An Exploration of Regional Climate Change Scenarios for Scotland

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Abstract

Based on a high resolution regional climate model (RCM) experiment, a climate change scenario for Scotland for the end of this century is constructed with the aim of exploring the added value of utilising a regional rather than a global model (GCM) for climate change scenario construction. Spatial variations in regional seasonal average temperature and precipitation change are analysed and the local response of 'extreme' weather events to climate warming is assessed using daily model output. The analyses suggest that in comparison with the GCM, the RCM does not provide fundamentally different *patterns* of seasonal climate change and daily weather response over Scotland, although it does capture more subtle spatial variations in these changes. The RCM also simulates more realistic daily weather events than the GCM, although the *relative* changes in the frequencies of daily extremes are not greatly different. However, with the limited length of the single model simulation analysed here, it is not easy to establish how robust and significant are the sub-national patterns of climate response across Scotland. To improve the quality and comprehensiveness of regional climate change scenario information, a number of research issues remain to be addressed.

Key words: extreme weather, climate change scenario, Scotland, regional climate model.

1. Introduction

To enable assessments to be made of the potential consequences of climate change in the UK, a set of national climate change scenarios for the UK (UKCIP98) was published in 1998 (Hulme & Jenkins, 1998). In spite of their wide applications in impacts/adaptation assessments over the last four years (*e.g.* Kerr, A. *et al.*, 1999; McKenzie Hedger, M. *et al.*, 2000), these scenarios possess certain limitations. One that is often quoted is that the scenarios are based on results from a coarse resolution global climate model (GCM) and provide little information about the sub-regional differentiation of climate change across a country such as Scotland. As a dynamic approach to 'downscaling' GCM-derived climate change information to smaller scales, regional climate models (RCMs) are in principal similar to GCMs (*i.e.* are physically-based), but resolved to finer space scales. Thus a GCM has a typical spatial resolution of about 350 km, compared to about 50 km for an RCM. Regional climate models still rely upon the boundary conditions extracted from GCM climate change experiments, however, and a downscaled regional scenario can only be as credible as the results from the host GCM – even though it may be more detailed.

The research discussed here uses results from an RCM experiment to

generate a more detailed climate change scenario for Scotland, and explores what 'added value' is gained by using an RCM, rather than a GCM, for climate change scenario construction. Given the representation of finer-scale processes in the RCM, including more realistic topography and land-ocean boundary designation, just how different are the changes simulated by the GCM and RCM? In particular, we examine geographical variations in the average monthly/seasonal changes in climate, and also changes in the daily magnitude-frequency distribution of temperature and precipitation across Scotland. The model used in this study is the second generation regional climate model of the Hadley Centre (HadRM2) and the experiment is the one conducted in 1997 using boundary conditions extracted from one of the GCM experiments used in the UKCIP98 national climate scenarios report (HadCM2 GGa2). HadRM2 has a spatial resolution of 50 km and was designed to represent a European domain. Only results for Scotland are analysed here. The experiment is reported in Noguer *et al.* (1998). This exploration of differences between GCM- and RCM-based scenarios is particularly pertinent given that the next set of national UK scenarios (UKCIP02) to be launched in the first half of 2002 are based largely on RCM experiments.

A general introduction to the data and methodology used in this study is given in section 2. Section 3 presents the seasonal climate change scenarios and examines the added information provided by RCM-based scenarios in comparison with the GCM-based ones. Changes in daily weather extremes and the difference between RCM- and GCM-derived daily weather scenarios are presented in section 4, while section 5 summarises the main findings of this study and identifies some remaining research issues.

2. Data and Methodology

We used results from two simulations performed with the HadRM2 model – a 30-year control simulation representing 'current' climate and a 20-year scenario simulation of climate representing the period 2080~2099. The *control simulation* represents European climate before human modification of the atmosphere (nominally the 19th century). It is driven by the boundary conditions extracted from the HadCM2 control simulation, a simulation in which greenhouse gas concentrations in the atmosphere were held constant. The 30-year period from which the boundary conditions were extracted was Years 146-175 in the GCM control simulation, nominally the period '2006-2035' without any human modification of the atmosphere. The *scenario simulation* assumed historical increases in atmospheric greenhouse gas concentrations from 1860 to 1990 and then a 1% per annum increase in concentrations towards 2100. The boundary conditions for this simulation were for the period 2080~2099 in the GCM simulation HadCM2 GGa2.

Table 1 summarises the model simulations used to derive the scenarios examined in this study and, for comparison purposes, the UKCIP98 Medium-high scenario. HadRM2 has a spatial resolution of 50 km and the elevation field of the model is shown in Figure 1. Scotland is represented by just one GCM gridbox, but by 33 RCM gridboxes. The RCM gridbox elevation over Scotland varies from 70 m to 600 m, compared to the single GCM gridbox elevation of 220 m.

Table 1. Model simulations used to derive scenarios examined in this study and the UKCIP98 Medium-high scenario.

		RCM-derived scenario in this study	**GCM-derived scenario in this study**	**UKCIP98 Medium-high scenario**
Underlying model experiment		RCM experiment (HadRM2)	Driving GCM experiment (HadCM2 GGa2)	HadCM2 GGa	HadCM2 GGa2
Control simulation	Period of simulation	Nominally 19th century	Years 146~175	1961~1990	1961-90
	External forcing	none	none	Historical increase in greenhouse gas concentration	Historical increase in greenhouse gas concentration
	Global mean temperature	n/a	13.47°C	14.33°C	14.33°C
Scenario simulation	Period of simulation	2080~2099	2080~2099	2080~2099	2070~2099
	External forcing	1% per annum increase from 1990 to 2100	1% per annum increase from 1990 to 2100	1% per annum increase from 1990 to 2100	1% per annum increase from 1990 to 2100
Global warming relative to control period average		n/a	2.57°C	3.17°C	3.11°C
Global warming relative to 1961~1990 average		n/a	3.43°C (=2.57+14.33-13.47)	3.17°C	3.11°C

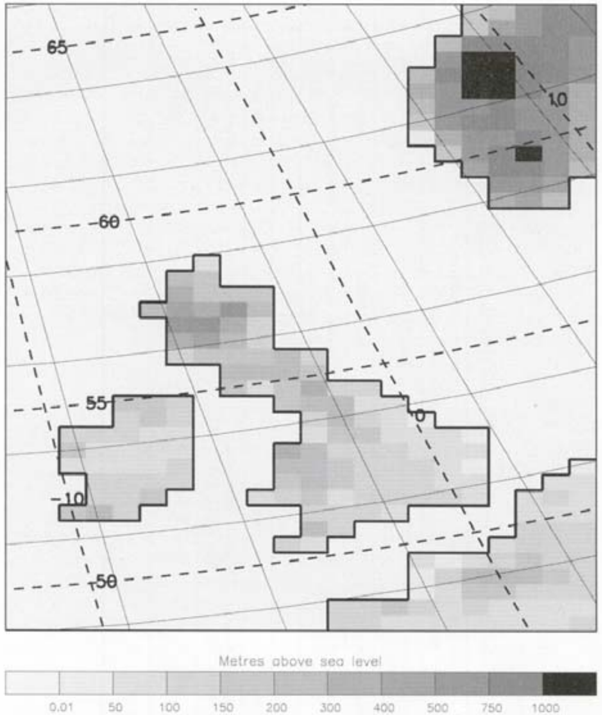

Fig. 1. HadRM2 surface elevation with some latitude and longitude values shown as dashed lines. The faint solid grid shows the outline of the HadCM2 GCM gridboxes within the HadRM2 domain.

These model simulations are used for two sets of analysis. First, we derived an average seasonal precipitation and temperature change scenario from the RCM simulations, to compare with those derived from the GCM. We assess the significance of the differences of these two scenarios across Scotland. To ensure comparability between the RCM and GCM scenarios we followed the procedure described in Box A. Second, we derived 'extreme' weather event scenarios for precipitation and daily mean temperature from the RCM, and examine changes in magnitude-frequency distributions, changes in return periods and changes in probabilities of threshold exceedances.

Box A: Ensuring Comparability Between the RCM and GCM Scenarios

Since the RCM control simulation used greenhouse gas concentrations appropriate for the mid-19th century, the definition of change in climate between the two RCM simulations is not consistent with that between the two GCM simulations. As shown in Table 1, the difference between a model simulation of 19th century climate and one of 1961–90 climate, although small (in this case 0.86°C), is not insignificant. To allow for the direct comparison of GCM- and RCM-based scenarios, we adjusted for this inconsistency by deriving the average global-mean temperature for the 1961–90 period of the respective GCM simulation (HadCM2 GGa2) and the average global-mean temperature for the period in the mid-19th century in the HadCM2 GCM control simulation. We linearly scaled back the RCM derived climate changes by the difference (0.86°C) between the global-mean temperature in these two periods.

Due to their finer spatial resolution, RCMs are generally better able than GCMs to represent the statistical character of observed daily weather (Giorgi *et al.*, 2001). One can therefore argue that changes in the daily characteristics of weather, including extreme weather events such as heatwaves and intense precipitation, may well be better captured by RCM simulations than by GCM simulations. A few emerging studies have examined this question (*e.g.* Durman *et al.*, 2001; Jones & Reid, 2001) and here we explore the question for Scotland. The analysis uses 30 (control) and 20 (scenario) years of daily data from the RCM simulations described above. Daily data from the RCM land boxes were analysed by two different approaches, the first using a quantile/percentile method to examine extremes and the second using theoretical distributions to define daily extremes with given return periods (details of these approaches are given in section 4).

Where maps of changing values are shown in section 4, they are expressed as (percentage) changes per 1°C global warming. This normalisation allows information from these diagrams to be used in conjunction with other climate change scenarios (*e.g.* the UKCIP98 scenarios) which represent a wider range of climate sensitivities, greenhouse gas emissions scenarios and time-slices.

More details on methodology and analyses of RCM-based regional climate change scenarios for Scotland are reported in Hulme *et al.* (2001).

3. Changes in Average Seasonal Climate

This section presents normalised regional temperature and precipitation scenarios in seasonal form. The RCM- and GCM-based scenarios are compared and differences highlighted and the range of geographical variation across Scotland in the regional scenarios is documented. We analyse the structure of this regional variation in terms of elevation and geographical location (east-west and north-south gradients).

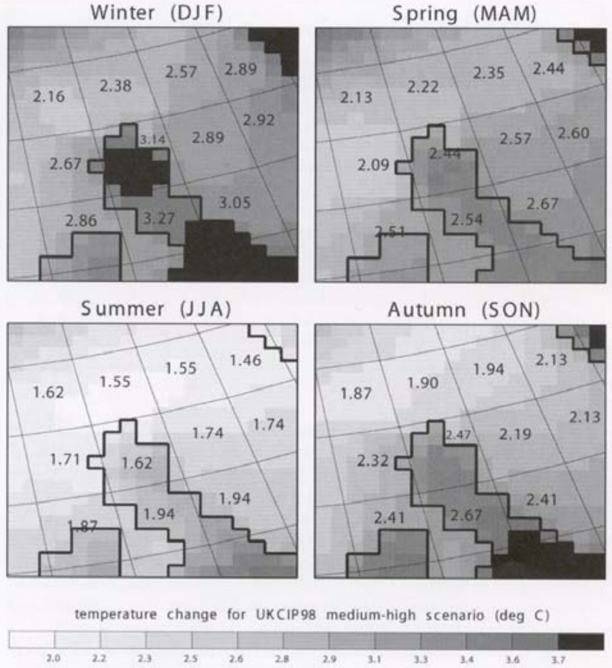

Fig. 2. Change in mean seasonal temperature (°C) for the period 2080-2100 based on the RCM-shaded boxes – and the GCM-overprinted numbers.

3.1. Normalised seasonal scenarios

Seasonal temperature changes are presented in Figure 2. They are normalised with respect to the UKCIP98 Medium-high scenario, in order to allow the comparison. Figure 2 shows the seasonal cycle in the temperature response, with the largest warming in winter and the least warming in summer, a result both the RCM and GCM have in common. The amplification of warming over land relative to ocean is clear in all seasons.

Figure 3 shows the sub-regional structure of normalised seasonal precipitation changes derived from the RCM. Northern Scotland and the Northern Isles experience a small drying in winter. A strong west-east contrast exists in the summer precipitation response, with summer wetting in the west and drying over eastern Scotland. In autumn, this west-east contrast persists, although the

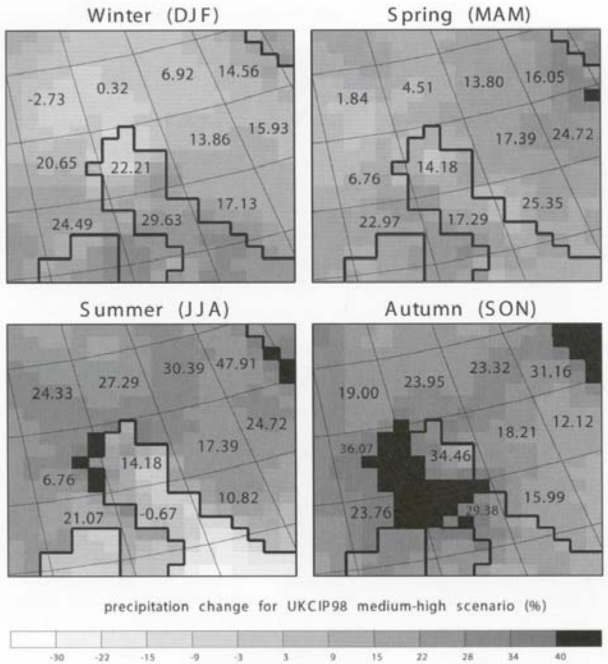

Fig. 3. Change in mean seasonal precipitation (%) based on the RCM-shaded boxes – and the GCM-overprinted numbers.

difference is in the magnitude of the wetting rather than in the sign of the precipitation change.

It is worth noting that most of the RCM-derived regional variations in climate response mentioned above are to some extent captured by the GCM scenario, albeit at coarser scale. Thus in winter, the magnitude of precipitation change in the GCM decreases from south (29.6%) to north (0.3%), as it does in the RCM, while in autumn there is a clear west-east gradient in the magnitude of the precipitation change in the GCM, from 36.1% in the west to 18.2% in the east, again as in the RCM. The RCM is therefore providing a finer scale interpretation of the regional patterns of average seasonal climate change across Scotland, patterns that are essentially captured by the GCM. The RCM is not providing us with fundamentally different patterns of change, at least for changes in average seasonal climate.

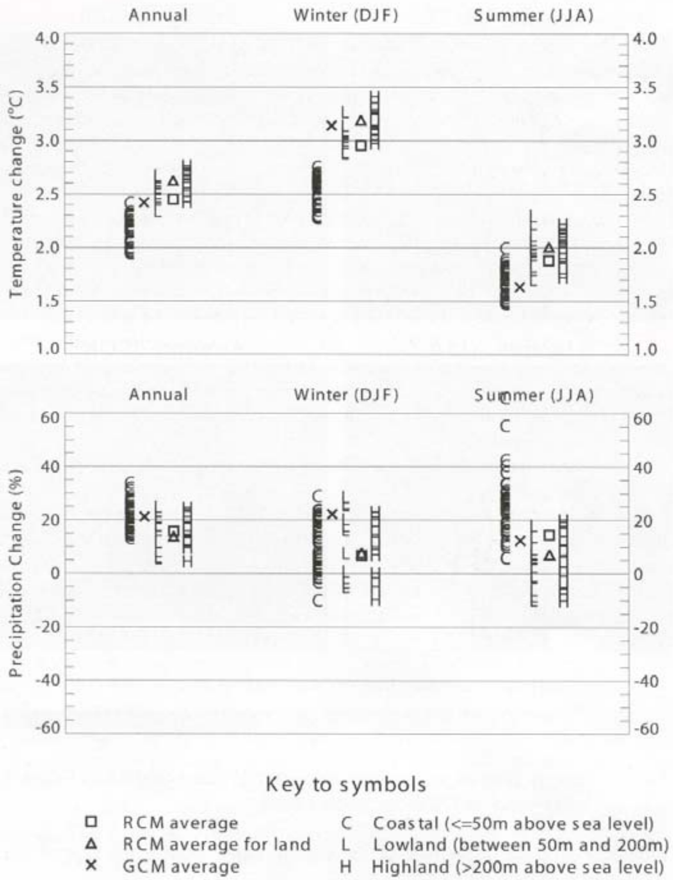

Fig. 4. Seasonal temperature and precipitation changes (2080-2100 with respect to 1961-90), for individual RCM gridboxes (C, L, H), for averages of all RCM boxes within GCM gridbox (bold squares) representing Scotland, and only RCM land boxes (bold triangles), and for the corresponding GCM scenario (bold crosses)

3.2. Spatial variations

To explore further the extra information the RCM provides, spatial variations in the average seasonal climate response across Scotland are analysed. Figure 4 presents the effects of elevation and land/ocean designation on the strength of warming and on the character of the precipitation changes. The information shown in Figures 2 and 3 is plotted as three 'families' (C = Coastal waters, L = Lowland, and H = Highland) according to the elevation values of the individual HadRM2 gridboxes.[1]

The temperature changes for individual RCM gridboxes in the upper panel of Figure 4 demonstrate again the contrast between land ('L' or 'H') and ocean ('C'), with stronger warming over land. This effect is more pronounced in winter than in summer. The spread of values in each 'family' demonstrates that the picture is not radically different for land or ocean boxes – the coastal effect is merely a modifying influence. There are only very slight differences between the 'lowland' and 'highland' boxes, with a slight (up to 0.3°C) amplification of warming with elevation in winter and no difference in summer. The ability of the RCM to resolve elevation differences across Scotland only has a minor effect on the resulting temperature change scenario.

A comparison of the GCM simulation with corresponding average values for the RCM is also shown in Figure 4.[2] The GCM temperature changes are all within the spread of values given by the individual RCM temperature changes. This confirms that the two models are not giving radically different answers. For annual temperature change, the RCM land average is a few tenths of a degree warmer than both the GCM change and the full RCM average. In winter, it is the average of all RCM boxes that has warmed slightly less than the GCM and in summer both RCM averages exceed the GCM value.

The spatially-averaged RCM values for precipitation change over Scotland (Fig. 4, bottom panel) are also close to those of the corresponding GCM simulation, with the exception of winter. In this season the GCM yields a considerably larger increase in precipitation than that suggested by the RCM. In summer, large increases in precipitation occur for model ocean boxes compared to land boxes, where both wetting and drying occurs. This land-ocean contrast in precipitation response is different to that for temperature (see the top panel), where the greatest land-ocean contrast occurred in winter. Land and ocean boxes give a very similar spread of values in winter and the land-ocean contrast in the annual average precipitation change is therefore small. In comparison with temperature changes, there are some larger differences between the RCM and GCM for precipitation changes, especially in the winter. The large natural spatial and temporal variability in precipitation limits the confidence to be placed in scenarios for this variable when they are drawn from a single, short (20-year) RCM experiment such as the one used in this study.

The regional detail in the RCM-based scenario can be explored further by examining dependencies between latitude and longitude with climate change. The relation between temperature change and longitude for all the RCM gridboxes within Scotland is shown in the left-hand three panels of Figure 5. There is as expected a land-ocean contrast, strongest in winter and weaker in summer. Over ocean areas (asterisks) there is no dependence of temperature change on

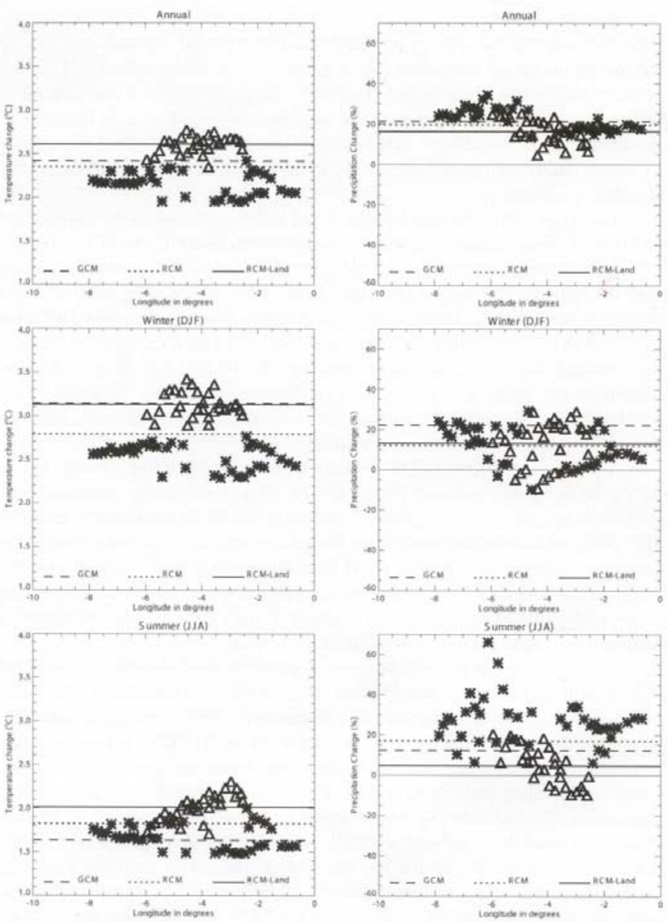

Fig. 5. RCM temperature and precipitation changes for 2080-2100 with respect to 1961-90 plotted against longitude. Triangles are for land boxes and asterisks for ocean boxes. The representing GCM and corresponding RCM averages for the whole of Scotland are overlaid as horizontal lines.

longitude, but for land areas (triangles) there is some evidence of amplified summer warming over eastern areas. Similarly, for precipitation change (right-hand panel of Fig. 5), in winter no difference is obvious between east and west, or between land and ocean. In summer, however, there is a distinct contrast between ocean and land areas. The land areas have precipitation changes varying from a 12 % reduction (in the east) to a 20 % increase (in the west).

With respect to latitudinal contrasts within the RCM scenario, as shown in Figure 2 the Northern Isles and most northerly land areas experience slightly less warming (0.2-0.5 °C) than the rest of Scotland. For precipitation, as shown in Figure 3, in winter there is increased precipitation further south and little change, or a slight decrease, in the north for both land and ocean areas. In contrast, for summer precipitation there are reductions or small increases in the south and larger increases in the north, although the effect is small and complicated by the contrast between land and ocean.

In summary, elevation, longitude and latitude are all factors in determining the regional pattern of climate response over Scotland, but the relationships are not simple. The strongest signals detected in the analysis above are the contrasting response between land and ocean, and the existence of west-east gradients in summer temperature and precipitation change. This pattern in summer temperature and precipitation change can be explained by the role of sensible/latent energy. Due to the relationship between circulation and topography the drying is greater in the east. This leads to less evaporation, less energy converted to latent energy and more energy retained as sensible heat, hence the greater degree of warming.

4. Changes in Daily Weather Extremes

To examine the significance of the RCM simulation for regional daily weather scenario derivation, 'extreme' weather event scenarios for precipitation and daily mean temperature are constructed. The differences between the changes in daily weather extremes for Scotland derived from the RCM and GCM are also assessed in this section.

The analyses use 30-years of daily mean temperature and precipitation sequences derived from the control RCM simulation representing 'current' climate and 20-years of daily data from the scenario RCM simulation for the period 2080-2099. We also use the equivalent daily series extracted from the HadCM2 GCM simulations. Only data for RCM land boxes are analysed. The method used to derive the daily weather scenario is given in Box B. To allow combination of our regional scenario with a wider range of GCM-based scenarios, results in this section are normalised with respect to 1 °C of global warming.

4.1. RCM-derived extreme weather event scenarios

Using the data and methodology described above, threshold values for extreme weather events ('hot' temperature and 'intense' precipitation) are derived, together with changes in the number of days with 'extreme' weather conditions in each season. These are calculated both in absolute and relative terms.

For daily mean temperature, threshold values for 'hot' days are defined by

Box B: Derivation of Daily Weather Statistics

To investigate extreme daily weather events ('hot' temperature and 'intense' precipitation), the daily series were first sorted into descending order. For precipitation, the seasonal 'extreme' threshold amount was defined as the value reached that provides 10 % of the total seasonal precipitation, *i.e.* the maximum daily precipitation threshold that delivers 10 % of the total. This quantile approach was that used by Osborn *et al.* (2000) in their analysis of UK daily observational precipitation data. For daily mean temperature, threshold amounts were defined as the 90th percentile of daily ranked events for each season, thus adopting a more conventional percentile approach to defining thresholds.

A return period analysis is also conducted to define daily extremes with given return periods. Here, theoretical distributions were fitted to the maximum daily values for each respective season's distribution. A Gumbel distribution was fitted to maximum daily precipitation in each season to allow the estimation of return period amounts. The selection of Gumbel distribution here is based on (a) the shape of daily precipitation distribution is strongly skewed; and (b) the parameters in Gumbel distribution are relatively easy to calculate (Palutikof *et al.*, 1999). In contrast to precipitation, for maximum daily mean temperature the distribution shape is roughly symmetrical, hence a normal distribution was fitted by season to obtain the temperature thresholds associated with given return periods.

both the 90 % percentile method and the return period approach. Not surprisingly, this threshold temperature increases substantially across Scotland with global warming. Normalised changes in the threshold amounts (Fig. 6) are largest in winter and spring and smallest in summer. There is relatively little sub-national structure to these changes, although an east-west difference is most notable during the autumn. The effect of enhanced greenhouse gas concentrations on extreme temperature is also examined by analysing the normalised changes in the number of 'hot' days (Fig. 7). As with the rise in threshold amount, the number of 'hot' days increases in all seasons and all over Scotland under future climate. In relative terms, the increase is greatest in winter, where very mild days increase by up to eight per winter for 1 °C of warming. There is not much regional structure to these changes, with just a slight hint of greater increases in southwest Scotland and slightly smaller increases in the northeast.

Similar analysis was carried out for precipitation. The frequency of wet days (defined as model precipitation greater than 0 mm/day) decreases in the RCM across most of Scotland and in most seasons. Since there is a general increase in total seasonal precipitation (Fig. 3) across the country, this implies a general tendency towards more intense precipitation over Scotland under enhanced greenhouse gas concentrations. The 'intense' precipitation amounts are defined using both the quantile method and Gumbel distribution fitting approach (return period approach).[3] The obtained threshold values for 'intense' precipitation

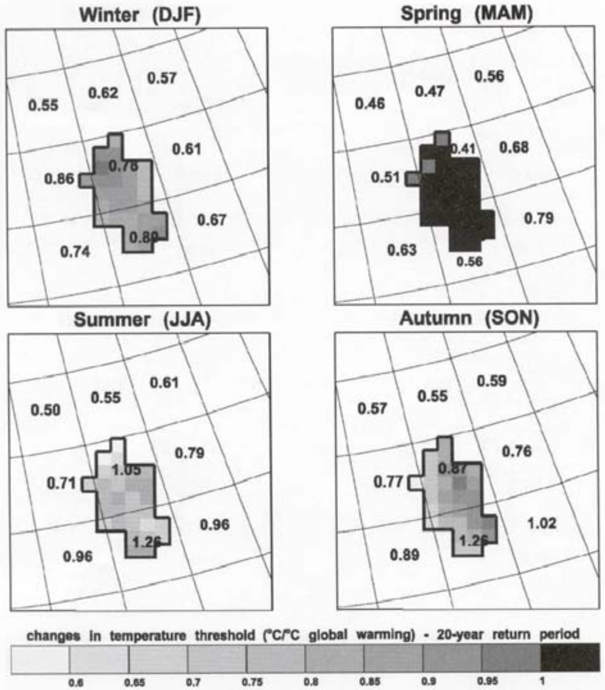

Fig. 6. Change (°C per 1 °C global warming) in the 20-year return period daily mean temperature. Results from the two RCM simulations. Equivalent GCM results are overprinted on GCM gridboxes.

are highest over the western part of Scotland and, throughout Scotland, slightly higher in autumn and winter than in the other two seasons. Changes in the threshold amounts indicate the effect of climate warming on the 'intense' precipitation rate. Normalised percentage changes are generally higher in the west than the east of the country, with the largest increases of 15% or more occur in summer for the quantile-derived threshold and up to 15% increase in autumn for the two-year return period intensity (Fig. 8). Normalised changes in the number of days when the quantile threshold is exceeded for both control and scenario periods are presented in Figure 9 by season. Generally, the number of 'intense' precipitation events increases over Scotland, especially in the west. The highest increases occur in the summer and autumn seasons.

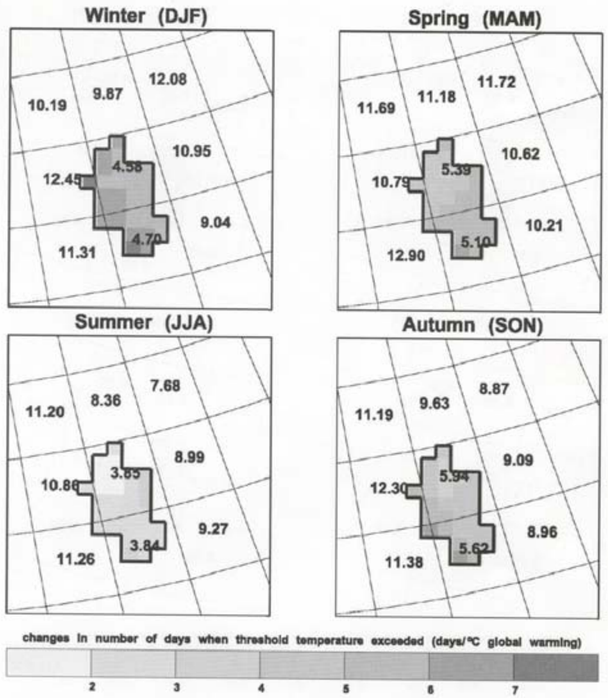

Fig. 7. Change (number of days per 1 °C global warming) in the number of 'hot' days defined using the percentile method and using the RCM control simulation threshold. Results from the two RCM simulations. Equivalent GCM results are overprinted on GCM gridboxes.

4.2. Comparison between RCM- and GCM-based daily weather scenarios

The absolute threshold values, and the relative changes in these thresholds, estimated from daily mean temperature and precipitation are assessed to examine whether they differ greatly between the RCM and GCM simulations. Figure 10 shows that the absolute thresholds of 'hot' temperature events differ substantially between the RCM and GCM for all seasons except winter. For the 20-year return period thresholds, the RCM yields values that are between 2° and 3 °C higher than the GCM, *i.e.* the RCM simulates more intense daily temperature extremes than

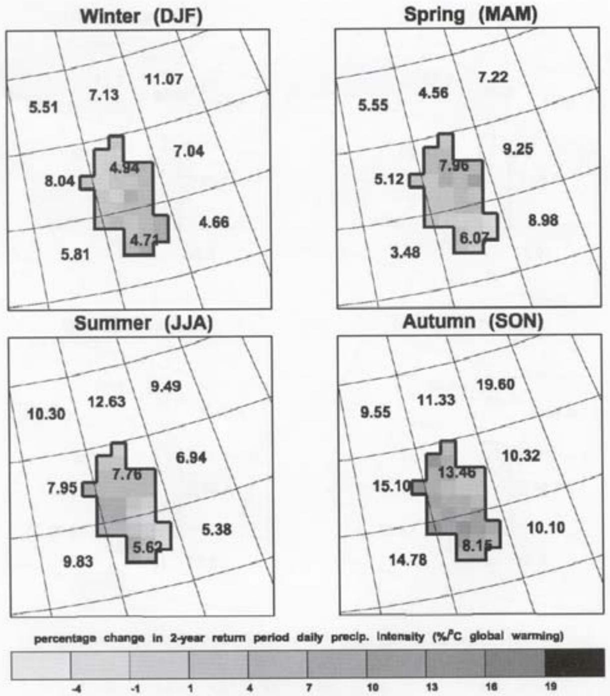

Fig. 8. Change (percent per 1 °C global warming) in the two-year return period daily precipitation intensity. Results from the two RCM simulations. Equivalent GCM results are overprinted on GCM gridboxes.

does the GCM. This is not a surprising finding and has been reported elsewhere (Giorgi *et al.*, 2001). The GCM is integrating over much larger scales than the RCM and is more influenced by ocean effects and is therefore unable to simulate local temperature 'hotspots' to anything like the same accuracy as a RCM.

When we compare, however, the *relative* changes in these threshold values due to climate warming we find a fair level of agreement between the GCM result and the aggregated RCM result, more so for the number of 'hot' days events (Fig. 7) than for the 20-year return period thresholds (Fig. 6). For example, the GCM suggests nearly five more 'very mild' days in winter for each degree of

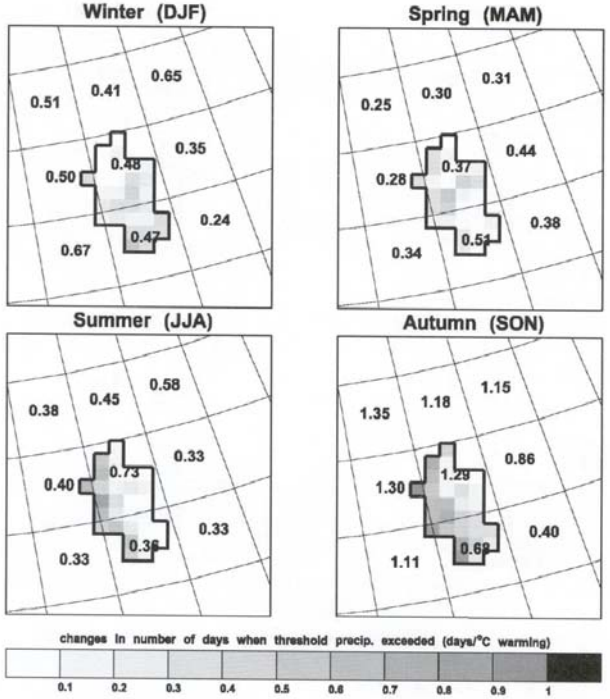

Fig. 9. Change (number of days per 1 °C global warming) in the frequency of 'intense' daily precipitation events defined using the quantile method. Threshold used is that from the RCM control simulation. Results from the two RCM simulations. Equivalent GCM results are overprinted on GCM gridboxes.

warming over northern Scotland, compared to an aggregated RCM change[4] of about six extra days (Fig. 7).

Figure 11 shows that the absolute thresholds of 'intense' precipitation events also differ very substantially between the RCM and GCM. For the 20-year return period thresholds, the RCM yields values between 20 and 30 mm/day higher than the GCM, *i.e.* the RCM simulates much more intense daily precipitation extremes. The same as with temperature, the GCM is integrating over much larger scales than the RCM, therefore is unable to simulate the local intensity of precipitation to anything like the same accuracy as the RCM.

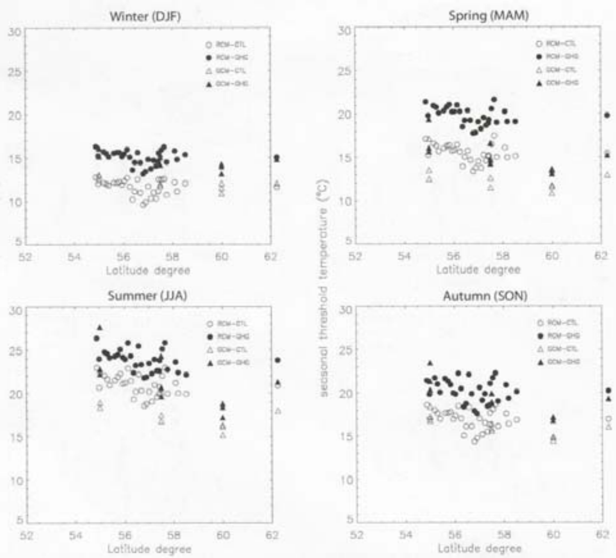

Fig. 10. Seasonal 20-year return period daily temperature (°C) for each land RCM and GCM gridbox in Scotland. The symbols plotted to the right of each plot indicate the domain average for Scotland.

The more interesting result is again for the *relative* changes in these threshold values for the RCM and GCM when expressed as a percentage change per degree of global warming. For both the return period thresholds (Fig. 8) and the number of 'intense' events (Fig. 9), the GCM result is broadly similar to the aggregated RCM result – although of course not showing any sub-national structure. Thus, for example, the relative (percentage) increase in the two-year return period winter daily precipitation intensity from the GCM is 4.9% over northern Scotland compared to an aggregated RCM change of about 3.1% (Fig. 8). This result is repeated for most of the analyses. In *relative* terms, therefore, the two models are yielding comparable estimates of changing frequencies/intensities of extreme weather.

5. Conclusions and Discussions

A climate change scenario for Scotland for the end of this century based on a high resolution (50 km) regional climate model experiment and consistent with the UKCIP98 Medium-high scenario shows, relative to 1961-90:

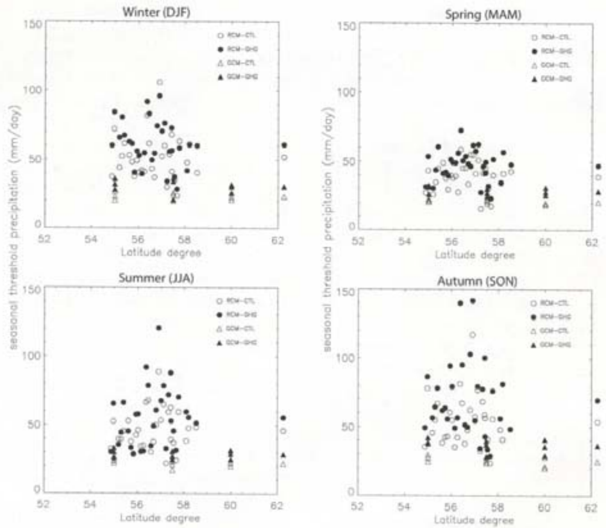

Fig. 11. Seasonal 20-year return period daily precipitation intensity (mm/day) for each land RCM and GCM gridbox in Scotland. The symbols plotted to the right of each plot indicate the domain average for Scotland.

- An annual average warming of between 2° and 3° (Fig. 4) with the largest warming in winter (up to 4 °C in northern Scotland) and the least warming in summer (slightly above 2 °C). This compares with a global average warming for this particular scenario of about 3.1 °C. Annual precipitation increases by around 20% (Fig. 4) with the largest increase in the west and south of the country in autumn (about 15% increase) and lesser drying in the Northern Scotland and the Northern Isles in winter. The strongest signals of spatial variation in seasonal climate change are the contrasting response between land and ocean, and the existence of west-east gradients across Scotland in summer temperature and precipitation change.
- 'Hot' days become more frequent by up to 20 per year for each degree of global warming. Precipitation intensities throughout most of Scotland increase in all seasons. Percentage changes in two-year return period daily precipitation intensities are generally largest in autumn – up to a 15% increase for each 1 °C of global warming.

Comparisons between the GCM- and RCM-based scenarios suggest that the regional patterns of average seasonal climate change and daily weather response provided by the RCM are broadly similar to what is essentially captured by the

GCM. Hence, the RCM is not providing fundamentally different patterns of change, merely a finer scale interpretation of the general patterns. In particular, the RCM gives improved representation of the coastline, though still imperfect with regard to the Scottish Isles, and captures some of the subtle effects of elevation, longitude and latitude on the regional climate response, effects which cannot easily be extracted from the GCM simulations. Although the GCM is integrating over much larger space scales than the RCM, and is therefore unable to simulate local extreme weather events ('hot' temperature and 'intense' precipitation' days) to the same accuracy as a RCM, the *relative* changes in the frequency of such events in the GCM and RCM scenarios are comparable.

The regional scenario analysed here can be used to evaluate the physical impacts of climate change, such as changes in the risk of alluvial flooding or storm damage, or explore social impacts such as in tourism, health, and planning for Scotland. However, they are derived from just one realisation of just one RCM driven by just one GCM forced with just one greenhouse gas forcing scenario. The scenario does not therefore give a definitive sub-regional picture of prospective climate change over Scotland and must be cautiously interpreted. In particular, we have no easy way to establish how robust and significant – relative to natural climate variability – are the sub-national patterns of response across Scotland. Presenting results as normalised changes (*i.e.* changes in climate per degree of global warming) does nevertheless allow the scenario to be generalised by combining these normalised regional patterns with a wider range of GCM-based scenarios – such as the UKCIP98 set.

This study is by no means comprehensive, but has allowed some assessment to be made of the types of information that can be extracted from RCM simulations, over and above what can be gained from GCM experiments. Making progress in terms of the quality and comprehensiveness of climate change scenario information for regional or local impact/adaptation studies will require a number of questions to be addressed. These include quantifying the uncertainties associated with 'downscaling' techniques; designing optimal combinations of GCM and RCM experiments; assessing how appropriate it is to use daily data from RCM experiments directly in impact studies; and assessing how sensitive estimates of climate change impacts are to differences between GCM and RCM-based scenarios. Some of this work will be reported in the new UKCIP02 climate scenarios due to be published in the spring of 2002.

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Endnotes

1. Coastal areas are marked with 'C' and correspond to the Orkney, Shetland, the Inner and Outer Hebrides with some coastal and inshore waters. Due to their small sizes, these boxes are actually treated as ocean within the RCM. Areas with elevation between 50~200 m are marked with 'L' while those with elevation above 200 m marked with 'H'.
2. To permit like-for-like comparison with the GCM, the aggregated RCM values are calculated from only those boxes that fall within the GCM gridbox centred on (57.5 N, 3.75 W), which approximately corresponds to the central highlands and northern Scotland.
3. Threshold amounts are obtained for the 1 in 2-, 5-, 10- and 20-year return periods for both RCM and GCM simulations. However, owing to the only 20 years of scenario data, patterns of change are most robust for the 2- and 5-year return periods.
4. Average of the HadRM2 land boxes falling within the GCM box centred on (57.5 N, 3.75 W)

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