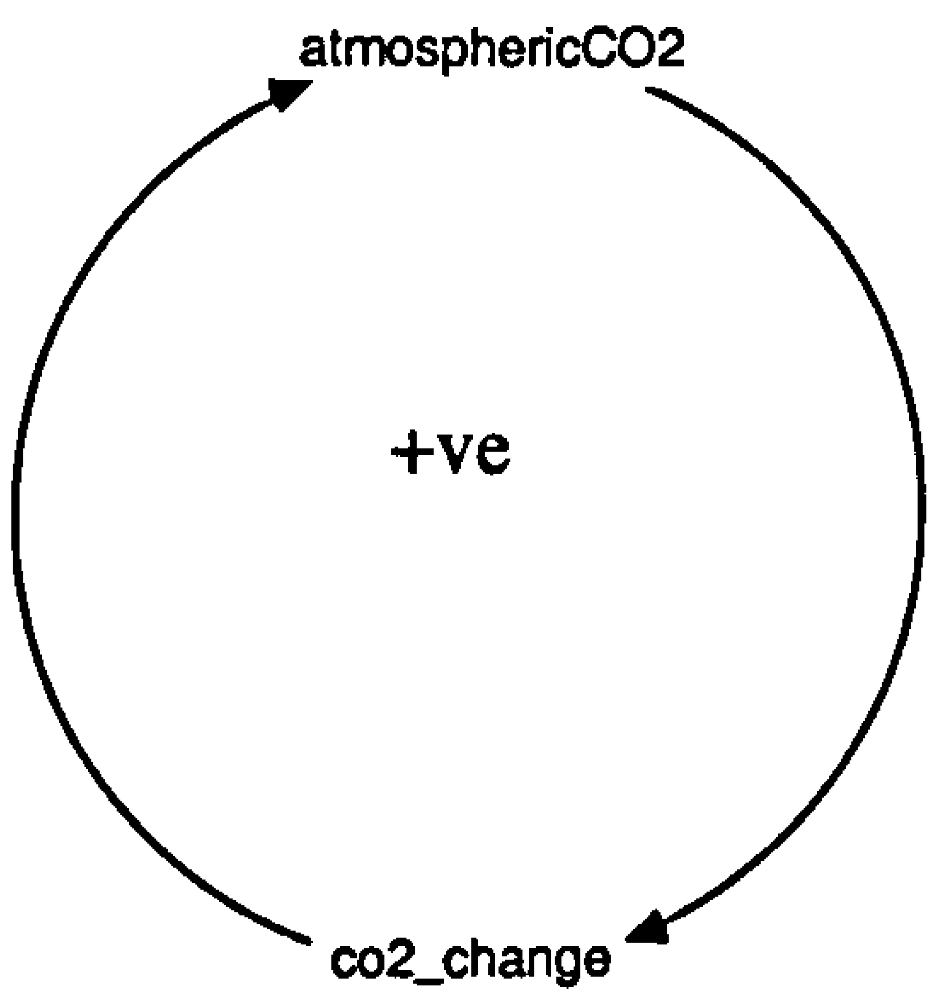
Within the climate sector there is one other feedback loop which involves the store of carbon dioxide in the atmosphere and the rate at which this changes through time. For each of the four IPCC scenarios there is a different relationship between CO_2 levels and the rate of change. In each case the rate of change of CO_2 is controlled by a graphical function. The values used for each of the model scenarios are given in table 6.1.

Although defined as a feedback loop, the rate at which carbon dioxide in the atmosphere increases is determined by factors which are beyond the boundaries of the model, such as global population change and processes of industrialisation in the developing world. This "CO_2 change" should therefore be seen as an exogenous variable.

Level of Atmospheric CO_2 (ppm)	Low scenario Rate of Change of CO_2 ($ppmDT^{-1}$)	Medium Low Rate of Change of CO_2 ($ppmDT^{-1}$)	Medium High Rate of Change of CO_2 ($ppmDT^{-1}$)	High Scenario Rate of Change of CO_2 ($ppmDT^{-1}$)
270	0.275	0.275	0.275	0.275
323	0.725	0.725	0.725	0.725
376	2.125	2.125	2.1	2.1
429	2.425	2.425	3.725	4.225
482	2.3	2.425	4.05	5.0
535	0.350	2.325	4.9	5.88
588	0.350	2.325	5.0	6.712
641	0.375	2.325	5.0	6.825
694	0.325	2.325	5.0	6.788
747	0.3	2.325	5.0	6.788
800	0.35	2.325	5.0	6.750

Table A.1 Rates of change of atmospheric CO2 for the different scenarios.

Loop 5

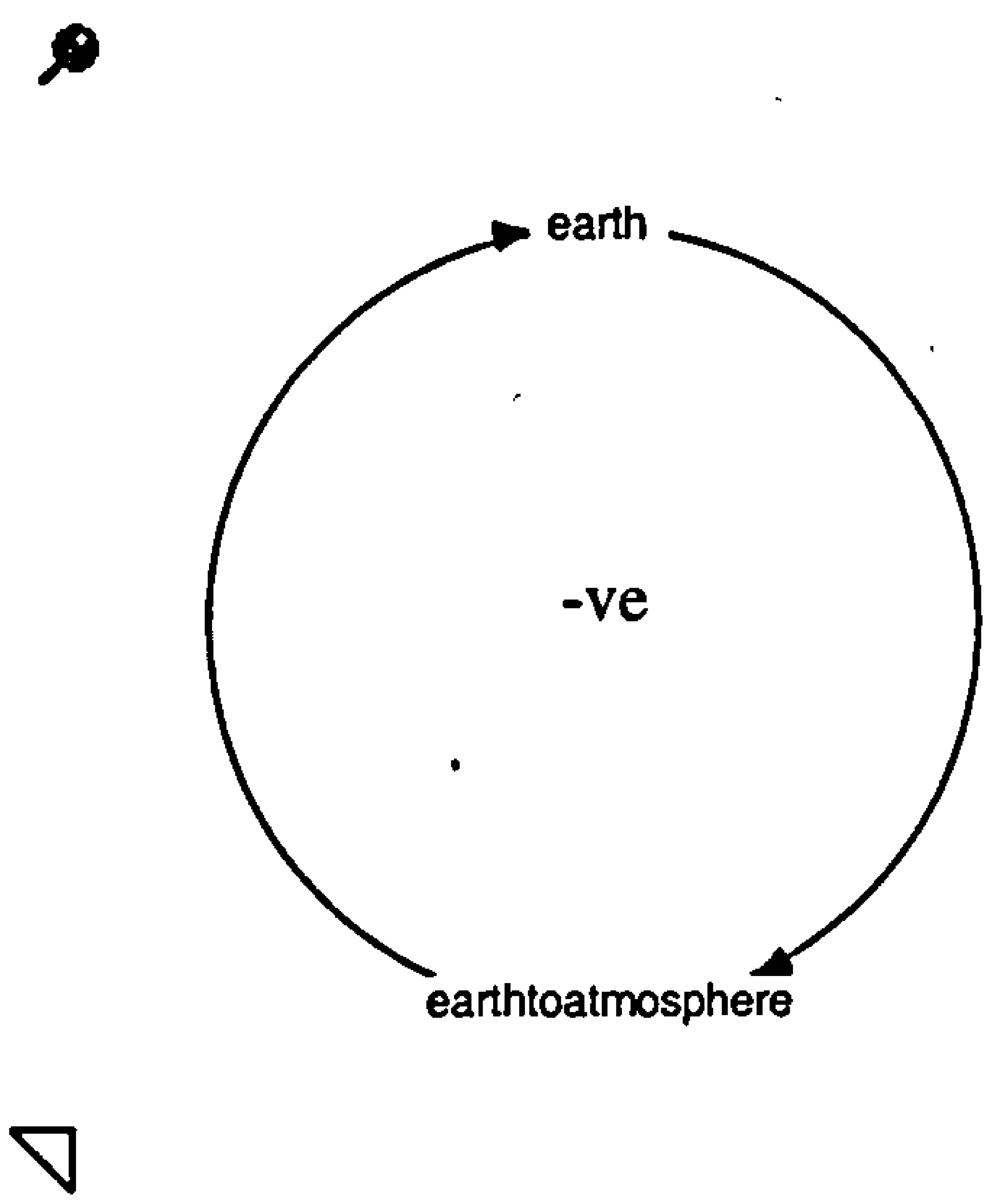


In each case these figures generate levels of atmospheric carbon dioxide which are accurate for the period from 1970 to present and which generate future concentrations which are in keeping with the forecasts from the IPPC Special Report on Emissions Scenarios (IPCC 2000).

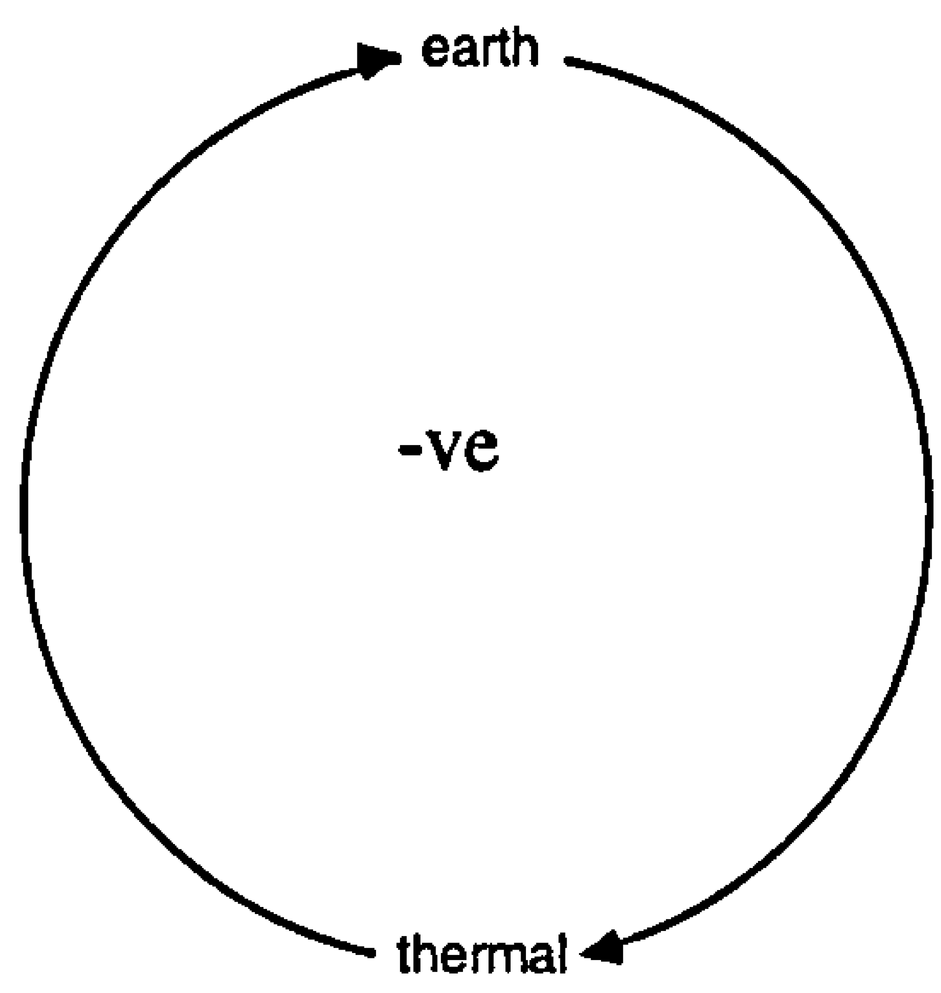
Loop 5 is a positive feedback loop. At no point does the rate of change become negative. The only difference between the four scenarios is that the rate at which this change occurs is different, with the higher scenarios having a more rapid increase than the lower. In all cases the level of CO_2 in the atmosphere continues to rise for the duration of the simulation.

Within the climate sector there are also five loops which affect the store of energy in the Earth's surface. Loops 6,7 and 8 show the simple feedback loops which represent the flows of energy from the earth as long wave radiation to the atmosphere, as thermal transfer to the atmosphere and as long wave radiation lost to space. All three are negative feedback loops.

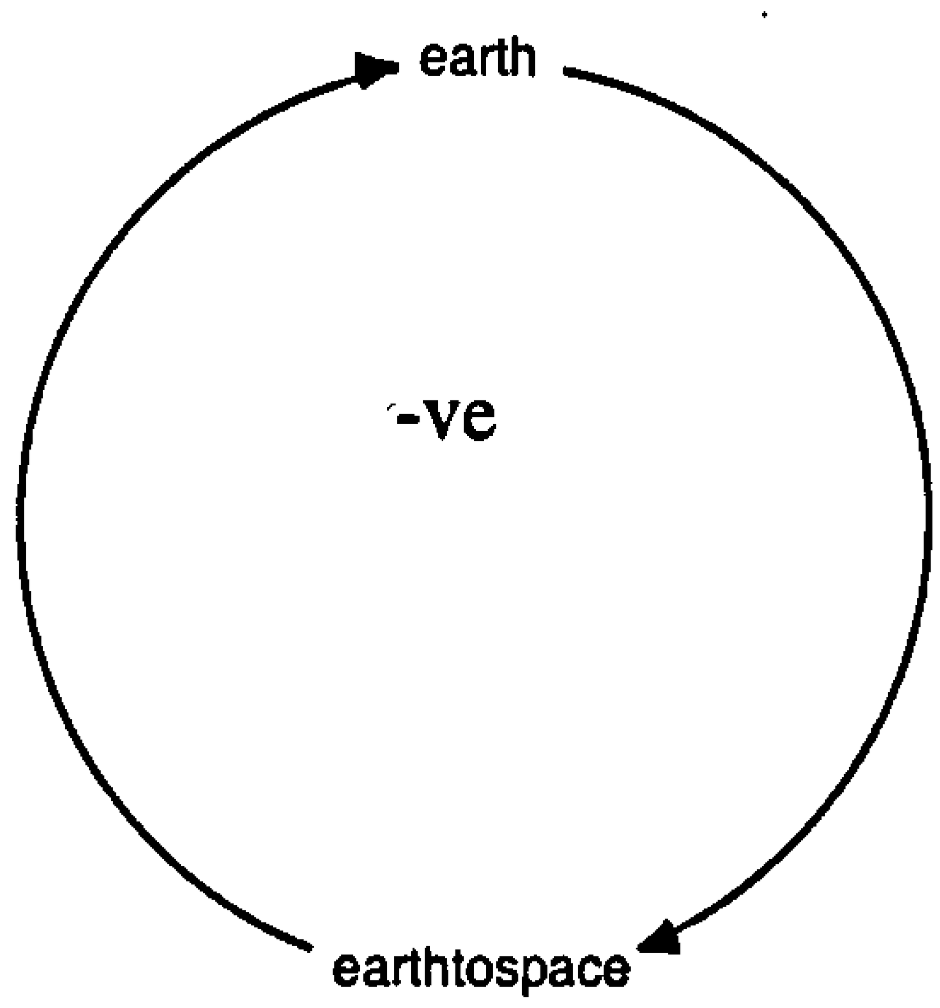
Loop 6



Loop 7

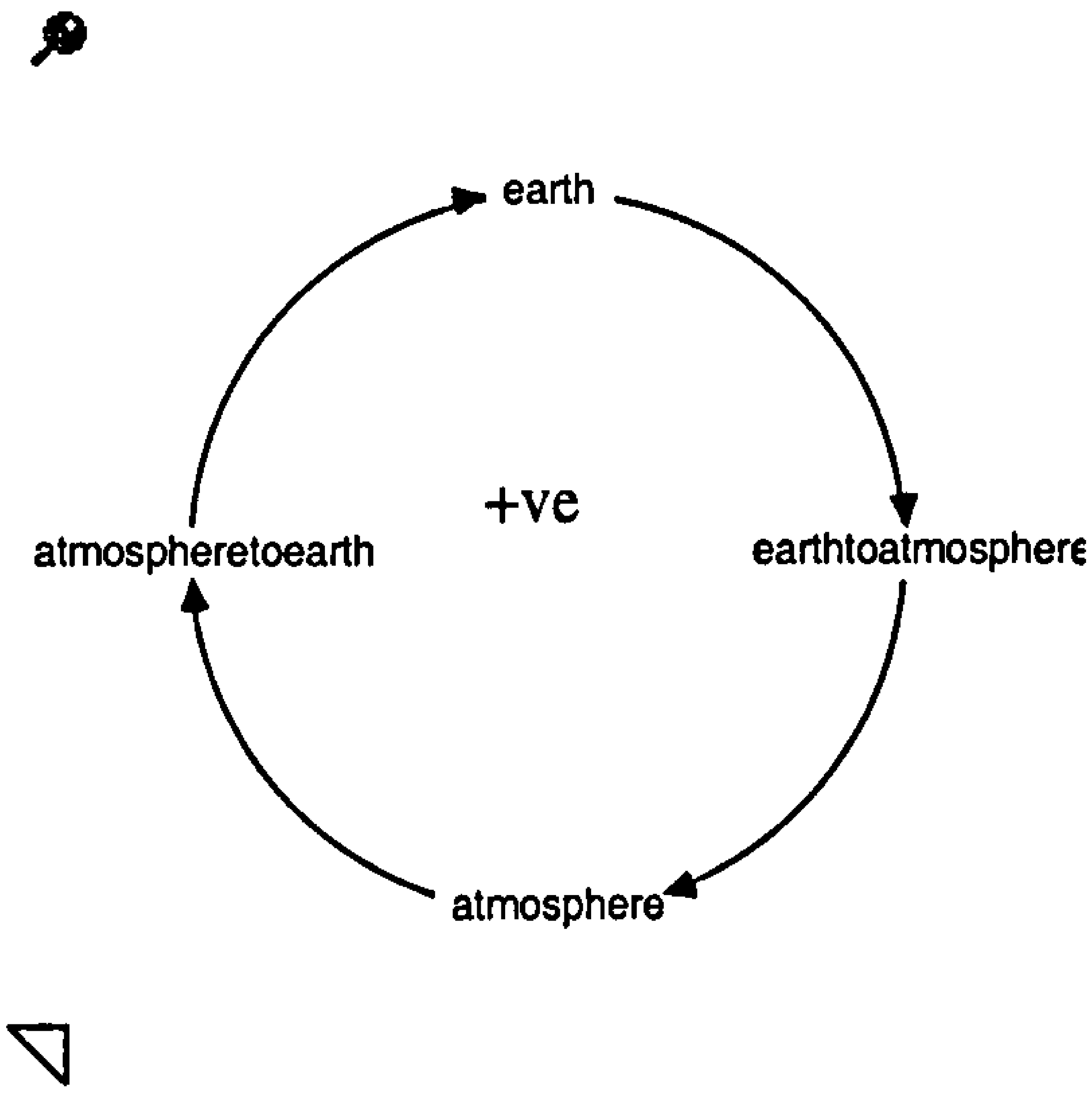


Loop 8

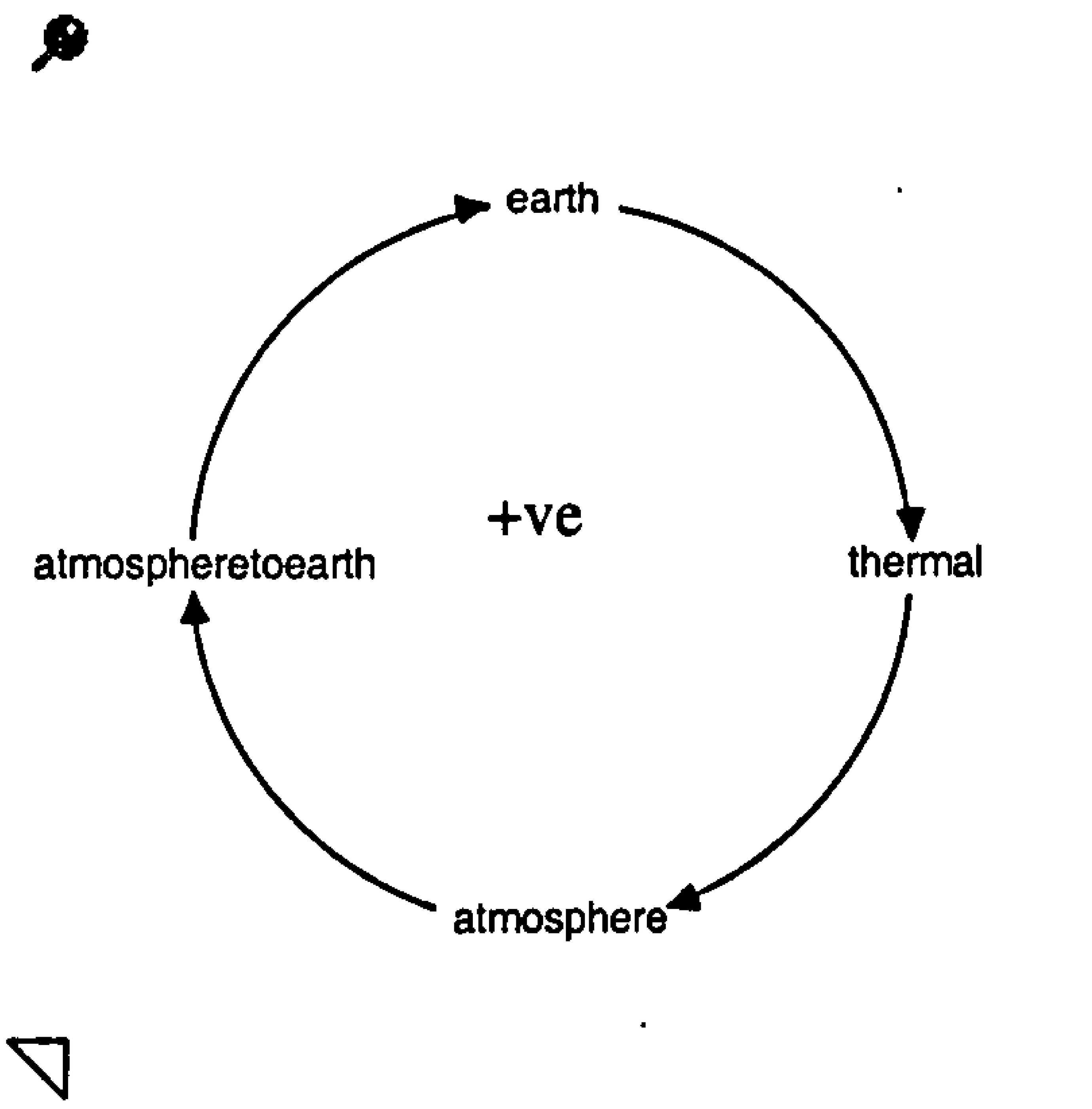


Loops 6 and 7 also form part of larger loop structures which are shown in Loops 9 and 10. Both of these are positive feedback loops, representing the transfer of energy from the Earth's surface to the atmosphere as either radiation or as thermal transfer, and then re-emitted from the atmosphere back to the Earth.

Loop 9



Loop 10



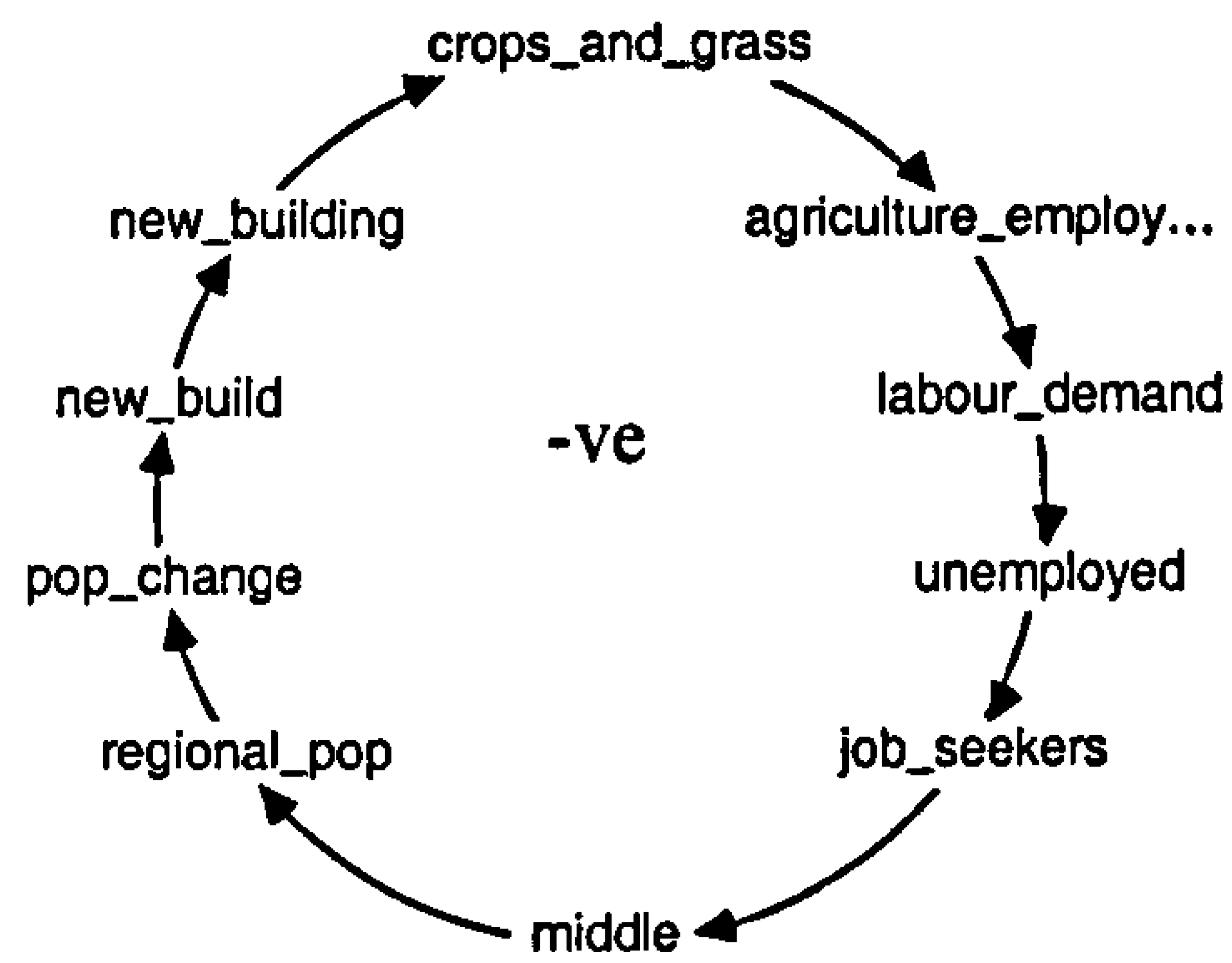
The interaction between these different feedback loops causes an initial oscillation in the stores of energy and hence an oscillation in the mean surface temperatures generated. This quickly subsides and further fluctuations are due solely to the built-in variability in seasonal and regional temperatures.

Land Use Sector

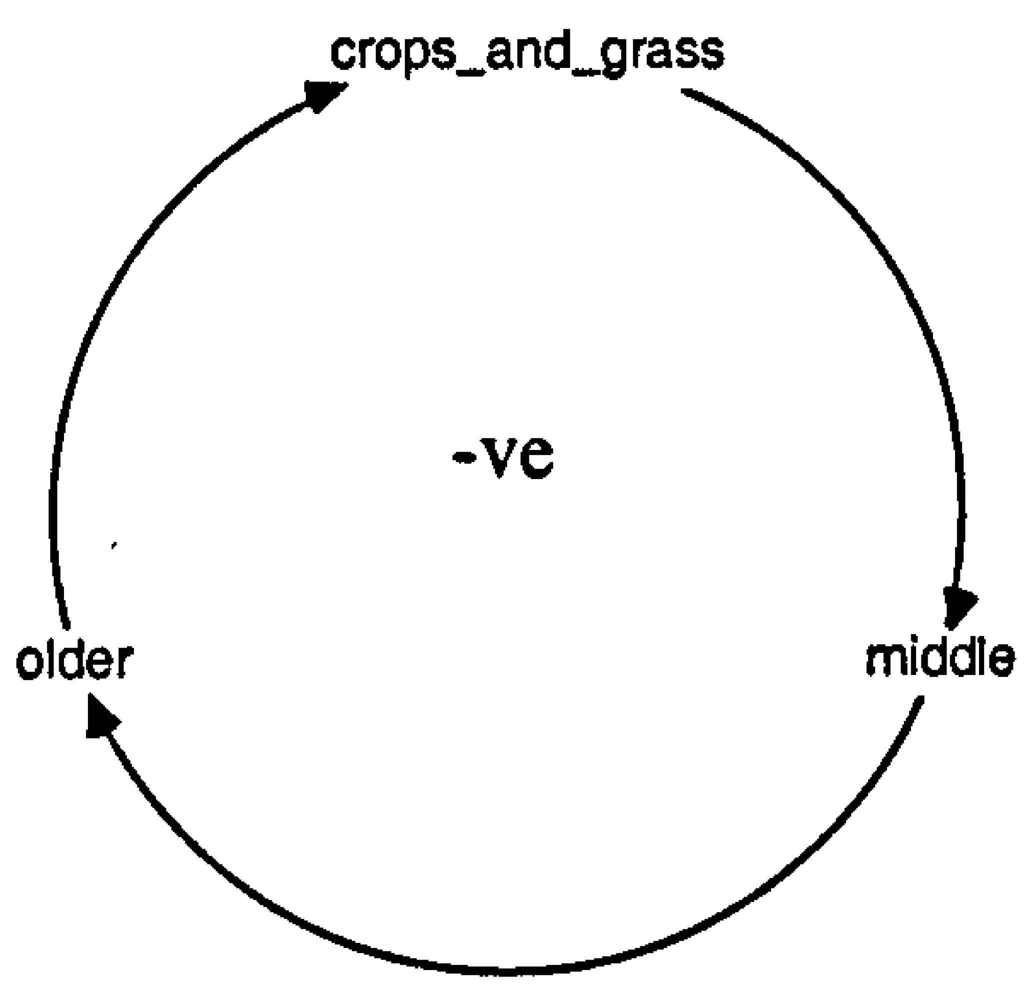
Three feedback loops originate in the Land Use sector. Two have an effect on the extent of crops and grass, both negative, and one, also negative, affects the area of rough grazing.

Both of the loops which originate in the stock representing the area of crops and grass have a very similar structure. They both represent the effect of increasing population on the extent of crops and grass through the building of new homes. Loop 11 does so by considering the impact of the "middle" population group on the total population, whereas Loop 12 includes the effect of the increase in the "older" group on total population. Because of the number of elements included in these feedback loops, loop 12 is represented in a simplified form, all other "missing" elements being the same as those in Loop11, with the addition of a link between the "middle" and "older" age groups.

Loop 11



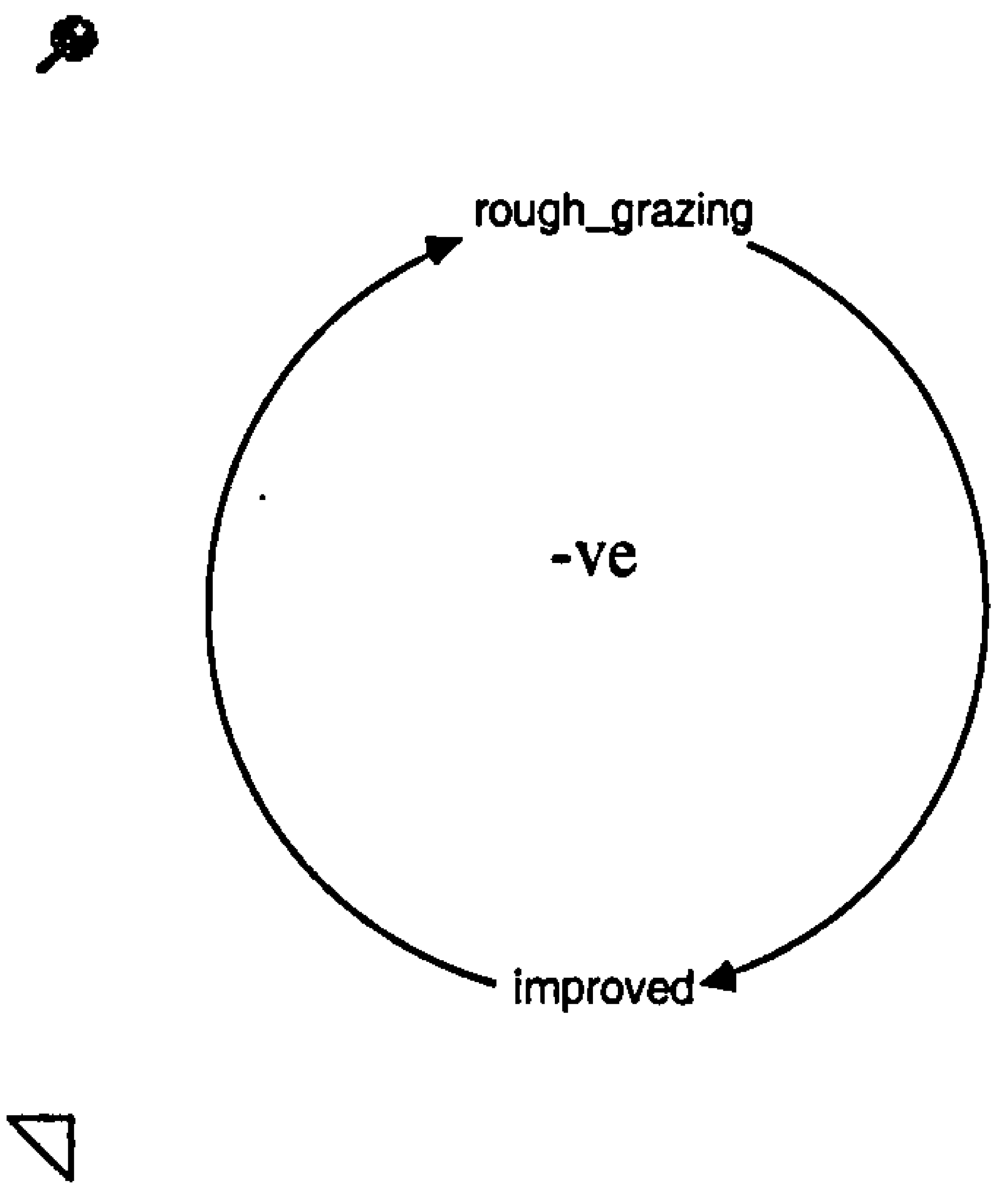
Loop 12



The overall effect of these two loops is to stabilise the areas of crops and grass in each region. An increase in cultivated area, generated by increased temperatures, increases employment which can increase in-migration and hence the building of new homes, which in turn reduces the area of crops and grass.

One feedback loop is associated with rough grazing and is a simple negative feedback loop. This involves the area of rough grazing and the rate at which it is converted to crops and grass and is illustrated as loop 13

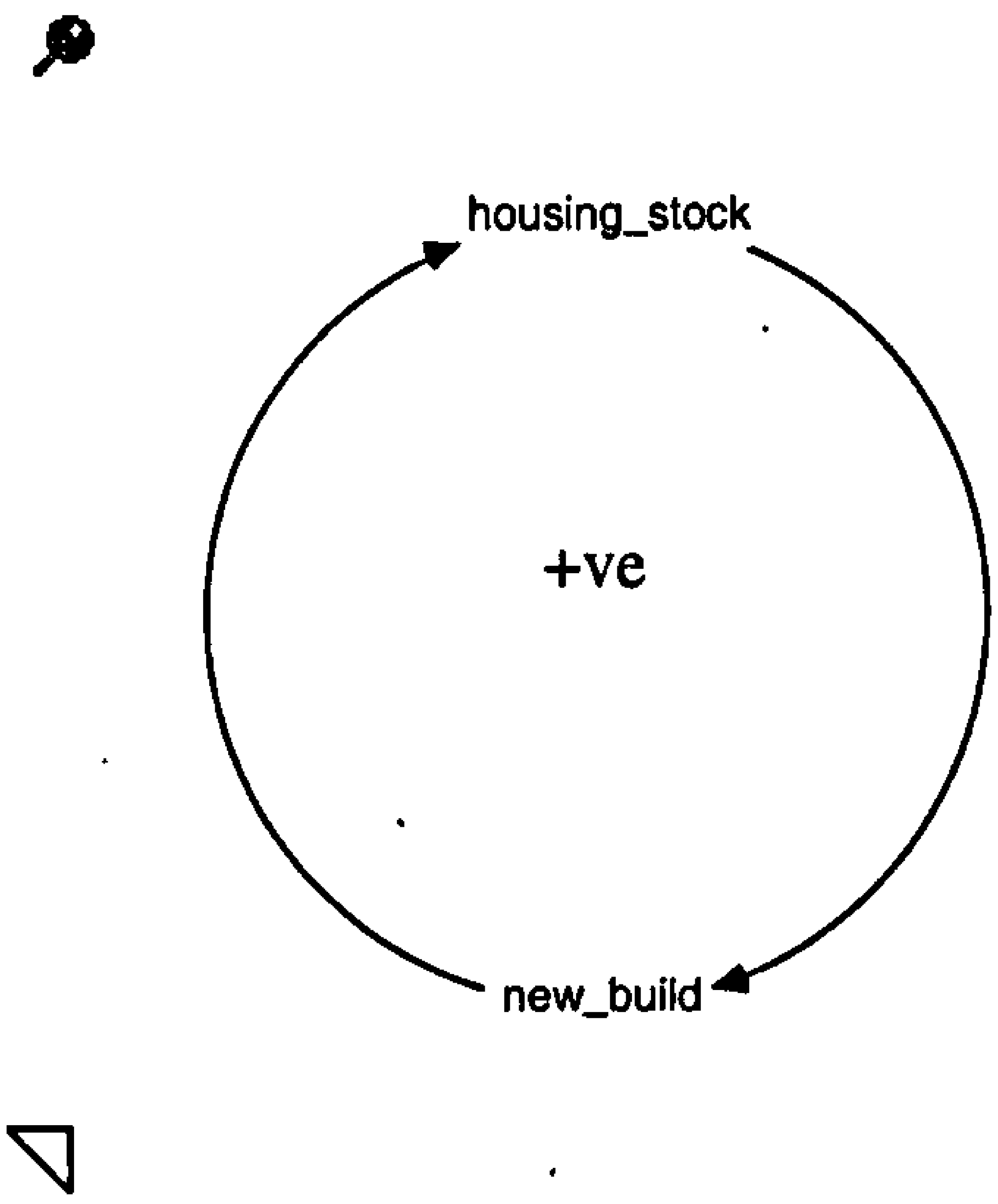
Loop 13



Housing Sector

One feedback loop exists within the housing sector, linking the housing stock to the rate of new building. The rate of new building is driven by population change in both Stirling and Fife, in accordance with the relationship derived from historical data. In Argyll no such relationship exists, with new building continuing despite a declining population over the past 3 decades. The structure of the loop is the same for all three regions and is illustrated as Loop 14.

Loop 14

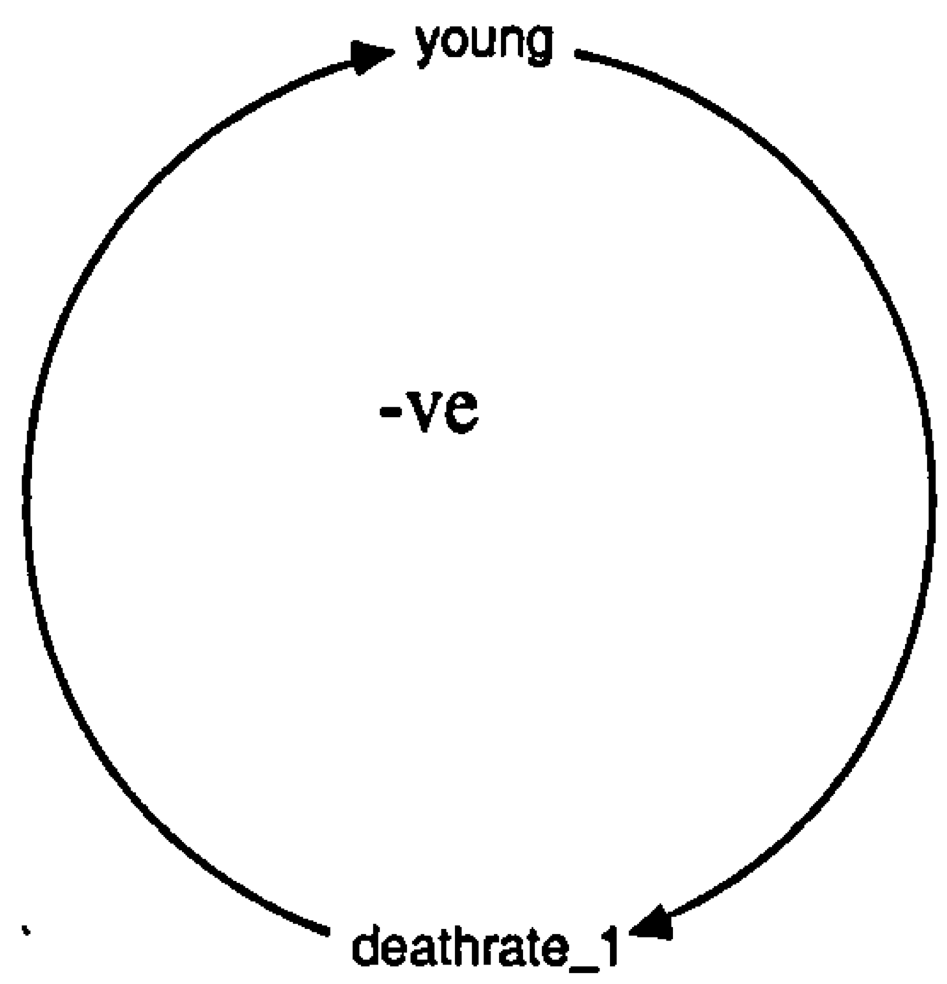


Population Sector

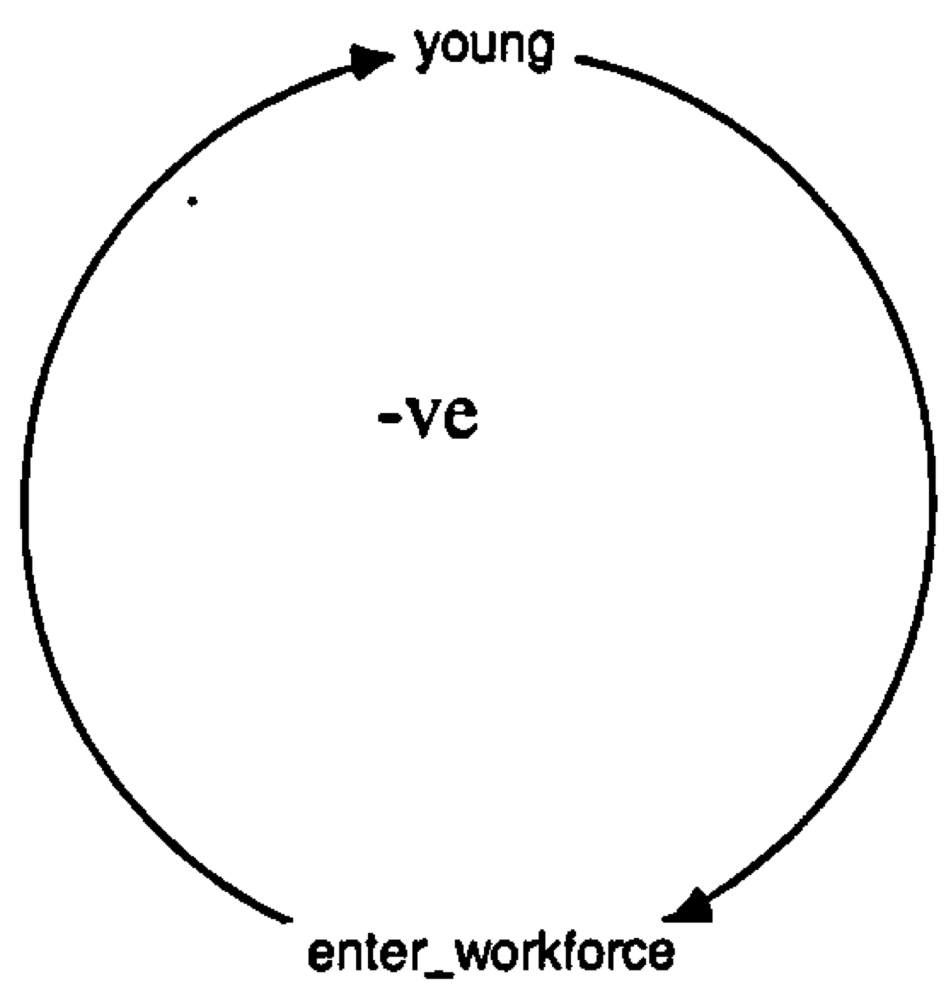
It is perhaps not surprising that in a socio-economic model many variables have an impact on the population. Within this model there are, in total, 19 feedback loops running through the population sector, some being simple but others quite complex and involving variables from a number of different sectors. The population "stock" is split into 3 age cohorts, and certain feedback loops are repeated for each of the age groups. The full listing of these loops follows, starting with the "young" age group and working through "middle" and "older".

Two relatively simple negative feedback loops can be identified as having an effect on the "young" section of the population. These involve the mortality of young people and their ageing and moving into the "middle" group. Loop 15 shows the loop associated with the deathrate for this group, a simple percentage figure, and loop 16 shows the movement of young people into the middle age group, again a simple percentage of the young group.

Loop 15

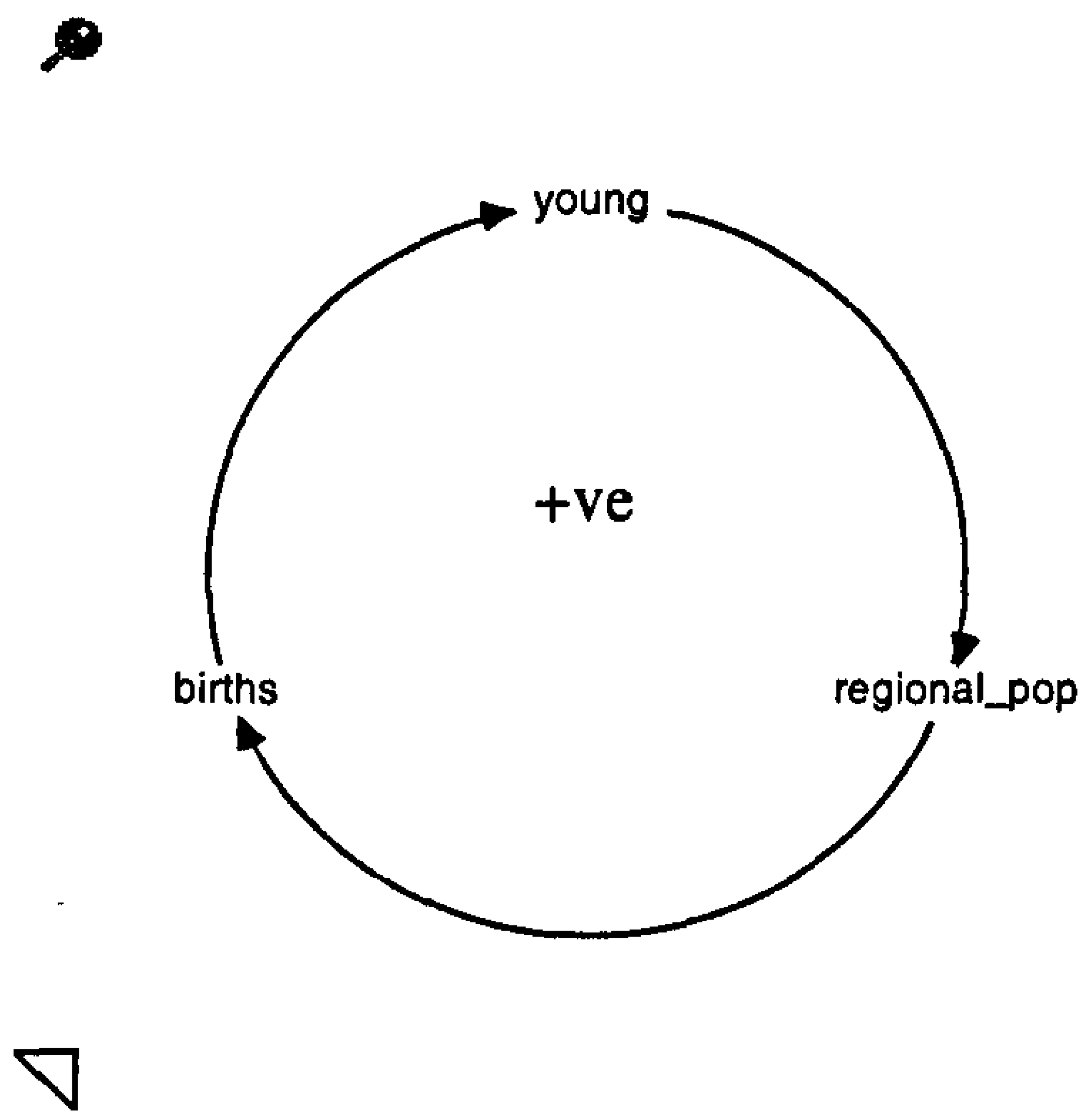


Loop 16

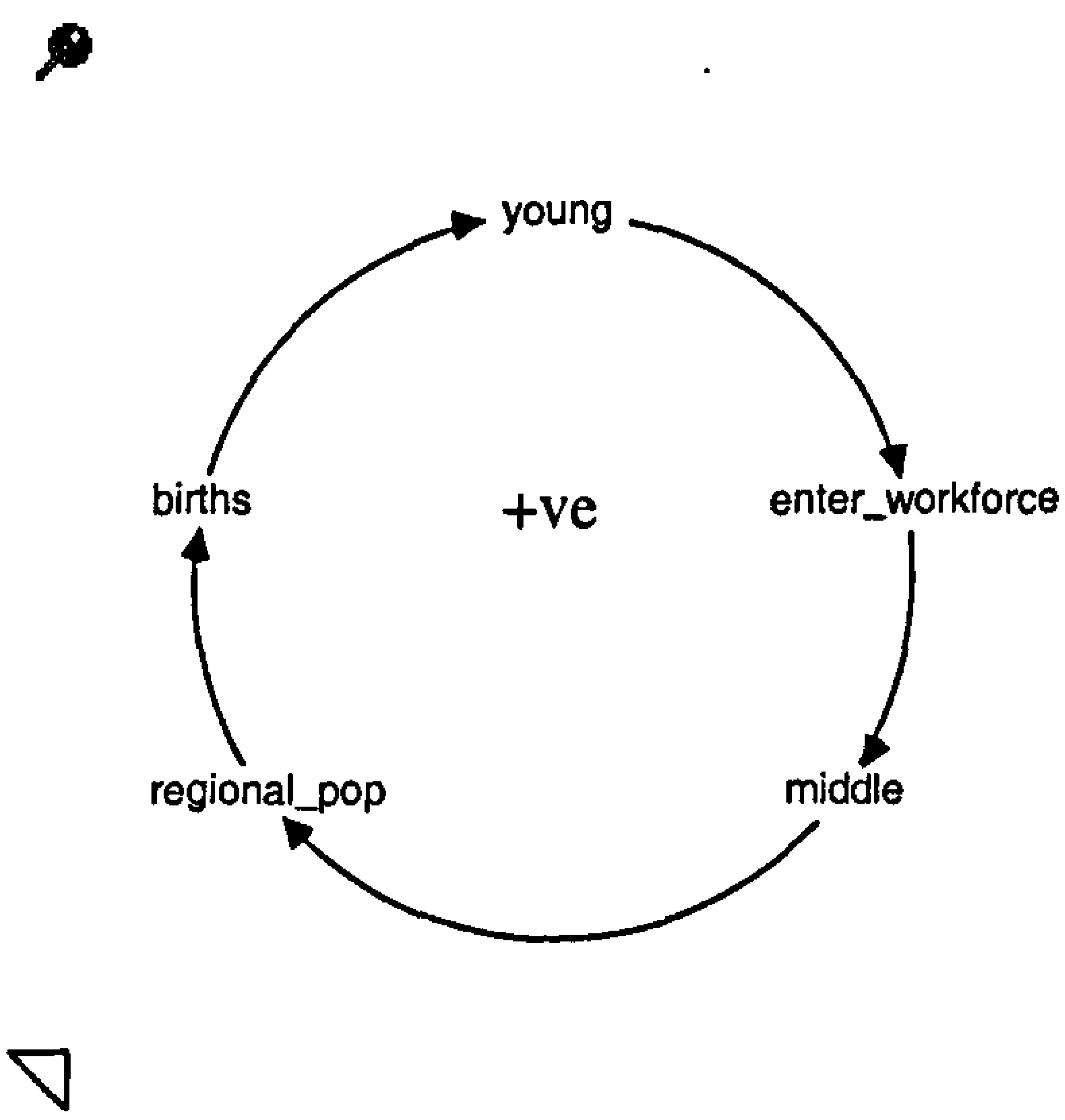


The remaining three feedback loops associated with the "young" age group involve the impact on the regional population and hence the impact on the birthrate, which is defined as a rate per thousand of population. Loops 17, 18 and 19 show how the young age group influences the regional population directly, via the middle age group and via the older age group respectively. In each case this defines a positive feedback loop.

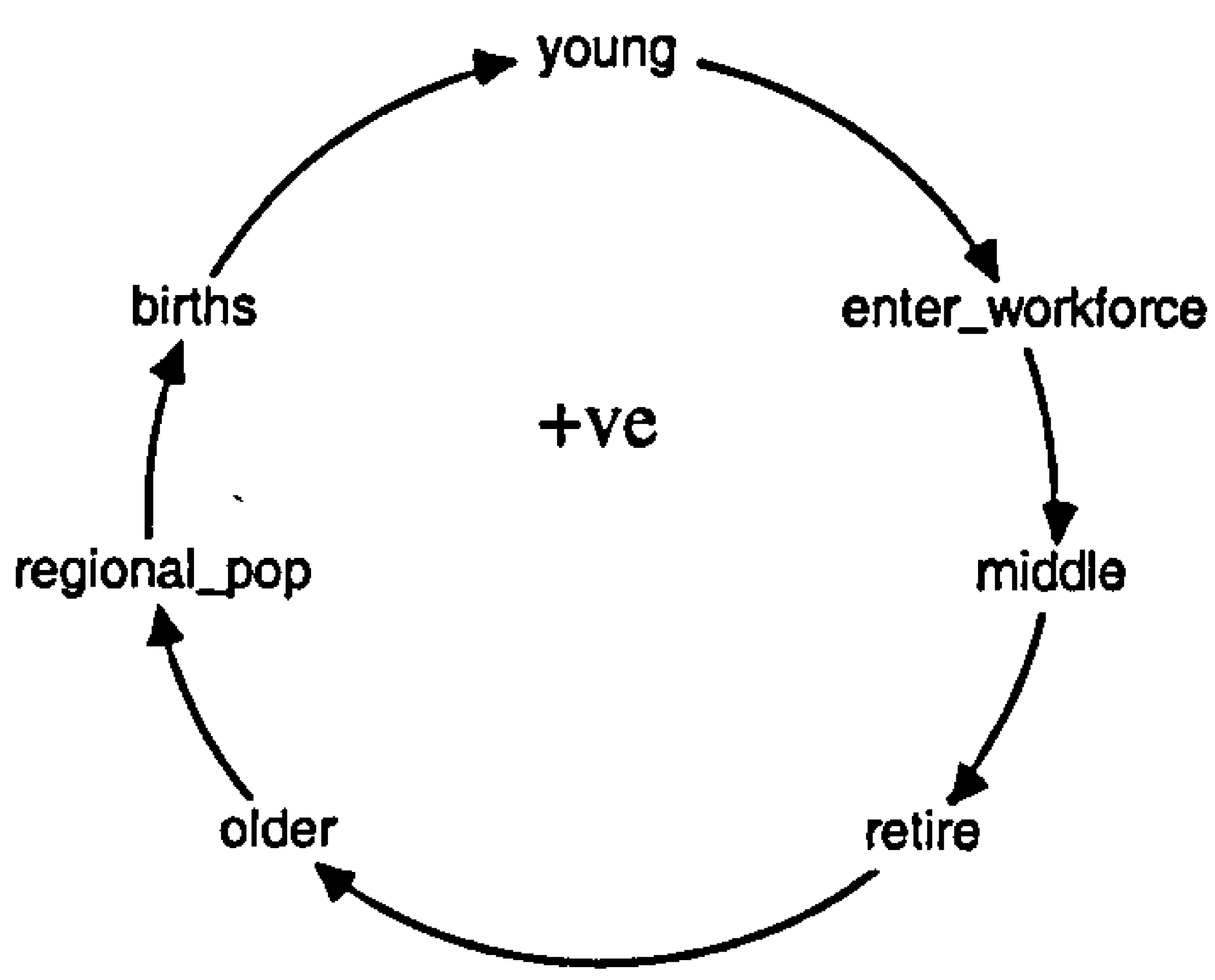
Loop 17



Loop18



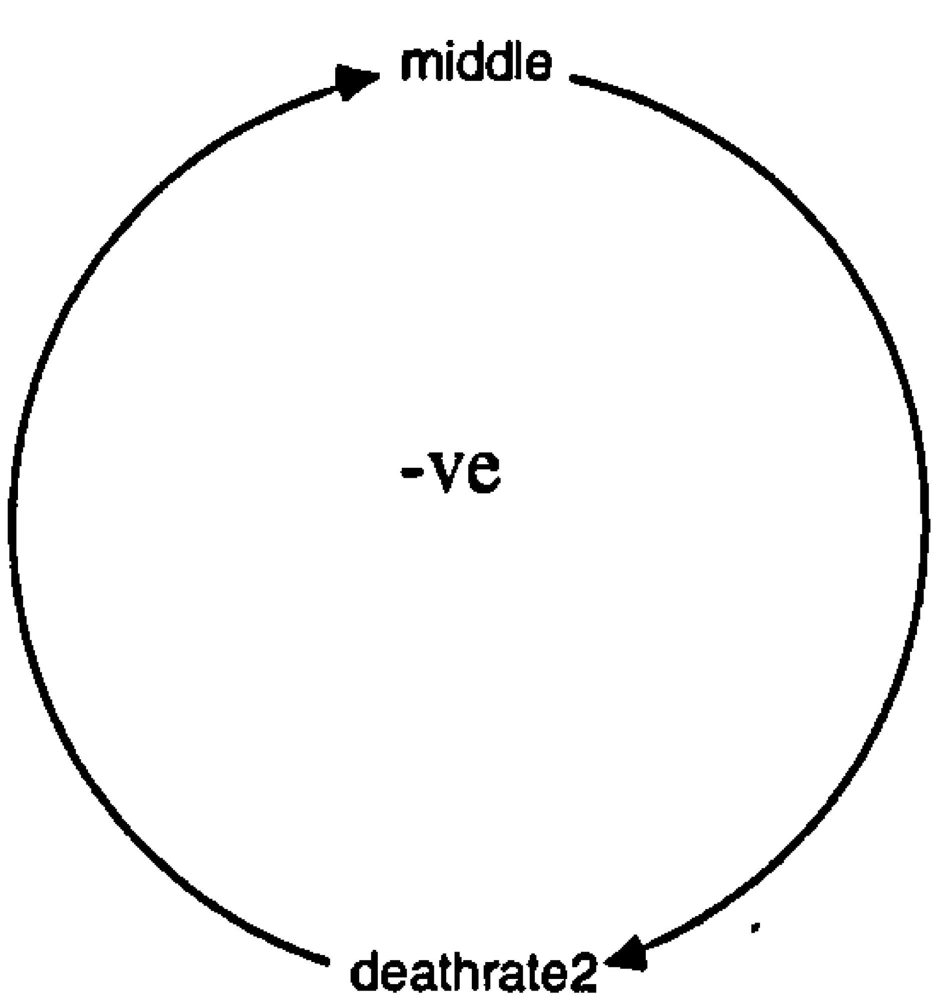
Loop19



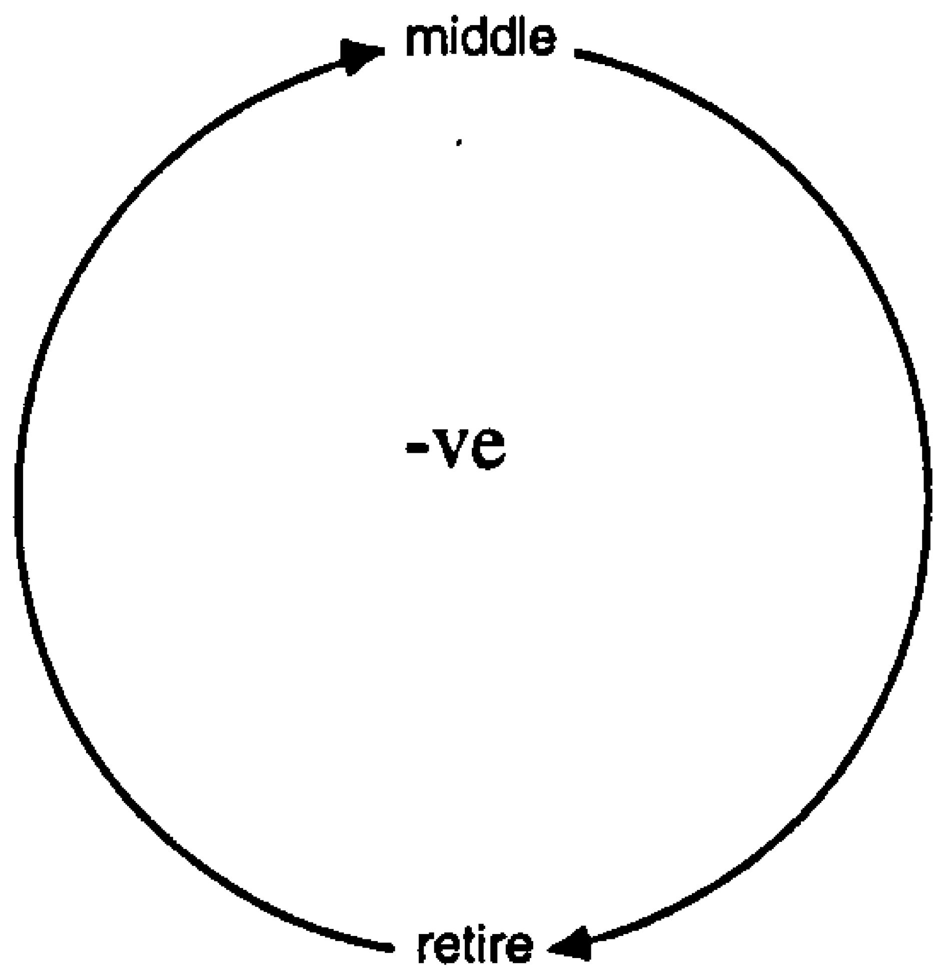
The “middle” age group is affected by loops similar to those for the young group but has additional loops associated with the employment and land use sectors. The full listing of these loops is given below.

Loops 20 and 21 are negative feedback loops, involving the death rate for this age cohort and the rate at which retirement occurs.

Loop 20

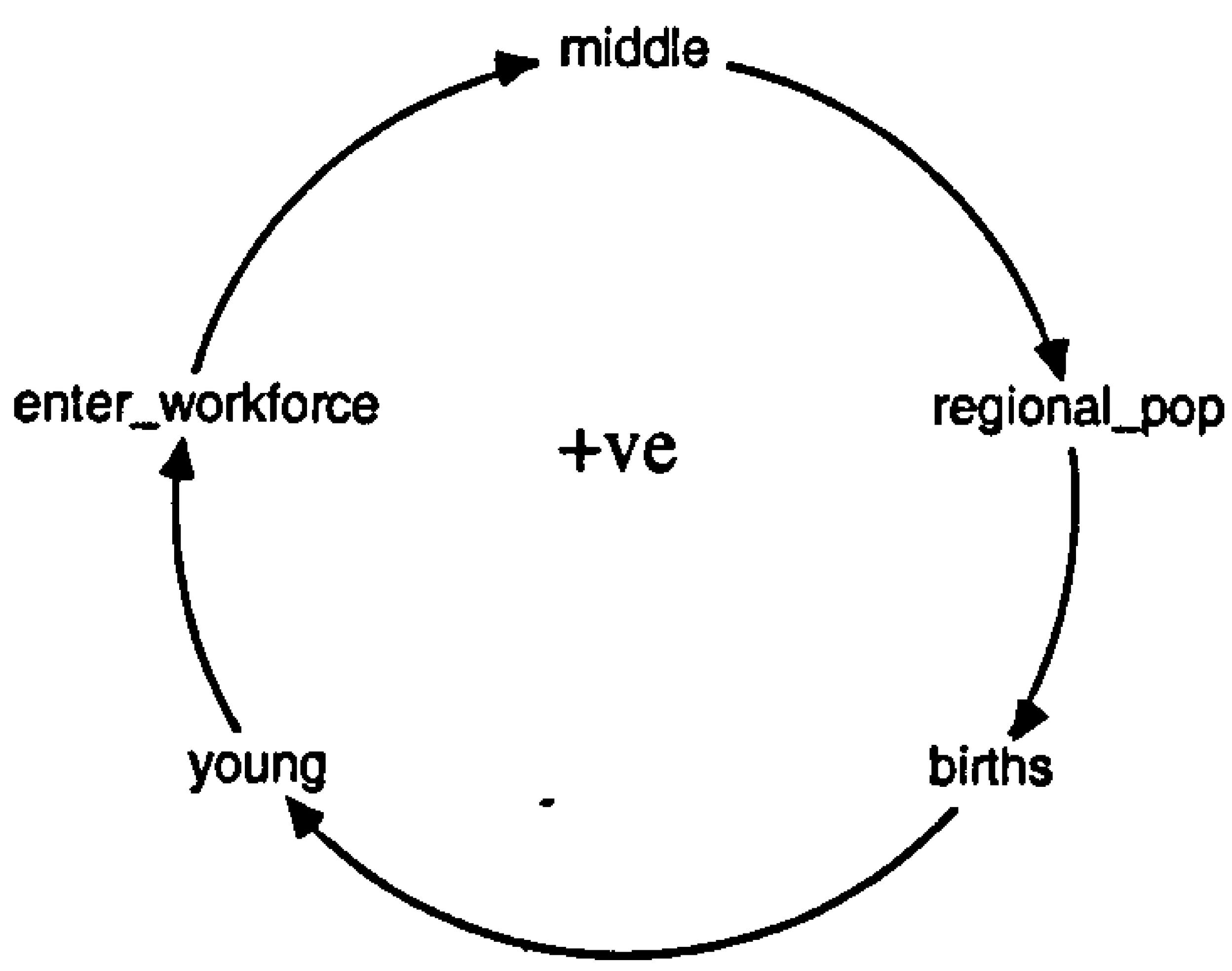


Loop 21

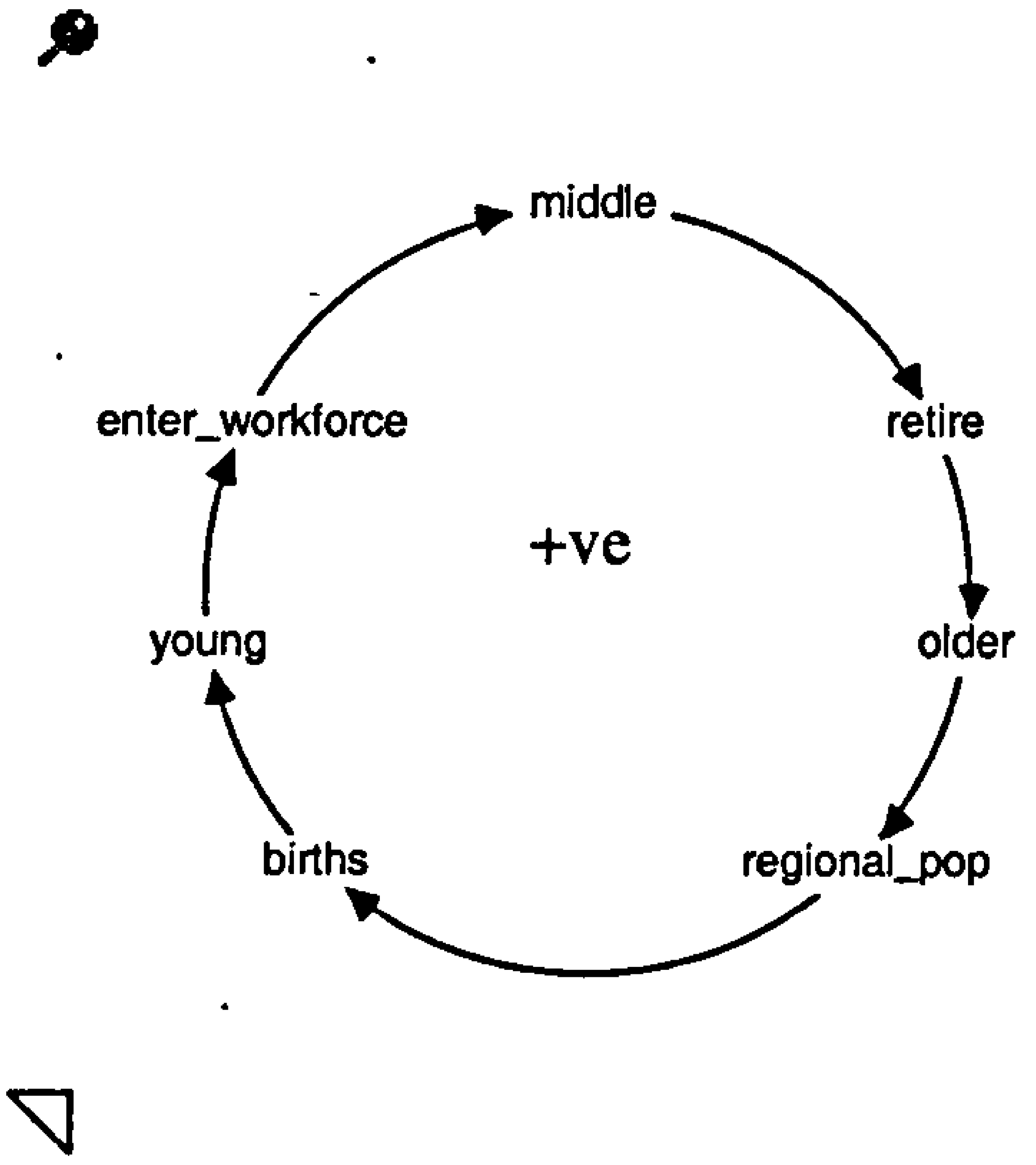


Loops 22 and 23 are both positive feedback loops involving the birth rate as a function of the total regional population.

Loop 22

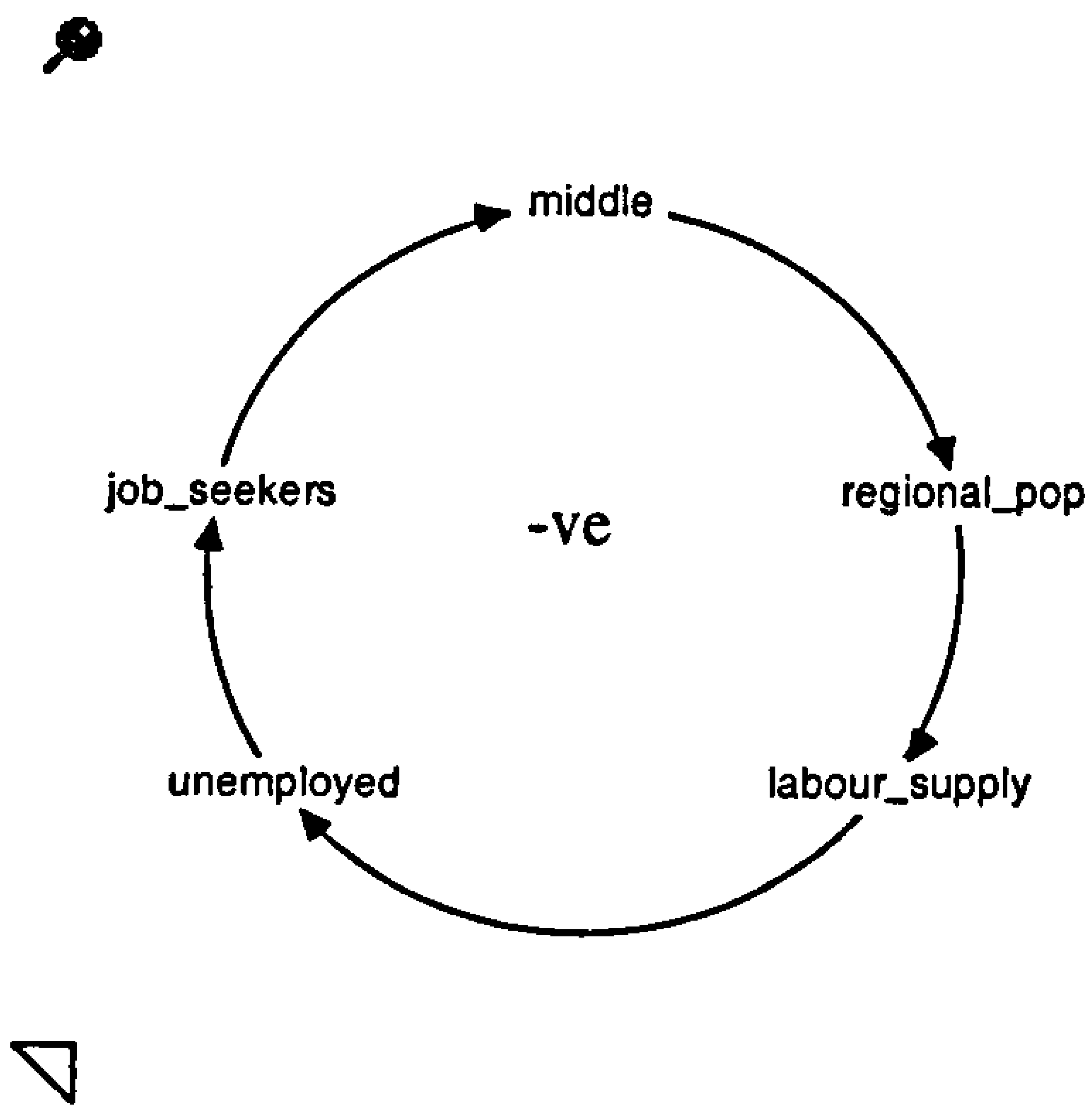


Loop 23

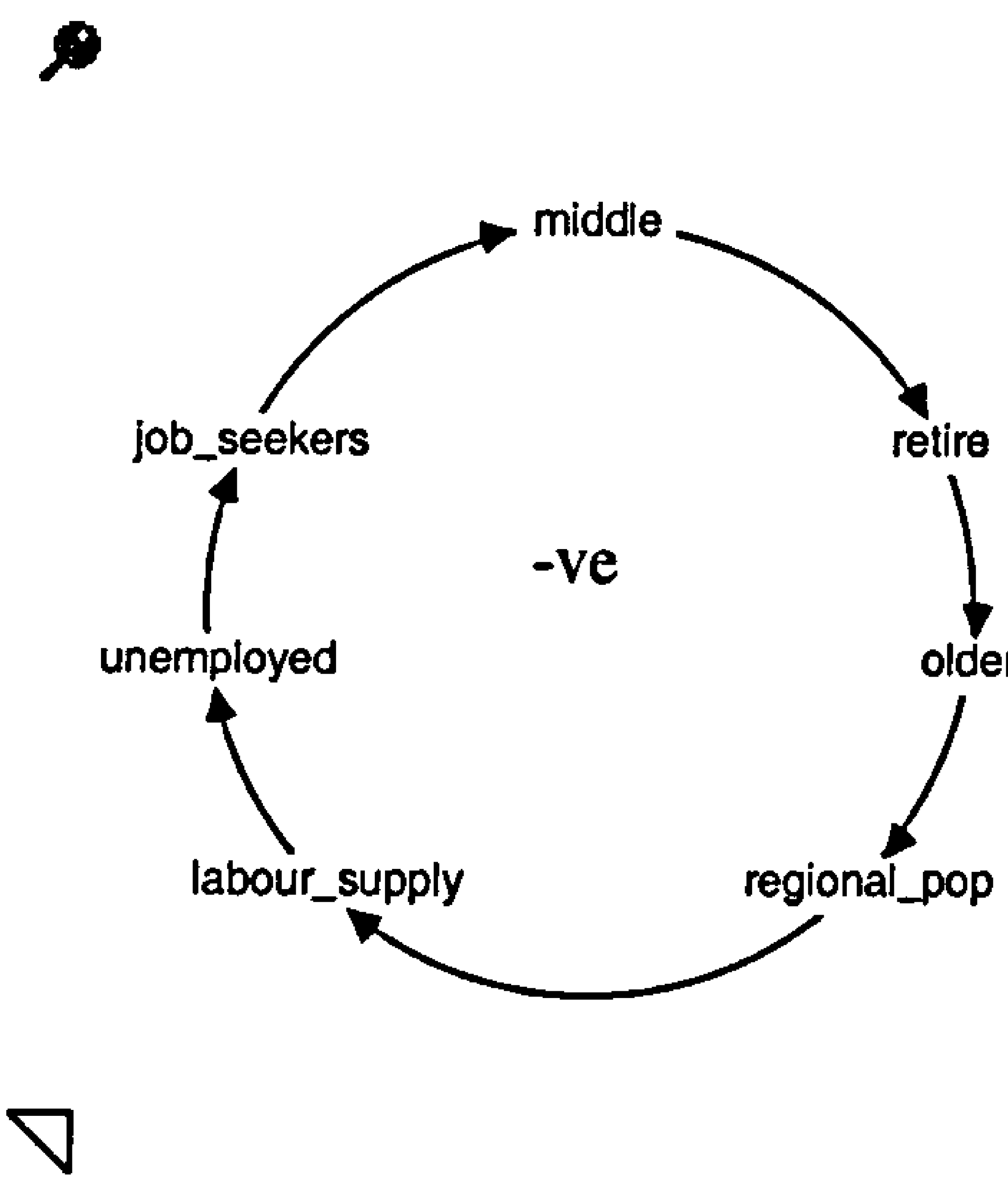


Loops 24 and 25 are both negative feedback loops, involving the labour supply for each region, the level of unemployment and hence the numbers of migrants required to alleviate any labour shortage. In both loop 24 and 25, the greater the labour supply the fewer job seekers will be required to boost the working population. Loop 26 is similar, but involves the numbers working in the "non-climatic" sector- those jobs which are considered to be unaffected by climate change. These jobs affect labour demand, unemployment and hence in-migration of working people. An underlying assumption here is that wage differentials are not significantly great between regions to alter the patterns of migration. Factors other than real wages, such as quality of life, also influence migration but these are hard to quantify and therefore are not included in the model.

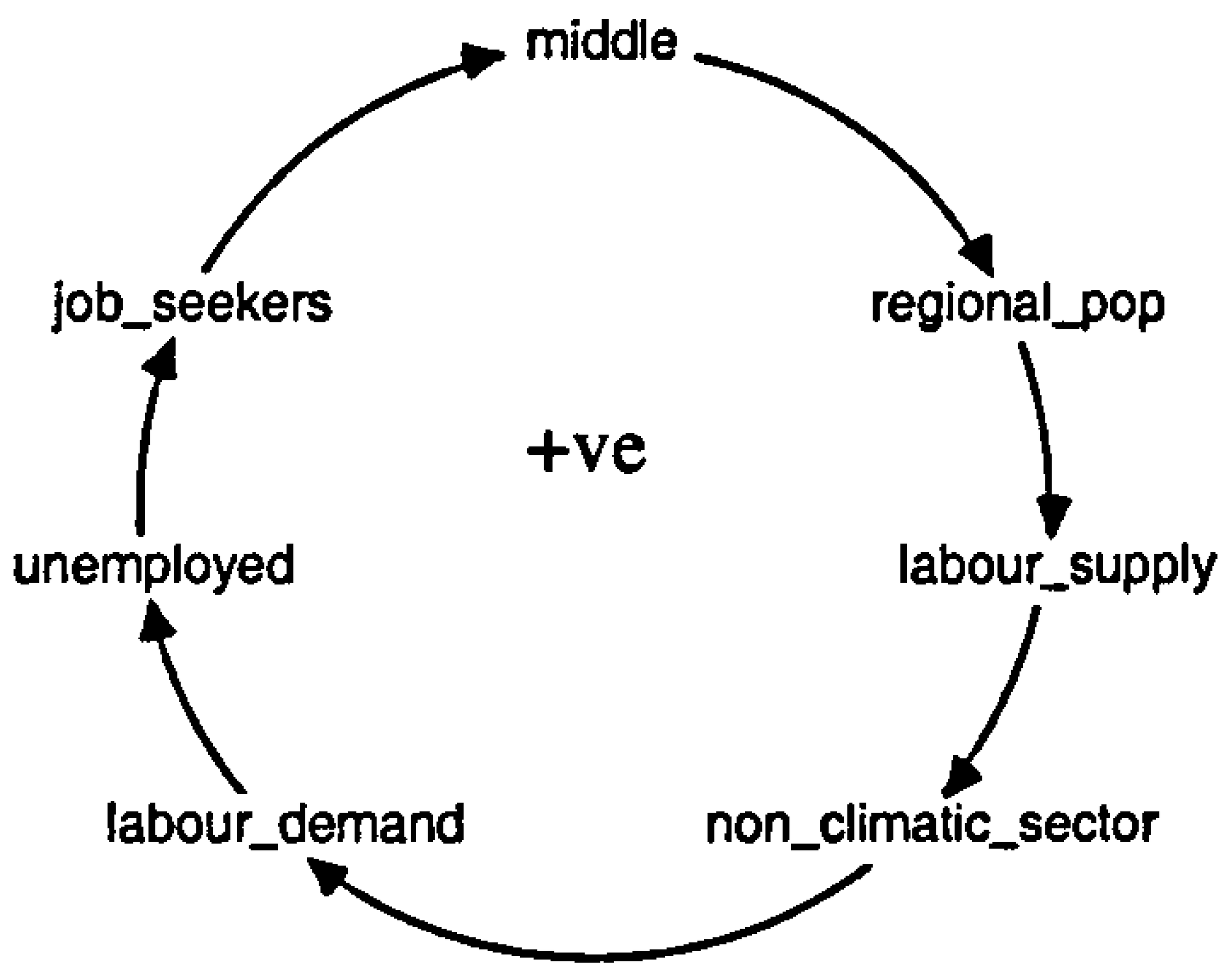
Loop 24



Loop 25

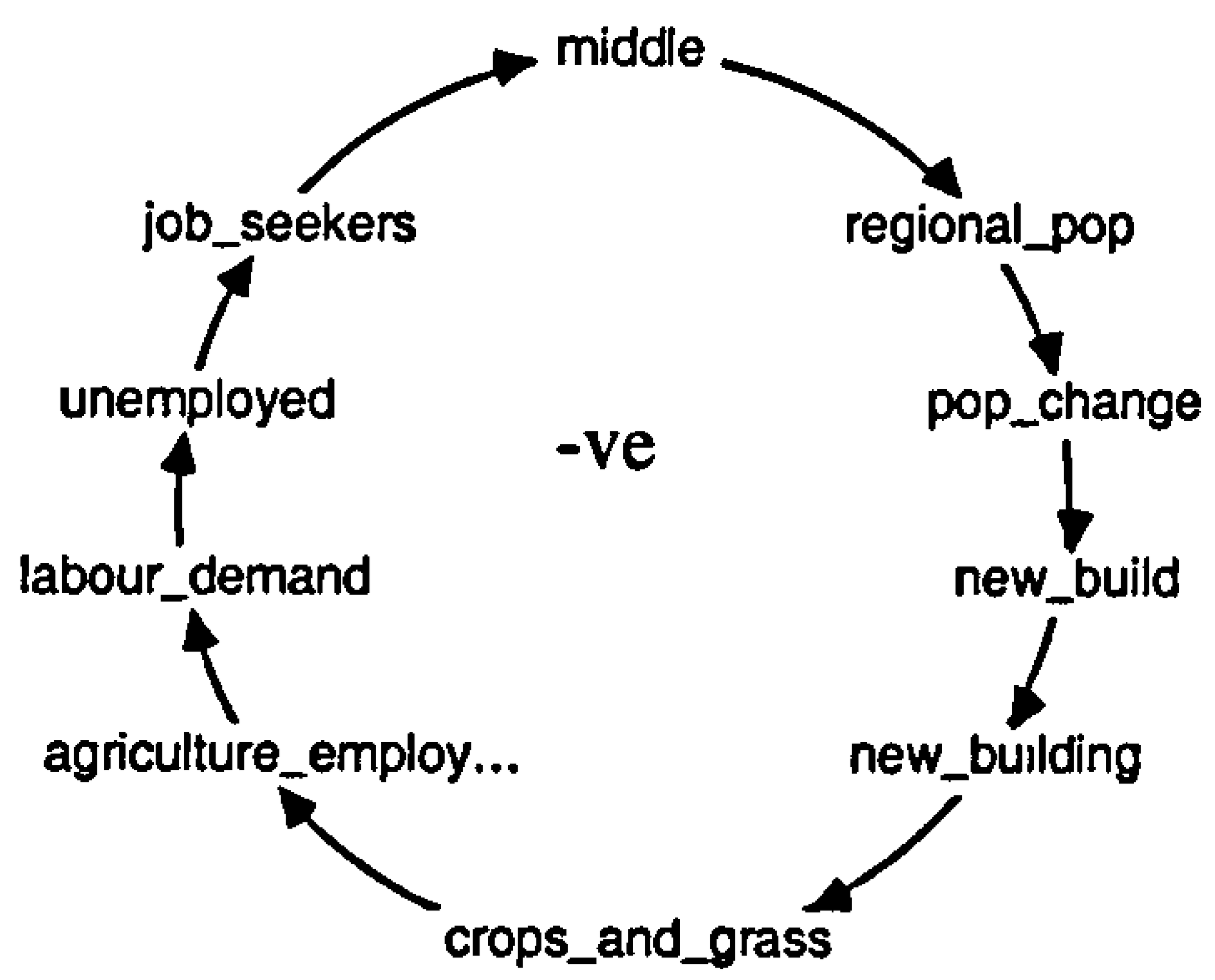


Loop 26

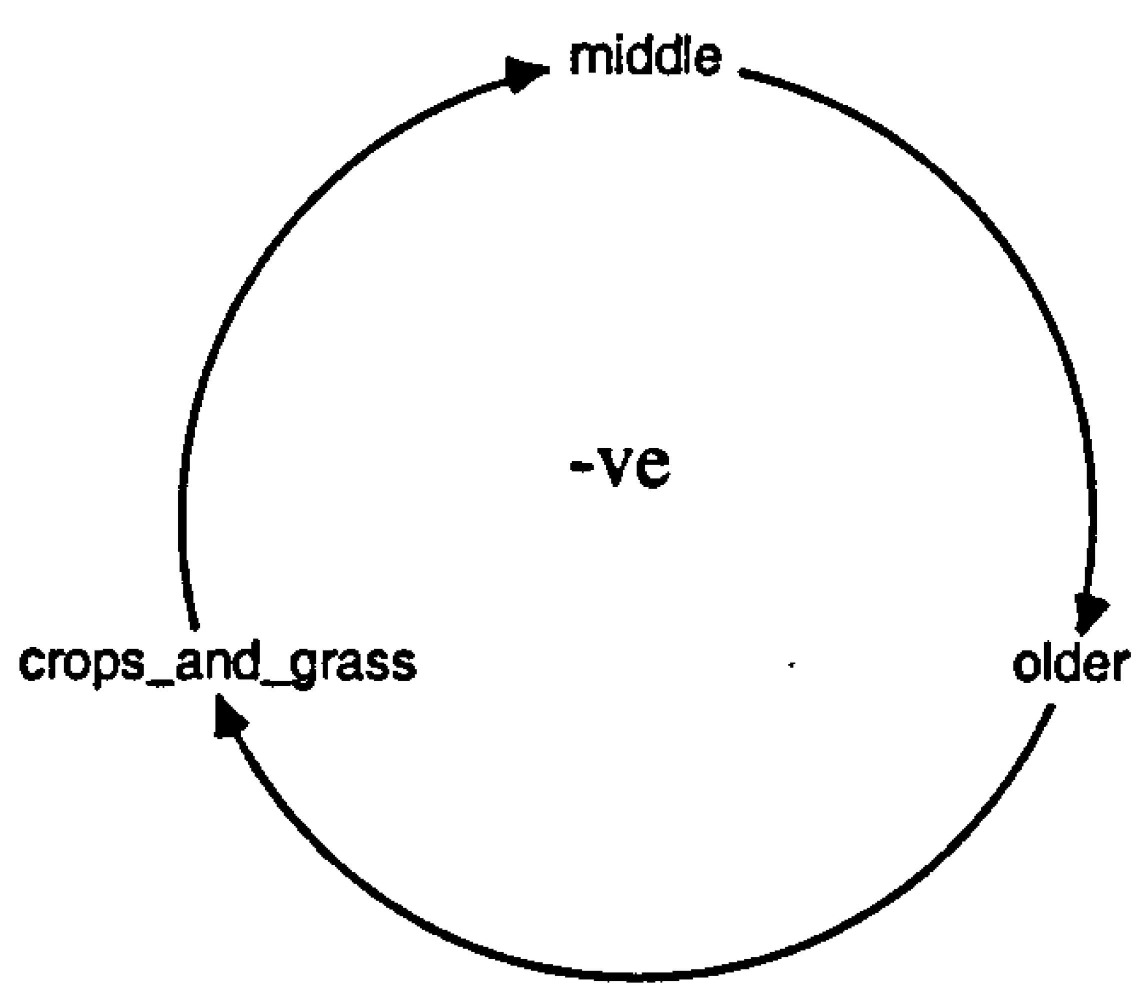


Loops 27 and 28 are both negative feedback loops which involve the effects of changing population on the demand for housing. This in turn alters the area of crops and grass available, and in turn affects agricultural employment. The impact of this on the different regions differs in magnitude as a result of the differing densities of population. In all cases there is a very small change in the area of agricultural land resulting from population changes. Changing employment ultimately affects in-migration and hence the population. Loop 28 is a simplified version, identical to loop 27 but involving the additional component of the effect of the older population on the total population and hence the demand for housing.

Loop 27

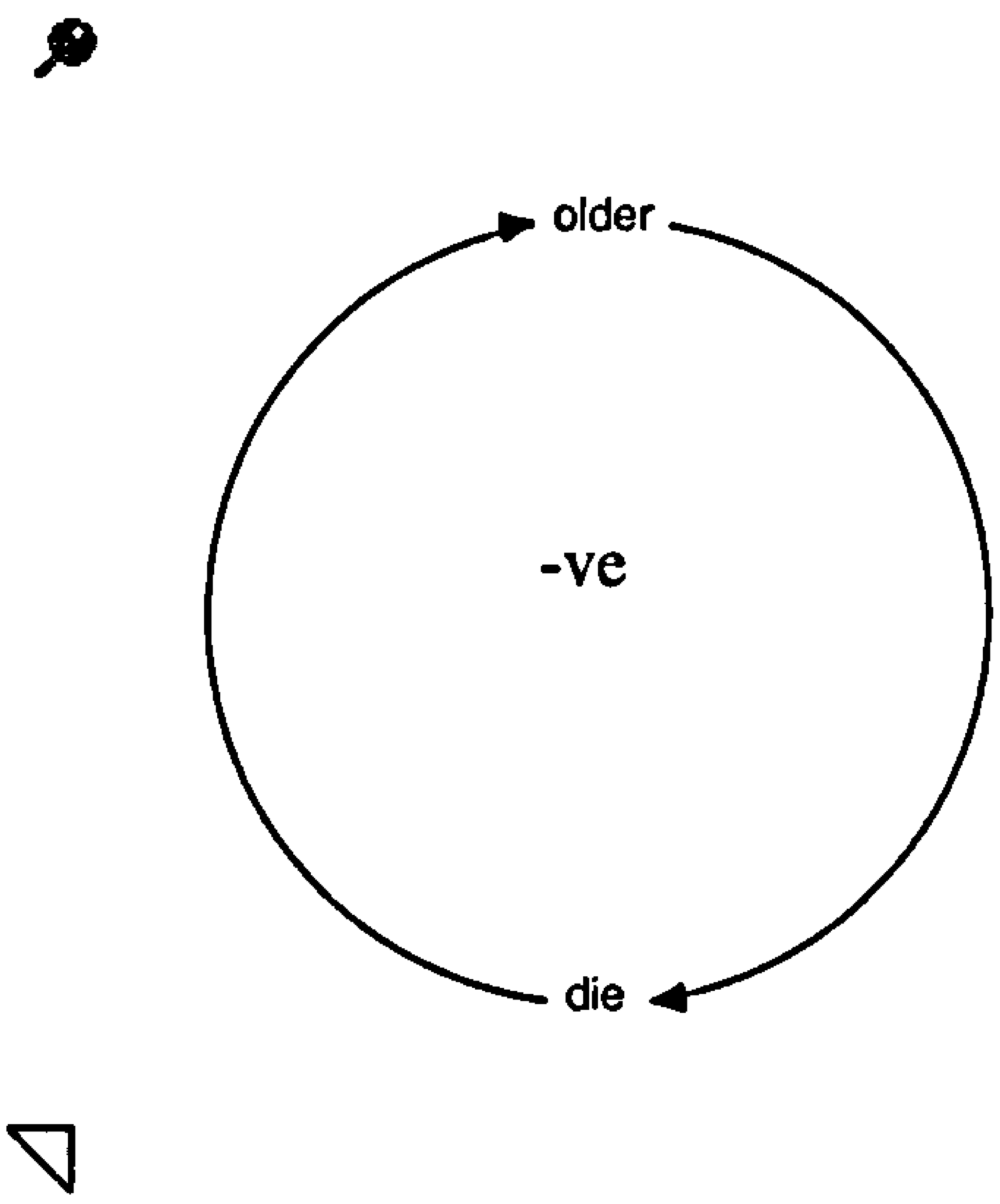


Loop 28



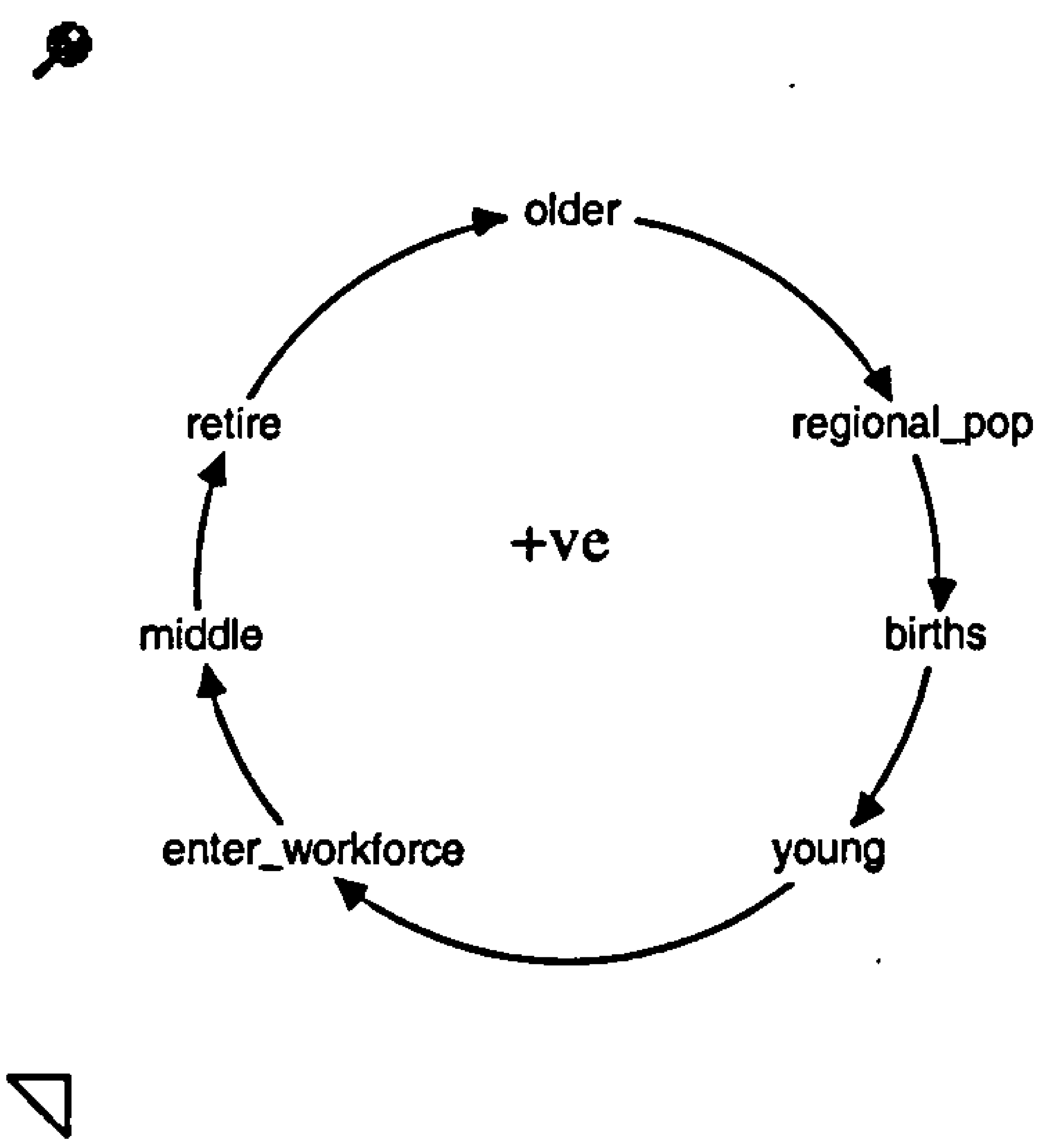
Fife feedback loops run through the "older" age group, bearing a similar structure to those listed for the other sections of the population. Loop 29 is a negative feedback loop which involves the older population and the mortality rate for this age group.

Loop 29



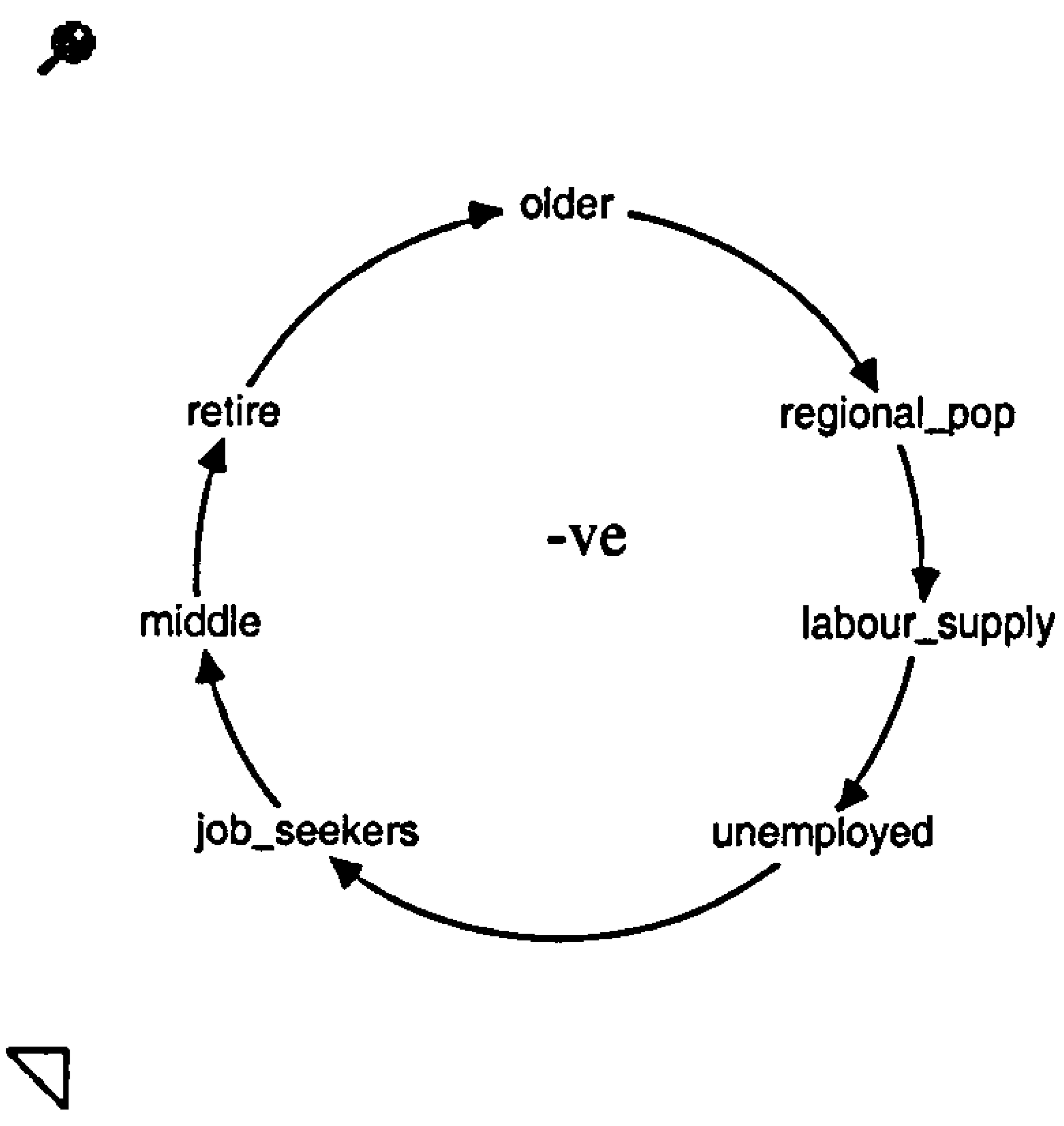
Loop 30 shows the effect of the older population has on the total population of the regions and hence the effect on the birthrate and through the ageing process back to the older section of the population. This is a positive feedback loop.

Loop 30



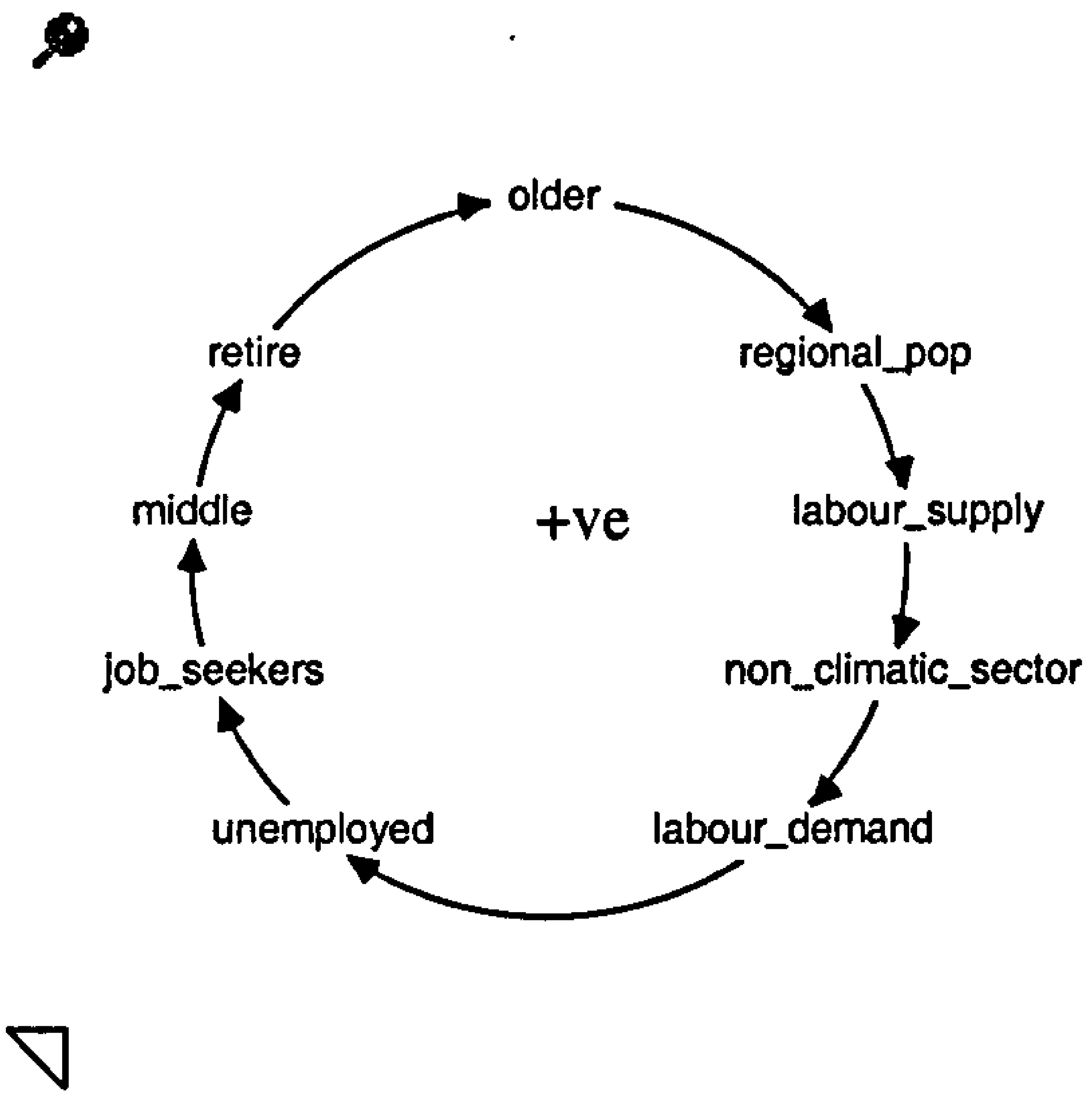
The effect the older population has on the regional population also affects the calculation of the labour supply. Through the link with unemployment and in-migration there is an effect on the population of the regions, this being represented by the negative feedback in loop 31

Loop 31

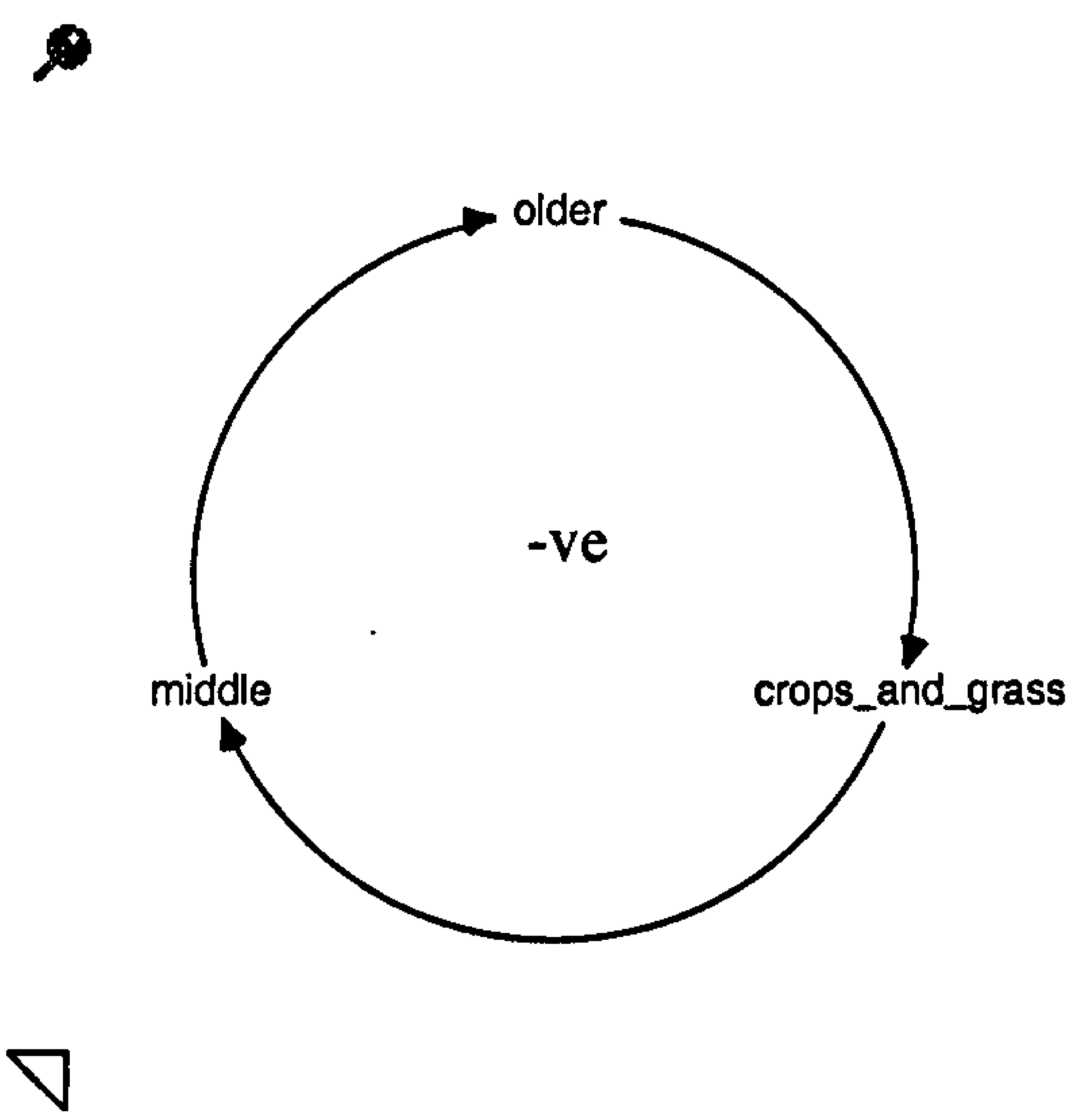


The last two loops for the population sector illustrate the structure of the links between population, employment, in-migration and the effect this has on the population. Loop 32 is a positive feedback loop involving the non-climatic sector of the economy. Loop 33 is a simplified version of the full loop which includes the effect of population change on the availability of farmland as a result of new housing. This in turn affects the agricultural employment and through unemployment and in-migration the population is then affected.

Loop 32



Loop 33



In total, 33 feedback loops were identified. Of these 19 are negative feedback loops and the remaining 14 are positive in structure. In order to identify which loops are the most important in the overall running of the model, sensitivity tests were carried out. These are shown in the main text in Chapter 9.