Global climate change and regional simulation modelling: preliminary results from Scotland 1970-2100

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Abstract: Recent attention on global warming has been directed to modelling global *and* regional simulations. The basic problem is one of developing statistically valid regional models which capture the complexities of global atmospheric and oceanic dynamics. Such models will be of even greater use for strategic planning and policy evaluation if linked to regional socio-economic variables. This paper reports on research which integrates a thermodynamically robust model of climate change in Scotland with a regionally disaggregated socio-economic model. It is argued that a relatively simple model captures much of the detail of atmospheric general circulation models (AGCM) but adds a regional dimension. The simple regional model includes changes to carbon dioxide concentration, solar cycles, atmospheric circulation and the thermal capacity of ocean fluxes. The way in which this regional model, running on a personal computer, captures changes in ecology, flooding, agriculture, housing and tourism are described as part of an ongoing research project. By developing a generic model of climate change which captures both global *and* regional variations, we are able to give statistically sound simulations of the seasonal variations in both precipitation and temperature for three regions of Scotland 1970-2000. The three regions are Argyll in the west, Stirling in the centre and Fife on the east coast. We are also able to link this regional climate model to socio-economic variables in the three Scottish regions. Several scenarios up to 2100 are explored to examine possible impacts of climate change on regional socio-economic structures. Some ways of developing the regional model of climate change are also described.

Keywords: *modelling; regional; climate change; socio-economic; Scotland*

1. INTRODUCTION

Three regions of Scotland were chosen for this study, Argyll on the west coast, Stirling in the centre and Fife on the east coast. Their locations are shown in Figure 1. Although these regions are relatively close together they show considerable differences across a range of measures. The landscape varies considerably with the west being mountainous and the east being low lying and fertile. Argyll has a population density of approximately 13 persons/km^2 and this rises to 39 for Stirling and 262 persons/km^2 for Fife. Tourism is a major industry in all three regions, with roughly 9% of the workforce in each of the regions being employed in related activities. Agriculture, although more productive in the east, employs a larger proportion of Argyll's population. Roughly 13% of the workforce make a living from agriculture in Argyll compared to 2-3% in Stirling and ~2% in Fife.

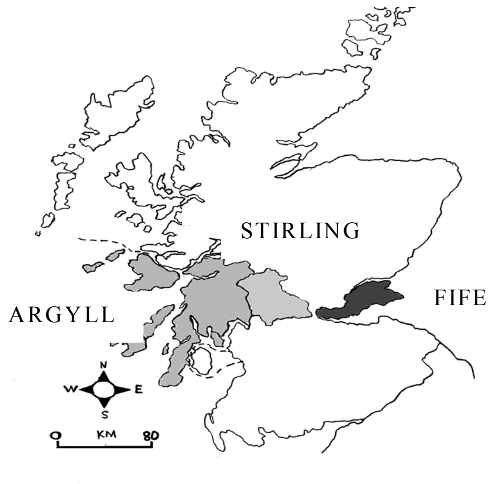


Figure 1 Scotland: The Study regions

Due to Scotland's location at the convergence of polar, continental, subtropical and maritime air masses the climate is variable, and considerable contrasts exist on a west/east gradient. Most noticeably the combination of prevailing warm westerly air flows and the mountains of the west coast produce a distinct precipitation gradient across the country. Thus low lying coastal sites in Argyll can expect around 1700-1800 mm of rain per year whereas low lying coastal districts in Fife can expect around 1/3 of this, perhaps 600-700 mm per year. Similarly temperature is influenced by the relative warmth of the Atlantic waters to the west compared to the North Sea surrounding the east coast. These factors combine to create quite different climates for the three regions, with both annual and seasonal patterns emerging which are distinct.

The main purpose of this study is to construct a model which can simulate the temperature and precipitation regimes of the three regions, calibrated on existing meteorological data for the period 1970-1999, and then to run this forward under different CO_2 growth scenarios to the year 2100. This climate sector will then be used as an input to a broad socio-economic model, again calibrated on existing data from the three regions, to allow climate impacts to be compared and policy options examined.

2. A SIMPLE CLIMATE MODEL

This sector of the model was constructed using StellaV5.1.1 and is essentially a stock/flow model, in which solar radiation is tracked into the stores of energy representing the atmosphere and the Earth's surface. Flows between these reservoirs and back into space attempt to capture the dynamic interactions of the system. Initially a basic temperature model was constructed, which generated mean surface temperatures for the planet as a whole, with and without atmospheric 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 solution time interval (dt).

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.

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.

2.1 Method

The basic model (Figure 2) 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

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

<u>Inflows</u>

1. Sun to atmosphere
2. Earth to atmosphere (radiative)
3. Earth to atmosphere (thermal)

<u>Outflows</u>

1. Atmosphere to space
2. Atmosphere to Earth

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

<u>Inflows</u>

1. Sun to Earth
2. Atmosphere to Earth

<u>Outflows</u>

1. Earth to space
2. Earth to Atmosphere (radiative)
3. Earth to Atmosphere (thermal)

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

2.2 Calibration of basic model.

Theory predicts that 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 (Drake, 2000). 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. Adjustments were made until a mean surface temperature of minus 6°C was achieved. This required only a minor change to the thermal transfer.

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.

2.3 Developing a Regional climate model for Scotland.

In order to more accurately simulate 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, the incoming radiation was adjusted to take into account variations in the angle of incidence of solar radiation at a latitude of 56° North throughout the year. This was included as "seasonal effect"

Thirdly a component was introduced to represent the varying duration of incoming solar radiation throughout the year ("day-length").

The final modification to solar flux is a factor which introduces an element of variability to the final seasonal temperatures ("seasonal variability"). 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.

At this stage the model produced separate outputs, in the form of an array, for each of the four 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. 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". For example 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.

2.4 CO_2 Emissions Scenarios

The purpose behind the development of this model was to generate simulated regional 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 IPPC Special Report on Emissions Scenarios (SRES), (IPPC, 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. 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 1.

Table 1 Future CO_2 scenarios (IPCC, 2000)

UKCIP02 Scenario	SRES Scenario	2020's CO_2 (ppm)	2050's CO_2 (ppm)	2080' sCO_2 (ppm)
Low	B1	422	489	525
Medium-Low	B2	422	489	562
Medium-High	A2	435	551	715
High	A1F1	437	593	810

These figures, as detailed in Table 1, were included in the regional climate model to provide four separate scenarios, each corresponding to a Low, Medium-Low, Medium-High or High growth of atmospheric CO_2. 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. Known values from 1970 and 2000 (323 and 364 ppm respectively) 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. Each separate version of the model was then ready to generate simulated temperatures under different conditions of increased CO_2.

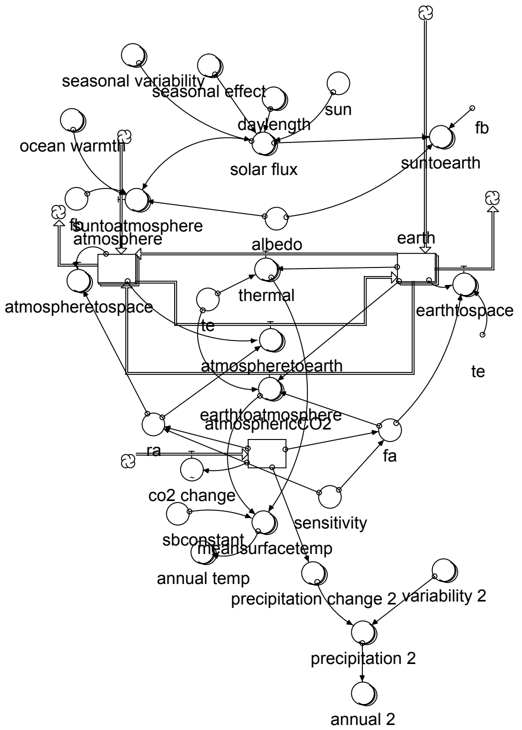


Figure 2 The structure of the climate model

2.5 Calibration of the regional climate 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 1970-2000 was extracted. This was then compared to the empirical data and adjustments to variability made to achieve an accurate match in terms of the mean and standard deviation of temperature.

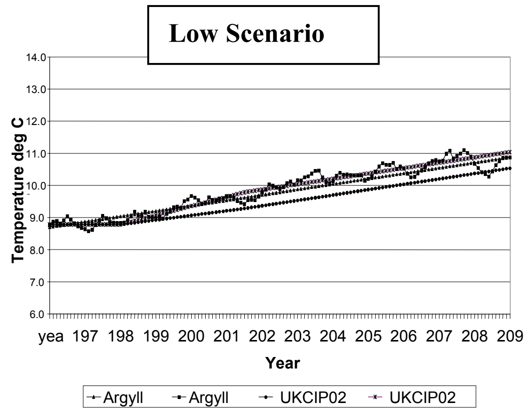
2.6 Introducing precipitation to the model

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. Projected changes in precipitation for each region and for each season were analysed with respect to the corresponding concentrations of CO_2 for the 2020's, 2050's and the 2080's. In each case a linear relationship was established and this was included in the model to generate precipitation change. Variability in precipitation was controlled in a similar manner to temperature and calibration on existing data carried out.

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 climate model is shown in Figure 2

Figure 3 shows a graphical comparison for Argyll of the extrapolation of the warming trend identified from empirical data; the output from the climate model in Stella (with variability); the lower and upper boundaries of the temperature change generated by the UKCIP02 model. This is illustrated for the Low and High scenarios. It can be seen that there is considerable agreement between the Stella model and the boundaries of the warming trend from the UKCIP02 model. Under the high scenario the warming trend is far more pronounced in both models and indicates that the rate of change increases relative to past warming.



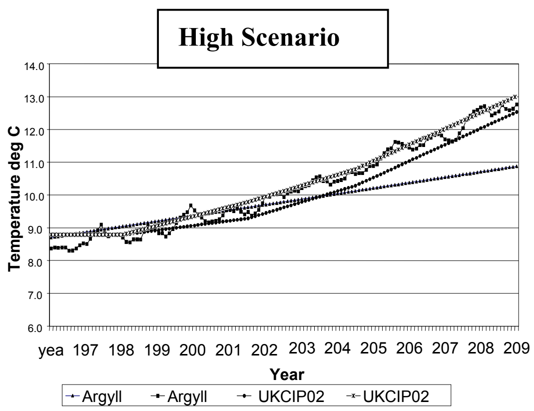


Figure 3 Temperature: Empirical trend and model outputs.

3. THE SOCIO-ECONOMIC MODEL

A socio-economic model was constructed with six sectors representing Population, Housing, Land use, Employment, Water resources and Emissions. Existing data relating to annual and seasonal figures for climatic variables were used to identify the effects of climate variability on a number of socio-economic factors. This assumes that if inter-annual variability of temperature and precipitation can be shown to have an impact on one or more socio-economic variables, then climate change will have an impact in proportion to the changes experienced. Calibration of the separate sectors was undertaken for the periods of time for which data was available, where possible 1970-2000.

The population sector includes past birth rates, death rates and data on migration combined with the most recent projections from the General Registrar of Scotland. These projections are for the next 15 years, beyond which they are assumed to be constant. The population is split into three age cohorts, with young people below the age of 20, those of working age defined as between 20 and 65, and the older age group above 65. This allows not just a simulation of total population but allows future age structures to be examined. In all cases there is a population decline over the next century, and an increase in the proportion of over 65's in each of the regions.

A link has been created between employment and migration allowing a labour shortage to generate in-migration. This not only slows the decline in the overall population of the regions, but alters the age structure as well, with the majority of immigrants being of working (and reproductive) age.

Forecasts of birth rates, death rates and projected household size were available from the General Registrar of Scotland (GROS, 1970 et seq.) and these were included in both the population and housing sectors of the model.

The housing sector is linked to the population sector, increased population requires an increase in housing provision. A decrease in population however, does not imply a loss of housing. Indeed one of the most significant trends is towards smaller households, the consequence of which is a shrinking population requiring greater housing provision. Increases in housing has a knock on effect to land use, with new housing being built on greenfield sites often close to existing settlements which tend to be in areas of productive agricultural land. The model allows the demand for new housing to be quantified through a range of simulated population scenarios.

The land use sector deals with the areas of land devoted to five activities. There is the urban land use, crops and grass, rough grazing and two types of forestry, commercial plantation of mainly exotic species and native or broad-leaved forestry.

Built into this sector is a connection to temperature increase, the total area of land available for these various practices being at present being limited by climatic factors. It is assumed that with climate change, areas currently unable to support livestock or forestry due to altitude will become available in the future as the range of plant communities expands with the warmer temperatures. The rate at which such land becomes available was obtained using the GIS package Arcview 3.1 working with 1:50000 maps of the regions. Lapse rates of 0.67 degrees Celsius per 100 metres being included.

This increase in available land has itself a link with employment as the different land use activities generate employment at different rates per hectare. Increasing temperature therefore increases available land, and if utilised, this leads to an increase in employment in that region.

Data relating to agriculture, including employment and land use, were supplied by the Scottish Executive Environment and Rural Affairs Department. These data were used in conjunction with data from The Forestry Commission and Highland Birchwoods, relating to forest cover, to construct the land use sector.

One link between climate and employment was established by examining two measures of tourist numbers. One was the number of "bed nights" sold per year for each Area Tourist Board and the other the total number of visitors to recognised visitor attractions. In each case a strong correlation was found between visitor numbers and both the present and previous year's summer temperature. This generated a regression equation which was used to simulate future tourist numbers. Data on tourist numbers was obtained from Visit Scotland.

Although this same relationship was detected in different locations, the link with employment varied between the regions. This reflected the different character of their respective markets, both in terms of the activities undertaken by visitors and the profile of the visitors themselves. In general terms however, increasing temperatures generate an increase in employment in the tourist industry. Similarly, via the land use sector, employment in agriculture could increase as temperatures rise, the impact of which would not be spread evenly through the local economies of the three regions. Such changes would have a major impact on the west coast where the existing impact of agriculture on employment is greatest already.

The water resource sector simply calculates whether on a seasonal basis for each region there is likely to be a deficit, when evapo-transpiration, use by the population including tourists, and runoff are subtracted from the incoming rainfall. As temperatures increase and the simulated summer precipitation declines the increases in evapo-transpiration account for a larger proportion of the available water resources. Similarly, the increase in tourist numbers adds to the human demand for water, particularly during the summer months. It is hoped that the regional and seasonal breakdown of these factors should allow the frequency of water shortages to be quantified, particularly in the drier east of Scotland.

The calculation of net emissions for each of the regions relies on national per capita carbon emissions being used in the absence of any data relating to regional variations. The emissions are therefore calculated by taking the projected population plus the contribution from the significant tourist numbers and multiplying by this national per capita figure. Subtracted from this is an assessment of the assimilation of carbon by the extensive forestry, both existing and projected, at a rate per hectare suggested from the literature (Ecocraft framework4, 2000). With current rates of afforestation continuing Argyll becomes a net carbon sink by this calculation by the middle of this century. The other two regions are net emitters however it is found that a 27% reduction in the per capita rate of carbon emissions brings Stirling into a carbon neutral position by the end of the 21st century.

4. CONCLUSION

This research has briefly described the construction of a combined climate/socio-economic model for three regions of Scotland. A thermodynamically robust climate model gives simulated regional variations under different climate scenarios. These simulations are in broad agreement with the regional simulations of climate change described by the UKCIP02 model

The influence of these different regional climate scenarios can be assessed, as can changes to a number of control variables, and the knock on effects of each change can be tracked through the socio-economic model. Variables to which the model is particularly sensitive can be identified, and variables which can be altered by human choice and decision making investigated for their positive or negative impacts.

One important feature of this combined model is its ability to examine the regional impacts of global climate change. There is evidence from the preliminary results that the changes brought about by global climate change will not have a uniform effect on social and economic factors in the three regions of the study. Within each of the sectors of the economy, which have been defined as climate sensitive, there are regional variations in the effects of increasing temperature, for example water resources and land use. Quite significant different impacts are forecast for similar sectors of these three regions.

These preliminary results have serious implications for national policy formulation, as well as strategic planning of infrastructure and resource allocation at the regional scale. Climate change will generate problems and opportunities, and it is hoped that this study will contribute to our ability to minimise the former and take advantage of the latter.

This work is still in progress but it is anticipated that the combined climate/socio-economic model will be of use for further detailed scientific research and strategic regional economic policy.

5. ACKNOWLEDGEMENT

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