National Climate Information Centre

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A spatial analysis of trends in the UK climate since 1914 using gridded datasets

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by

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Abstract

Monthly and annual gridded datasets covering the UK at 5km resolution have been created for a range of variables, using a dense network of station data and GIS-based regression and interpolation techniques. The datasets cover temperature and precipitation from 1914 to 2004, sunshine from 1929 to 2004, and a range of other variables from 1961 including air pressure, vapour pressure, derived temperature indices, snow cover, wind speed, and rainfall intensity. These datasets have been analysed in order to investigate patterns of change over time and space in the UK climate.

Linear regression and the non-parametric Mann-Kendall test are used to discover any trends present in the data. Time series are presented using kernel smoothing techniques. Regional differentiation in the patterns and changes is assessed by dividing the UK into 10 climate districts, and the trends are also calculated at each 5km x 5km grid point and presented on maps.

As expected, the most significant trends are found for temperature, with increases of up to 1°C since 1914. The most significant trend for precipitation is the decrease in summer values, but there are interesting spatial patterns with a strong increase in winter precipitation in north and west Scotland. These patterns are also reflected in reverse in the trends for sunshine.

1 Introduction

Perry and Hollis (2005b) described the methods used to generate a set of monthly gridded datasets covering the UK at 5km by 5km resolution, for 36 climate variables over the period 1961-2000. The production of these datasets was partly funded by the UK Climate Impacts Programme, and they are available for 24 variables from the following web address: http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/. These datasets have now been extended back to 1914 for temperature and precipitation and to 1929 for sunshine, following a programme of digitisation of pre-1959 station data from Monthly Weather Reports which increased the available station networks to an adequate density and coverage back to the dates shown. The gridded datasets for 13 of the variables are routinely updated with the latest month as part of regular monthly summaries, while several other variables have been updated to 2004 for this study.

The purpose of this paper is to describe an analysis of these datasets for patterns of change over time, including the spatial differentiation of these changes, and to identify any emerging features of the UK climate. The last 100 years is a period which has seen rapid climate change, partly in response to human influences caused by local, national and global social, economic, industrial, and land use developments. These changes have already had and continue to have impacts on different aspects of society, including health, agriculture, water resources, and energy demand. Therefore, it is important to investigate observed changes in the climate so that future climate predictions can be validated and put into context.

Most studies of national climate trends have been made using series of data from a small number of long-period stations (e.g. Begert et al., 2005; Kruger and Shongwe, 2004). Some authors combine data from several stations to create a single series for a country, e.g. Hanna et al. (2004) for Iceland, and Domroes and El-Tantawi (2005) for Egypt. The use of gridded datasets and their areally averaged series to analyse trends has the advantage of not being reliant on individual stations, which are vulnerable to missing data, inhomogeneities, and most importantly a limited spatial representativity.

Whilst most studies concentrate on analysing data for one or two climate variables, usually temperature or precipitation, studies which investigate a range of variables are often more illuminating (e.g. Hanna et al., 2004; Huth and Pokorna, 2005) as linkages between different aspects of the climate can be seen, leading to a picture of how the climate as a whole has been changing.

Section 2 describes the data used in this study, while Section 3 describes the methods used in the analysis and presentation of trends. Section 4 presents analysis results for groups of

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climate variables in turn, and this is followed by a discussion of the results and overall conclusions in Section 5. Mapped trends can be found in Appendix 1.

2 Data

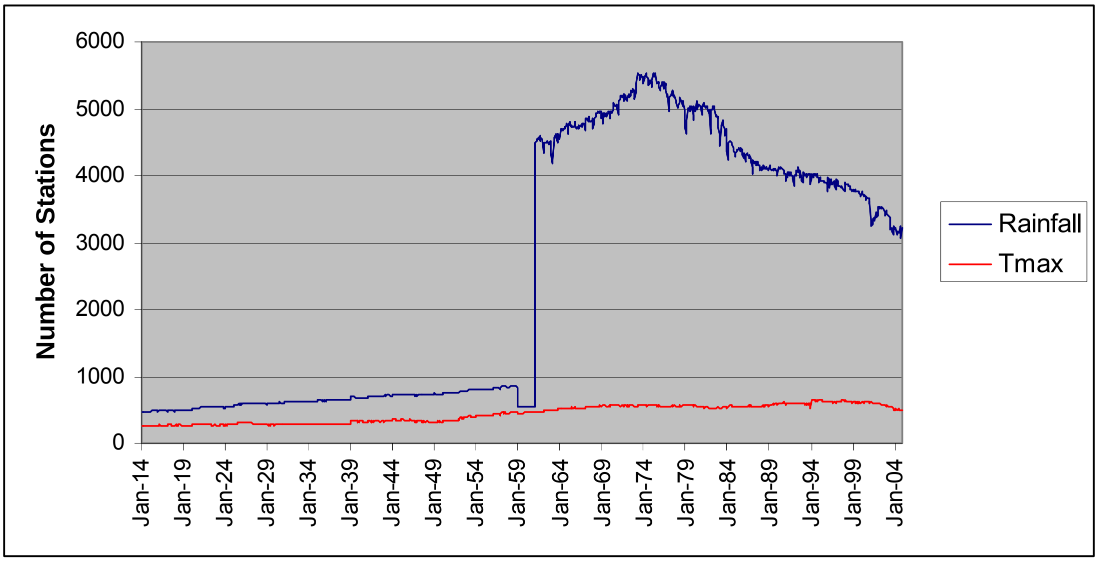
The methods used to generate the monthly gridded datasets are described in full in Perry and Hollis (2005b), but they will be briefly summarised here. The analysis makes use of ArcView GIS capabilities, using the custom EWB software. Depending on the variable being analysed, the station data can first be normalised with respect to the 1961-1990 long-term average, generated using the methods described in Perry and Hollis (2005a). The station data are then put through a multiple regression analysis, based on factors such as altitude, terrain shape, and nearby sea or urban areas. This is followed by spatial interpolation (inverse-distance weighted) of the regression residuals.

The climate variables covered include mean, maximum and minimum air temperature, precipitation, sunshine, days of frost and snow cover, and air and vapour pressure. A number of annual indices have also been calculated and gridded. These were derived from daily temperature (T) or precipitation data using the following definitions:

- Growing Season Length (GSL) = period (days) bounded by daily T_mean > 5 °C and < 5 °C (after 1st July) for ≥ 6 days.
- Heating Degree Days (HDD) = ∑ 15.5 – daily T_mean for T_mean < 15.5 °C.
- Growing Degree Days (GDD) = ∑ daily T_mean – 5 for T_mean > 5 °C.
- Heat-wave Duration (HWD) = ∑ days with daily T_max – 1961-1990 daily normal > 3 °C for ≥ 6 consecutive days.
- Cold-wave Duration (CWD) = ∑ days with 1961-1990 daily normal - daily T_min > 3 °C for ≥ 6 consecutive days.
    - Heat-wave and cold-wave durations were calculated separately for summer and winter half-years.
- Consecutive Dry Days (CDD) = the maximum number of consecutive days in the year with precipitation ≤ 0.2 mm.
- Greatest 5-day precipitation (>5DR) = the maximum annual 5-day precipitation total (mm).
- Rainfall Intensity (RI) = the average precipitation amount on days with precipitation ≥ 1 mm.

All available station data were used, ensuring a dense coverage across the UK of up to 600 stations for temperature and 5500 for rainfall. This enabled a fairly detailed analysis to be made, even though very localised and micro-climatic features such as frost hollows are unlikely to be modelled. However the network used changed throughout the period, and the total number of stations is shown in Figure 1 for temperature and precipitation. The methods used are designed to minimise the effects of an evolving network, but the step change in the rainfall from 1961 has been shown to create a small bias (Perry, 2005). The data used has undergone quality control, but has not been tested for homogeneity.

Figure 1: The number of stations used to create monthly gridded datasets for UK Precipitation and Maximum Temperature, 1914 – 2004.



The analysis described in this paper is based on the raw gridded datasets, as well as series of areal averages of the 5km grid point values covering the ten climate districts and the four countries which make up the UK.

3 Methods

Diagnostic plots and charts of the data were used to identify patterns or features of the climate which required further investigation. These included time series plots of the geographically-averaged de-seasonalised monthly data, normalised with respect to the monthly averages over the whole series. Seasonal and annual summaries were also made, identifying extremes as well as the overall seasonal cycle. The seasons used in this work are as follows: December, January and February (winter); March, April and May (spring); June, July and August (summer); and September, October, and November (autumn).

The time series data were smoothed by applying a triangular-shaped kernel filter, with 14 terms either side of each target point. At the ends of the time series, only the 14 points to one side of the target point were used, increasing to the full 29 year bandwidth by the 15th year from each end. This non-parametric filter enables the long-term fluctuations in the climate to be clearly seen without assuming that the trend follows a stated model. These time-series plots help to give an impression of the pattern of change over time, as well as the degree of inter-annual variability.

The data were analysed for trends using linear regression, and the significance of trends was tested using the non-parametric Mann-Kendall *tau* test (Sneyers, 1990). Values in bold indicate statistical significance at the 1% level, while *italicised* values indicate significance at the 5% level. Care needs to be taken when interpreting results from linear trends as the assumption of a linear trend is not always valid. However, the trends do often approximate to linear, and the combination of linear trends with the Mann-Kendall significance test has been widely used in the analysis of climate trends (e.g. Domroes and El-Tantawi, 2005; Hundecha and Bardossy, 2005; Shen et al, 2005). In cases where the linear trend is clearly not valid, an alternative method of assessing the degree of change is to compare the recent climate since 1991 with the average for a 30-year baseline period such as 1961-1990 or 1921-1950. In these cases, the statistical significance was obtained via a 2-tailed t-test for the comparison of two sample means.

As well as for district and country series, linear trends were also calculated from series of values for each individual 5km x 5km grid cell, extracted from the gridded datasets. This enabled the mapping of changes in climate variables over the period of study, so that the spatial differentiation of the changes could be clearly seen.

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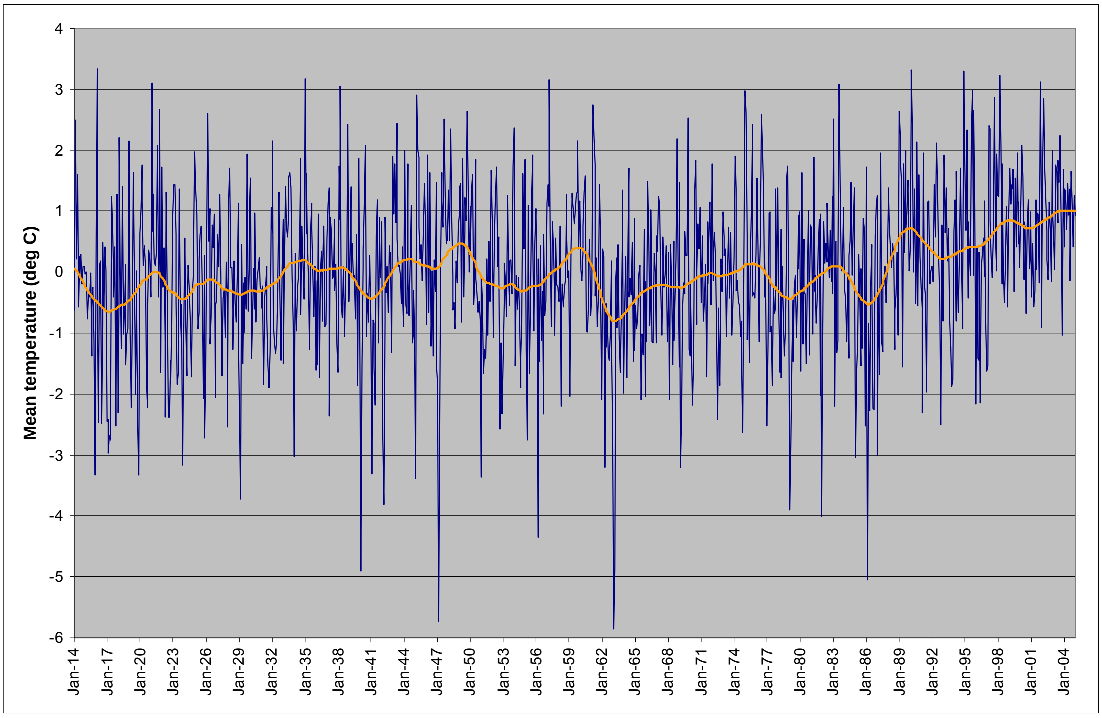
4 Results

4.1 Temperature

Figure 2 shows a time series of mean monthly temperature anomalies averaged over the UK. The particularly cold months of January 1947, January 1963 and February 1986 can be seen, as well as the marked increase in temperature since 1987.

Figure 2: De-seasonalised time series of monthly mean temperature areally averaged over the UK, with a 5-year weighted smoothing filter.



Jones and Lister (2004) found changes based on linear trends of 0.69°C for the Scottish mainland, 0.64°C for the Scottish Islands, 0.77°C for Northern Ireland, and 0.75°C for Central England in their series from 1861-2000, based on a few selected long-period stations, and found slightly smaller increases for the 1901-2000 period. The results presented here confirm that there has been a significant increase in annual mean temperature over the whole of the UK since 1914. As shown in Table 1, the trend is significant at the 1% level for 9 of the 10 districts, while for North Scotland it is only significant at the 5% level. The strongest increases have occurred in the Midlands, south-east England and East Anglia; in these areas, the mean temperature has increased by 0.9°C since 1914. The rate of increase has varied between different months and seasons, with the largest increases having occurred in the autumn, and the smallest increases in the winter, this being the only season where significant increases have not occurred for most districts.

Table 2 shows trends in the period since 1961 and, apart from in the autumn, the changes shown are greater than for the longer period. This shows the need for caution in interpreting trends for the shorter period, and although the rate of change was certainly faster during this period and significant increases took place, the large changes implied by the linear trend are probably misleading as the trend in mean temperature is clearly not linear and there was a drop in temperature coinciding with the start of the 1960's. To present a more robust measure of recent changes, the mean temperature since 1991 has been compared to the 1961-1990 baseline in Table 3. The annual changes are similar to those over the 1914-2004 period, but there have been greater increases during winter and spring.

Table 1: Change in mean temperature by district from 1914 to 2004 (°C)

	Scotland N	Scotland E	Scotland W	England E & NE	England NW & Wales N	Midlands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	*0.59*	**0.83**	*0.66*	**0.84**	**0.81**	**0.81**	*0.71*	0.48	*0.65*	**0.76**
Summer	0.50	*0.59*	0.43	**0.71**	*0.72*	**0.92**	**0.84**	0.60	**0.90**	**0.73**
Autumn	0.46	**0.85**	**0.68**	**1.01**	**0.94**	**1.14**	**1.11**	**0.80**	**1.12**	**0.68**
Winter	0.02	0.45	0.33	0.63	0.48	0.65	0.72	0.37	0.73	0.28
Annual	*0.37*	**0.66**	**0.51**	**0.77**	**0.71**	**0.86**	**0.83**	**0.55**	**0.84**	**0.60**

Table 2: Change in mean temperature by district from 1961 to 2004 (°C)

	Scotland N	Scotland E	Scotland W	England E & NE	England NW & Wales N	Midlands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	*1.03*	**1.23**	**1.20**	**1.47**	**1.48**	**1.55**	**1.51**	**1.36**	**1.54**	**1.10**
Summer	**1.06**	**1.12**	**1.08**	**1.47**	**1.24**	**1.52**	**1.71**	**1.08**	**1.52**	**1.07**
Autumn	*0.64*	*0.68*	*0.66*	**0.78**	*0.72*	**0.86**	*0.85*	*0.73*	**0.88**	*0.67*
Winter	1.03	*1.39*	*1.31*	**1.88**	**1.73**	**1.98**	**2.05**	*1.68*	**2.02**	*1.31*
Annual	**0.92**	**1.08**	**1.04**	**1.38**	**1.27**	**1.45**	**1.51**	**1.19**	**1.47**	**1.01**

Table 3: Change in mean temperature by district between the 1961-1990 and 1991-2004 averages (°C)

	Scotland N	Scotland E	Scotland W	England E & NE	England NW & Wales N	Midlands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	**0.65**	**0.77**	**0.76**	**1.01**	**0.97**	**1.05**	**1.07**	**0.89**	**1.04**	**0.77**
Summer	*0.51*	*0.50*	*0.52*	**0.80**	*0.62*	**0.81**	**1.00**	0.52	**0.83**	*0.53*
Autumn	*0.41*	0.36	0.40	0.37	0.39	0.44	0.39	0.41	*0.44*	*0.45*
Winter	0.59	*0.73*	*0.71*	*0.97*	*0.89*	*1.00*	*1.03*	*0.86*	*1.00*	*0.79*
Annual	**0.50**	**0.54**	**0.55**	**0.74**	**0.67**	**0.77**	**0.82**	**0.62**	**0.78**	**0.59**

Map 1 (see Appendix 1) shows the gridded differences of mean temperature between the 1961-1990 average and the 1991-2004 average for each season. The whole of the UK has seen increased mean temperatures in each season, except for a few grid cells on Scottish mountains which had a slight decrease in the autumn. The lowest increase occurred in south-west England, while inland parts of East Anglia experienced the greatest warming, especially in spring and summer.

Figure 3 shows that there have been two main periods of increasing temperatures: 1914 – 1950 and 1970 onwards. The most rapid warming has taken place since about 1985. It can be seen from Figure 3 that the western side of the UK has experienced less rapid temperature rises during this period: Northern Ireland, southwest England and south Wales, and north Scotland have increased at a slower rate than other districts in the last 30 years.

Figure 3: Annual mean temperature from 1914 to 2004 by district, smoothed with a triangular kernel filter with 14 terms either side of each target point.

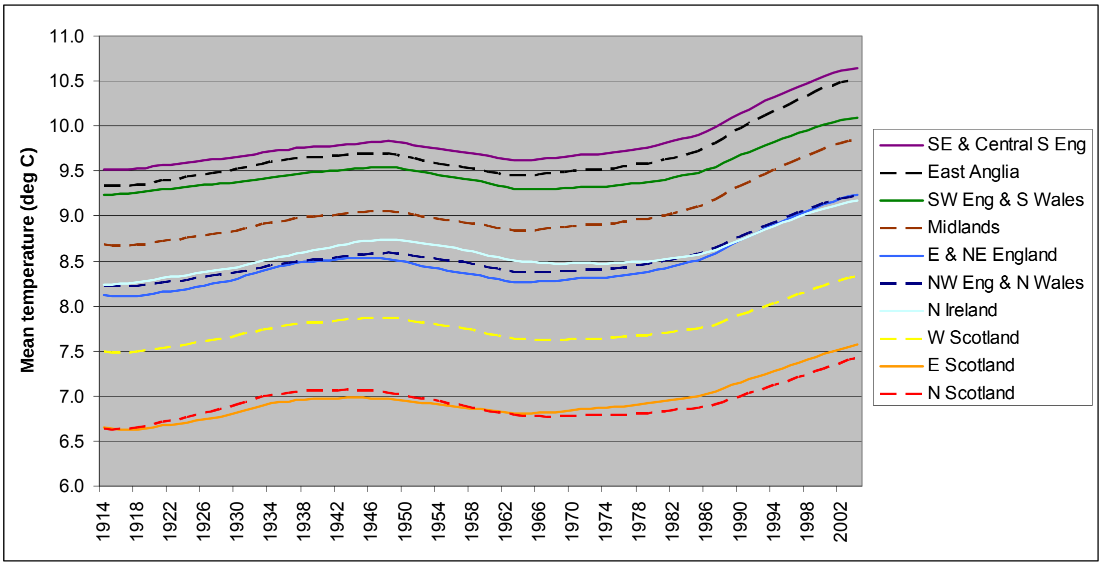


Table 4, Map 2 and Map 3 show the changes that have occurred in daily maximum and minimum temperatures for each district since 1914. Maximum temperatures have increased by more in the winter, while minimum temperatures have increased by more in the summer and annually (except for North Scotland where the winter minimum temperature has decreased). The increase in minimum temperature is significant at the 1% level for all districts except for North Scotland, with summer values rising by 1°C in some districts. Summer or winter maximum temperature increases are not significant, but annually the increases are significant for all districts, at least at the 5% level.

Table 4: Maximum and minimum temperature changes (°C) by district, 1914 to 2004

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Tmax winter	0.41	0.58	0.42	0.68	0.61	0.72	0.79	0.52	0.84	0.41
Tmax summer	0.58	0.37	0.20	0.40	0.53	0.77	0.71	0.66	0.76	0.66
Tmax annual	**0.55**	**0.55**	*0.37*	*0.54*	**0.59**	**0.68**	*0.63*	*0.55*	*0.68*	**0.57**
Tmin winter	-0.37	0.35	0.22	0.54	0.38	0.57	0.66	0.18	0.62	0.14
Tmin summer	0.30	**0.80**	**0.65**	**0.99**	**0.88**	**1.07**	**0.95**	**0.56**	**1.01**	**0.75**
Tmin annual	0.18	**0.79**	**0.68**	**0.96**	**0.84**	**1.02**	**0.99**	**0.55**	**0.98**	**0.62**

Similarly to the annual mean temperature, the summer maximum temperature (Figure 4) shows two periods of warming. Both this graph and Figure 5, which shows changes in winter minimum temperature, show the differentiation between the districts, with Northern Ireland, SW England, and N Scotland particularly standing out as having a slower rate of warming and a different pattern of change compared to the other districts. Winter minimum temperatures have been increasing since the early 1960's, but this followed a period of decline.

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Figure 4: Kernel smoothed summer daily maximum temperature by district, 1914-2004.

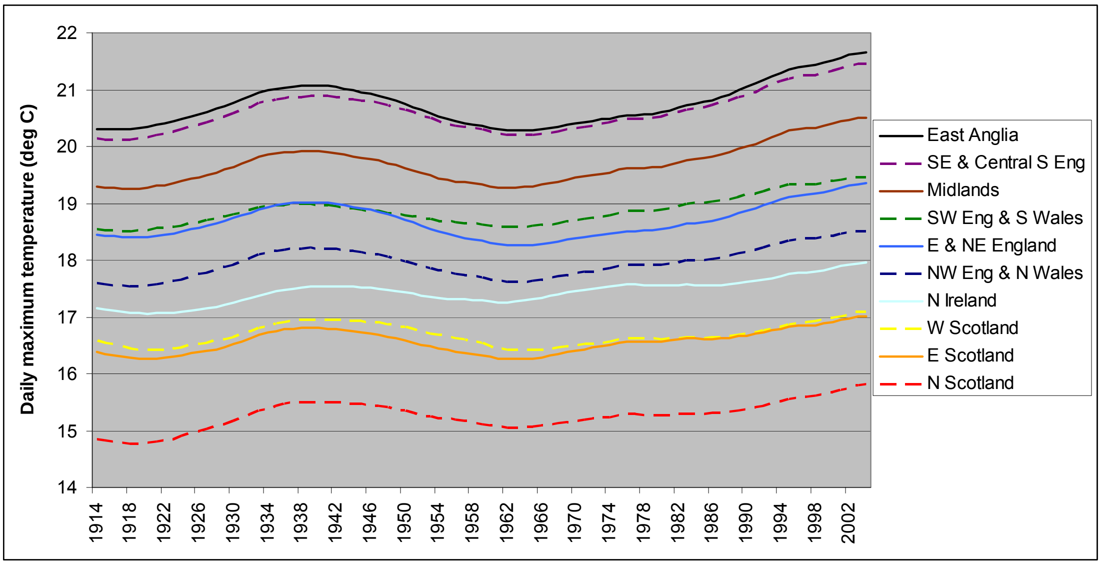


Figure 5: Kernel smoothed winter daily minimum temperature by district, 1914-2004.

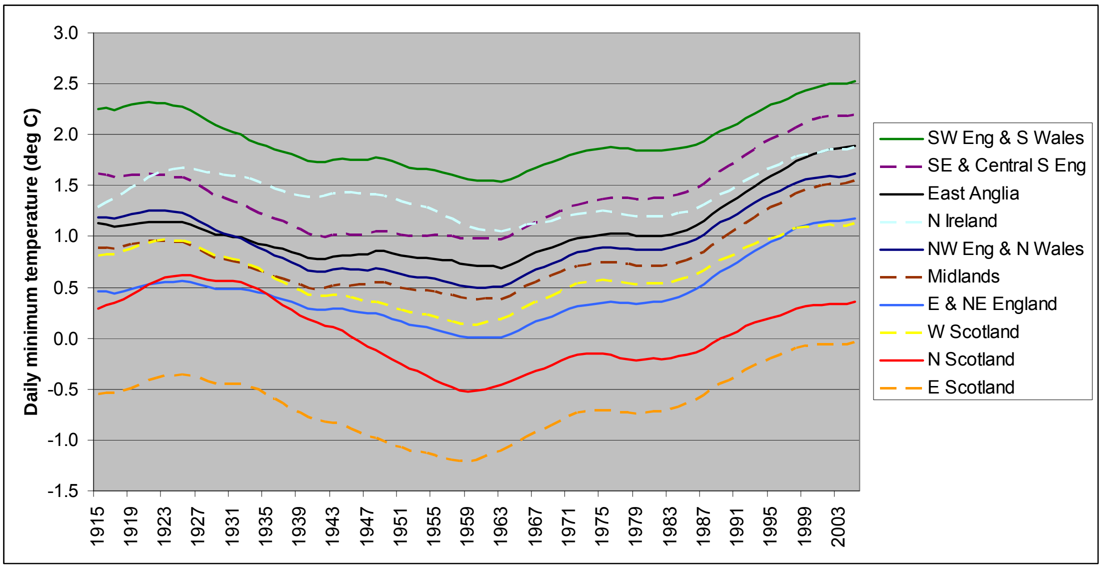


Table 5 gives trends for some annual temperature indices. For all districts there has been a significant decrease in heating degree days, which is obviously strongly linked to the rise in mean temperature in the period since 1961. Map 5 shows the geographical detail of the trends, and it can be seen that the greatest decreases have occurred in southern, eastern and central England. As can be seen in Figure 6, the decline in heating degree days has been quite steady despite high levels in 1979 and 1986.

The growing season has lengthened in all districts, but the increase is most significant over Scotland and northern England, with increases of 39 days for north and east Scotland. This suggests increasing potential for agriculture in those areas which previously had relatively short growing seasons. The faster increase in growing season length in North Scotland compared to south-east England can be seen in Figure 7 and Map 4. There was a particularly short growing season in 1979. The increases in growing season length are mostly due to warmer springs causing an earlier start to the growing season, but warmer autumns are also contributing. There have also been increases in growing degree days, significant at the 1% level for all regions of the UK. This measure reflects changes in the intensity of the growing season, as well as its length.

Table 5: Change in annual temperature indices by district from 1961 to 2003; heating and growing degree days (%); growing season length, winter cold wave duration and summer heat wave duration (days)

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
HDD	**-9.2**	**-10.7**	**-11.3**	**-14.2**	**-13.6**	**-15.1**	**-15.9**	**-13.9**	**-16.4**	**-11.7**
GDD	**23.7**	**22.5**	**21.1**	**22.0**	**20.1**	**21.6**	**21.0**	**16.5**	**20.2**	**18.2**
GSL	**38.7**	**38.8**	**34.0**	**37.4**	*24.8*	22.6	*26.5*	18.2	17.5	22.5
CWDw	-5.8	*-8.4*	*-8.9*	**-11.2**	*-10.3*	-10.2	*-11.5*	*-10.1*	*-12.0*	*-6.4*
HWDs	6.3	6.3	4.3	**13.3**	9.8	**15.3**	**15.8**	*10.4*	**14.3**	6.0

Figure 6: Actual and kernel smoothed annual heating degree days by country, 1961-2003.

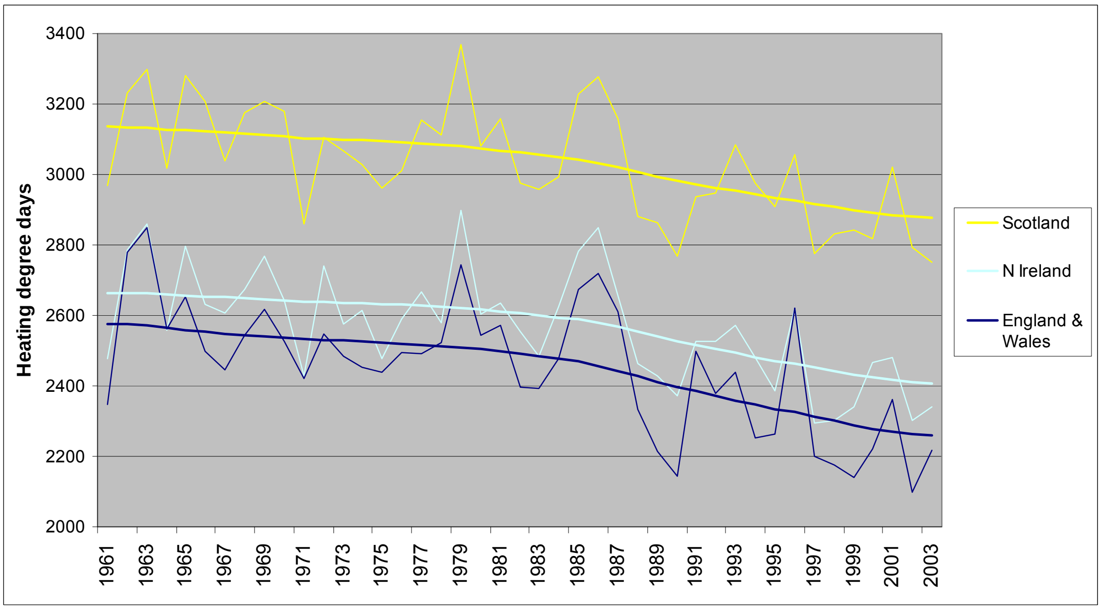
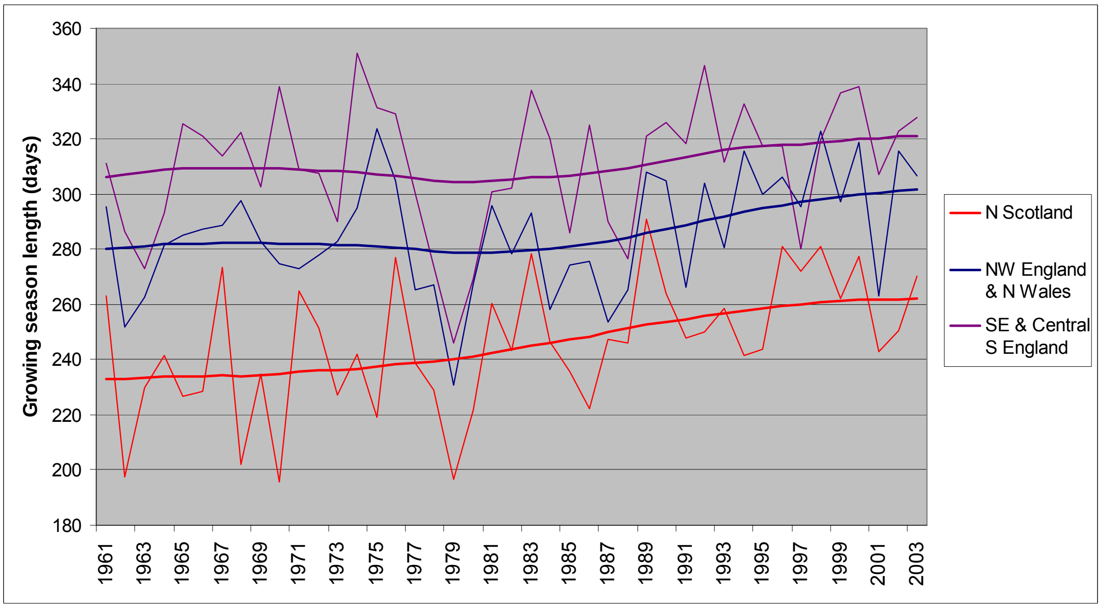


Figure 7: Actual and kernel smoothed growing season length (days) for three districts, 1961-2003.



The duration of winter cold waves has decreased, with this change being significant at the 5% level for most districts. There has been a rapid decline since 1986 so that significant spells of cold weather are now relatively rare (Figure 8). Looking at the mapped changes in Map 6, some of the greatest decreases have occurred in coastal areas such as south Cornwall, Cumbria, and Kent. Eastern and central England has seen a strong increase in summer heat wave duration, significant at the 1% level, but the change is much less marked for the western part of the UK. This is also evident in Figure 9, showing that increases in Scotland and Northern Ireland flattened out from the mid 1970's, while summer heat wave duration for other districts, most notably north-east England and East Anglia, have continued to lengthen. Map 6 shows that the greatest changes have occurred in inland parts of central England.

Figure 8: Kernel smoothed winter half-year cold wave duration (days) by district, 1961-2003.

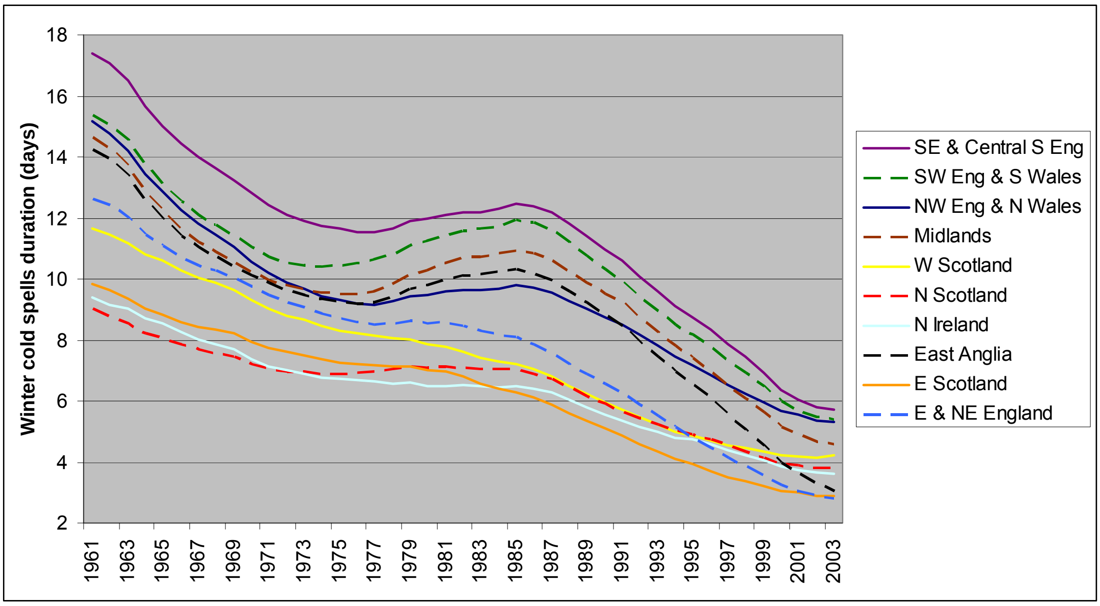
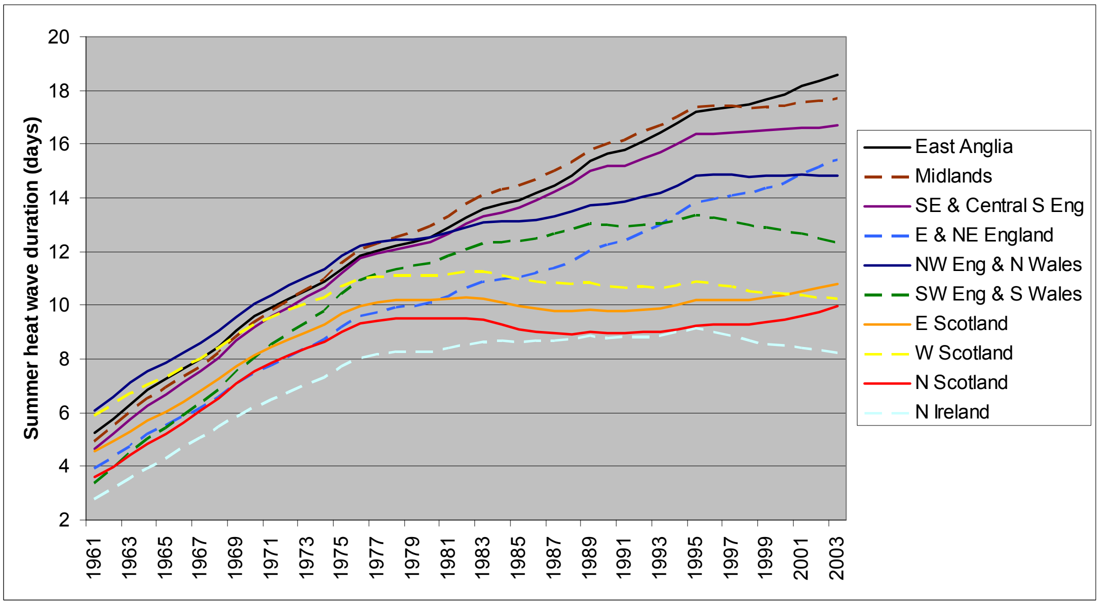


Figure 9: Kernel smoothed summer half-year heat wave duration (days) by district, 1961-2003.



4.2 Precipitation

Figure 10 shows a time series of UK monthly precipitation anomalies. There is a high degree of variability, with especially wet months (in percentage terms) in February 1990 and February 2002. February 1932 and August 1947 were the driest months with anomalies of just 11%. The year 2000 is the wettest year in the series overall.

Figure 10: De-seasonalised monthly time series of UK precipitation with a 5-year weighted average smoothing filter

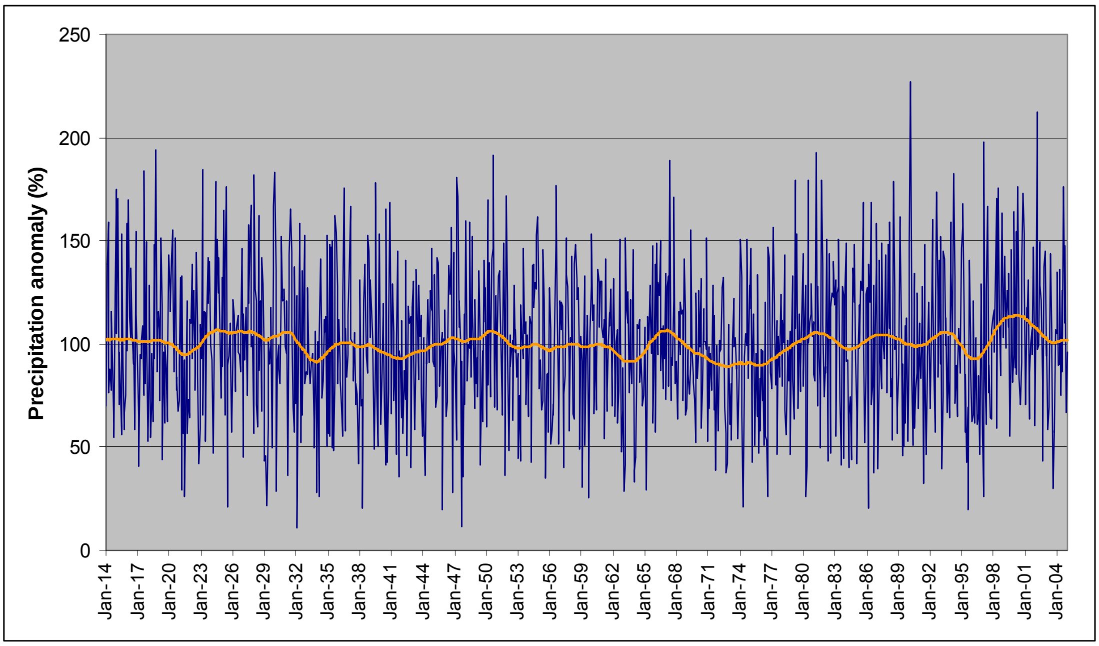


Table 6 shows that annual total precipitation has increased by nearly 10% in north and west Scotland since 1914, while in north-east England it has decreased by 5%. A strong, significant increase of 22% occurred in West Scotland in the spring, while north Scotland had its largest percentage increase in the winter. There was a decrease in precipitation for all districts in the summer, and this was significant at the 5% level for three districts. This is enhancing the strong seasonal cycle present in Scottish rainfall. Jones and Conway (1997) found no overall long term trend in area-averaged annual precipitation for England & Wales or Scotland from 1766 to 1995, but there was a significant increase in winter precipitation, especially in Scotland since 1986, which agrees with these findings.

Since 1961 there have been marked increases in precipitation in winter, especially in Scotland (Table 7). Map 7 shows that winter precipitation has more than doubled in a few parts of western Scotland, and increased substantially in many other areas, but areas to the east of high ground have had little or no increase. In the summer there is no clear pattern, and some areas have had an increase in precipitation, while others have seen a decrease.

Table 6: Change in precipitation by district from 1914 to 2004 (%)

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	13.9	6.1	*22.0*	6.6	9.7	6.3	5.4	10.8	4.6	19.6
Summer	-12.7	*-18.9*	-7.5	-14.3	*-20.9*	-13.2	-3.9	-19.4	-16.0	*-16.4*
Autumn	13.6	0.7	15.6	-2.9	1.7	1.8	5.5	5.8	8.5	8.3
Winter	20.9	-0.8	9.0	-7.4	-1.5	-6.4	-7.5	0.1	-5.6	-1.5
Annual	9.1	-3.8	9.0	-5.1	-3.3	-2.7	0.2	-0.1	-1.4	5.8

Table 7: Change in precipitation by district, 1961 to 2004 (%)

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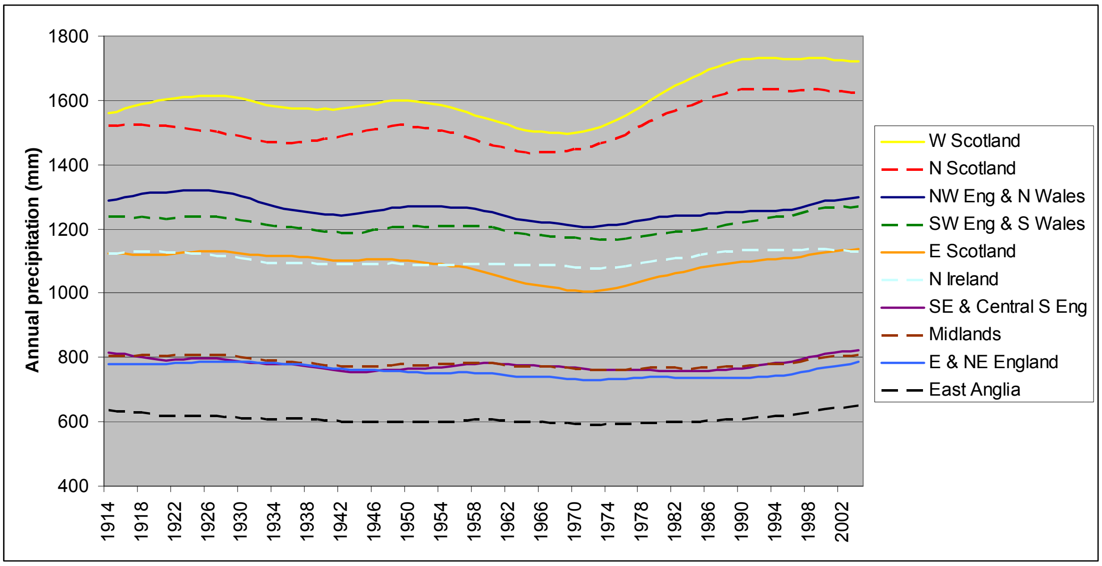
	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	16.2	9.4	17.3	-3.9	1.2	-3.0	-1.1	4.3	-6.5	2.8
Summer	-7.0	0.2	7.3	1.0	-7.0	-3.9	5.4	-1.7	-8.7	8.5
Autumn	5.3	22.2	5.9	13.8	7.0	22.7	22.4	24.4	21.1	-2.3
Winter	**68.9**	**36.5**	**61.3**	25.6	38.9	19.0	21.4	21.0	25.4	17.7
Annual	**19.8**	*17.4*	**21.9**	8.6	10.1	9.3	12.0	14.3	9.4	6.2

As can be seen in Figure 11, precipitation totals have been increasing since the early 1970's, most notably in Scotland, where rainfall has been at its highest level during the last 10 years. This followed an overall slight decrease during the period 1914 – 1970.

Figure 11: Kernel-smoothed annual precipitation by district, 1914 – 2004



The increases in days of rain ≥ 10 mm (Table 8) follow a similar pattern to that of total precipitation, but the percentage increase in wet days is greater than that for total precipitation, especially for England, Wales, and Northern Ireland. Again, the main increase occurs in the winter, especially in Scotland, with this increase taking place in the 1970 to 1990 period (Figure 12 and Map 8). Osborn et al. (2000) found for the UK during 1961-1995 an increasing contribution of heavy rainfall events in winter compared to light and medium events, while the opposite occurred in the summer.

Table 8: Change in days of rain ≥ 10 mm by district, 1961 to 2004 (days)

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	1.8	1.0	1.6	0.0	0.1	0.3	0.2	0.5	0.0	0.9
Summer	-1.4	-0.5	0.9	-0.3	-0.7	0.0	0.3	0.2	-0.1	1.2
Autumn	-0.2	2.3	0.1	1.1	1.0	1.8	1.4	2.7	1.8	-0.2
Winter	**8.3**	**3.5**	**8.2**	*1.9*	*4.3*	1.5	1.3	2.4	2.2	2.1
Annual	*8.2*	**6.2**	*10.6*	2.8	4.7	3.9	*3.5*	6.3	4.2	*3.7*

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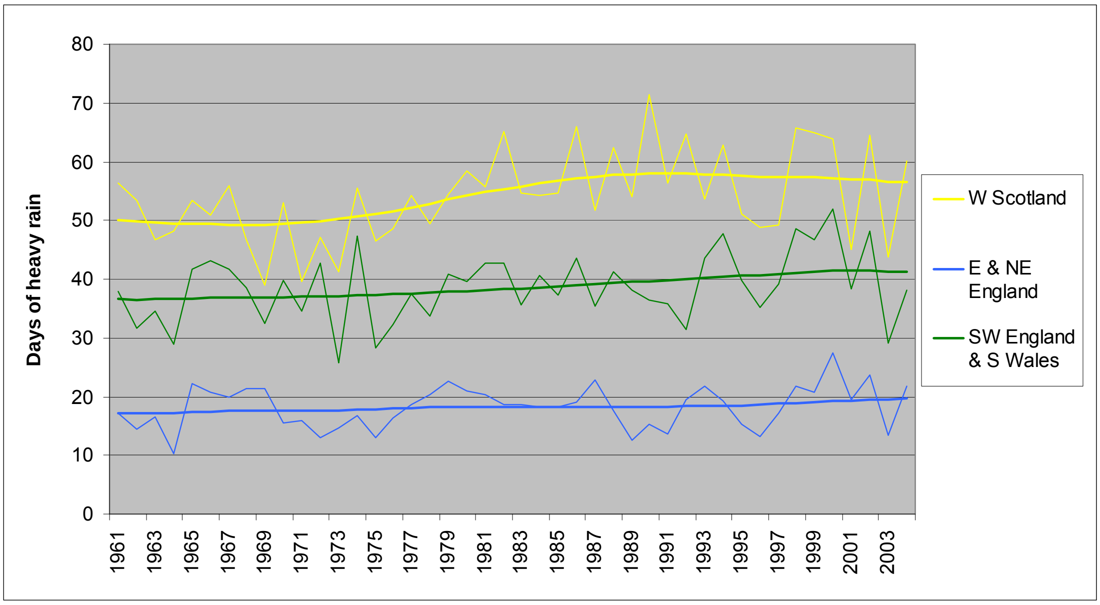
Figure 12: Actual and kernel-smoothed annual days of rain ≥ 10 mm for three districts, 1961 – 2004



There has been no significant change in the longest annual spell of consecutive dry days for any of the districts (Table 9). There have been significant increases in the annual maximum 5-day precipitation amount and in annual rainfall intensity, especially in Scotland and East Anglia. This is mostly explained by the overall increase in precipitation since 1961 (Table 7), but may also indicate an increasing contribution of heavy rainfall events to the overall total.

Table 9: Change in annual precipitation indices by district, from 1961 to 2004. a) consecutive dry days (days); b) greatest 5-day precipitation amount (%); c) average rainfall intensity on rain days (%)

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
CDD	-0.2	1.1	0.1	-0.3	-0.2	0.0	-0.4	-1.4	1.1	0.5
>5DR	*14.3*	**23.3**	**22.0**	*20.0*	3.7	*12.9*	**15.6**	*12.3*	2.1	4.6
RI	7.4	*7.6*	*7.8*	5.0	-0.2	*6.7*	**10.1**	*6.4*	6.3	2.1

4.3 Snow and Frost

Table 10 shows that there has been a strong downward trend in the number of days with snow cover at 0900 since 1961. The strongest trend has occurred in southern England (Map 9), where there are now about 75% fewer days with snow cover compared to 1961. Northern England has also experienced a very significant downward trend. The negative trend is present in all seasons, but is most significant in the autumn period, although absolute decreases are greatest in the winter, which is the season in which the most snow occurs. The 1980's were a particularly snowy period for the UK, as well as the start of the 1960's, with 1962/63 being the snowiest season for England and Wales. The decreases are weaker but still significant for most districts when starting from 1963/64, to avoid skewness introduced by the high values of 1962/63. The trend is weaker for Scotland and Northern Ireland, where the snowy period in the 1980's was especially significant, and the early 1960's snow less so (Figure 13).

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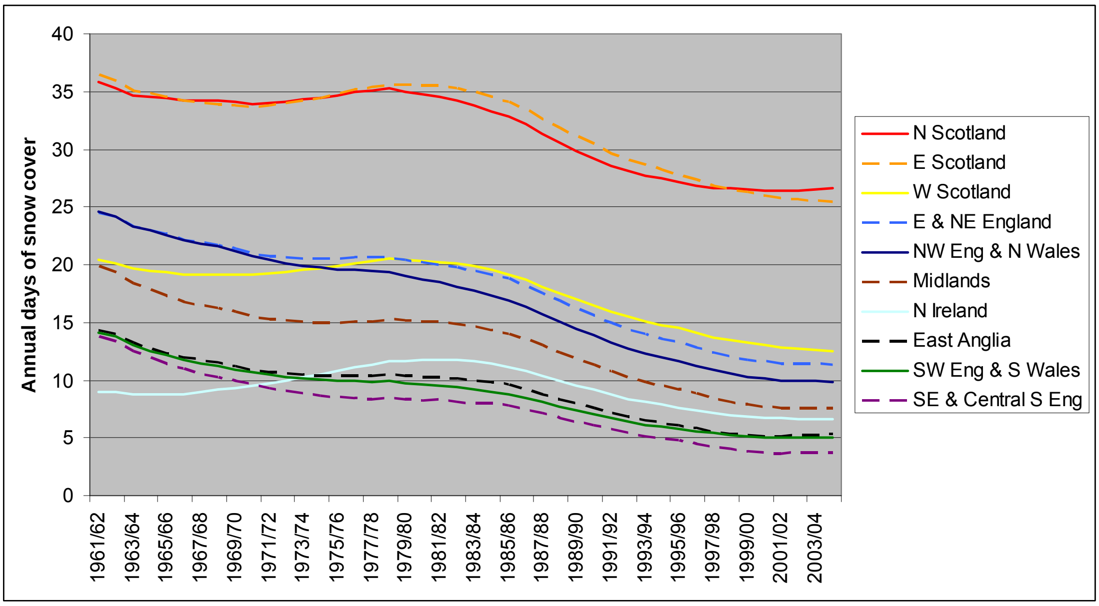
Table 10: Change in days of >50% snow cover by district (days), 1961/62 to 2004/05

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	-2.3	-2.0	*-2.0*	**-2.7**	**-3.8**	**-2.1**	*-1.1*	**-1.8**	**-1.5**	0.0
Autumn	**-3.3**	*-2.7*	**-2.0**	**-1.7**	**-2.1**	**-0.8**	*-0.4*	**-0.9**	**-0.3**	*-0.8*
Winter	-6.6	-8.9	-5.8	-11.7	**-12.1**	-11.8	-9.5	*-8.2*	*-9.9*	-2.5
Annual	*-12.9*	-14.2	*-10.3*	**-16.5**	**-18.6**	*-14.9*	-10.9	**-11.1**	**-11.7**	-3.5

Figure 13: Kernel-smoothed annual days of snow cover by district, 1961/62 – 2004/05



Similarly to snow, and reflecting the increase in winter minimum temperature (Table 4), there has also been a strong decreasing trend in days of air frost since 1961 (see Table 11 and Map 9). In Scotland there has been a reduction of about 25%, in Northern England about 30%, and in southern England and Northern Ireland about 35%. Although not all of the seasonal trends are statistically significant, they are consistent and combine to produce annual trends which are significant at the 1% level for all districts. Figure 14 shows that the trends are fairly constant over time, although the rate of change was fastest during the 1990's.

Table 11: Change in days of air frost by district (days), 1961/62 to 2004/05

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	*-7.3*	*-7.4*	*-5.5*	*-5.2*	**-7.0**	*-6.2*	*-4.8*	*-5.5*	*-5.5*	*-6.2*
Autumn	**-4.1**	*-4.7*	*-3.7*	*-3.7*	*-3.3*	-2.9	-2.5	-1.9	-2.3	*-3.3*
Winter	-9.0	*-10.8*	-9.8	*-12.8*	-12.1	-12.7	*-13.9*	-11.4	*-13.6*	*-11.9*
Annual	**-21.9**	**-25.1**	**-20.6**	**-23.3**	**-24.0**	**-23.1**	**-22.2**	**-19.8**	**-22.3**	**-22.6**

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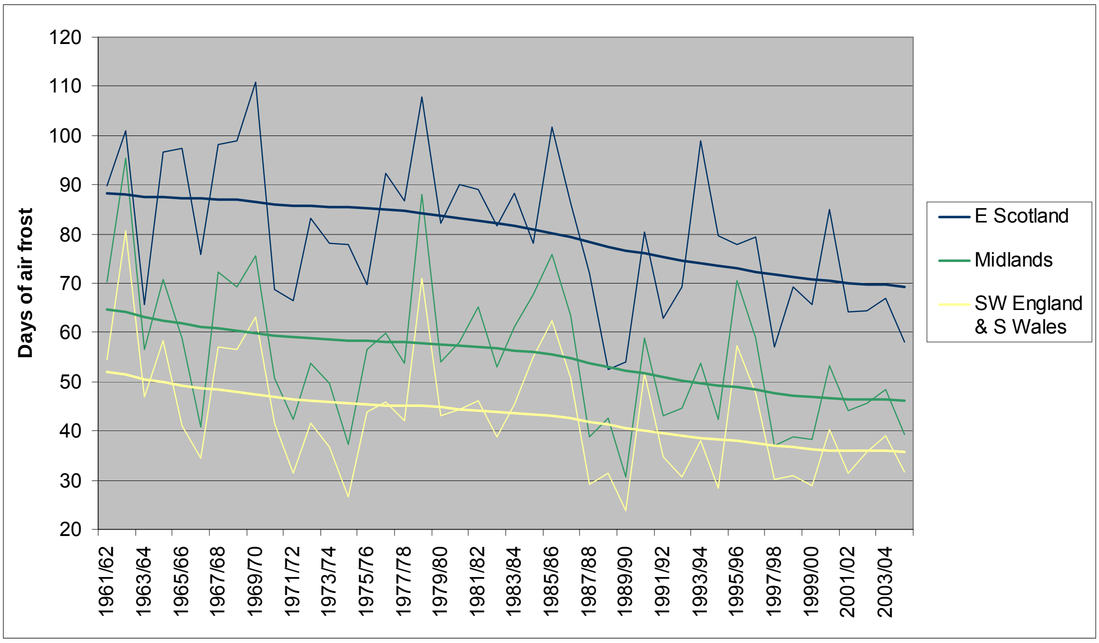
Figure 14: Actual and kernel-smoothed annual days of air frost for three districts, 1961/62 – 2004/05



4.4 Sunshine

Table 12 shows the percentage change in sunshine, based on a linear trend starting from 1929. It shows that the greatest and most significant changes occurred in the winter season, when there has been an increase in sunshine of about 20% for central and northern England. Sunshine has also increased in these areas by about 10% in autumn, and by 8% over the year as a whole for eastern and NE England. These increases could be a result of the Clean Air Acts of 1956 onwards, which has led to a decrease in air pollution. North Scotland has seen a significant overall decrease in sunshine, however, and sunshine levels have also decreased in Northern Ireland and in SW England and south Wales.

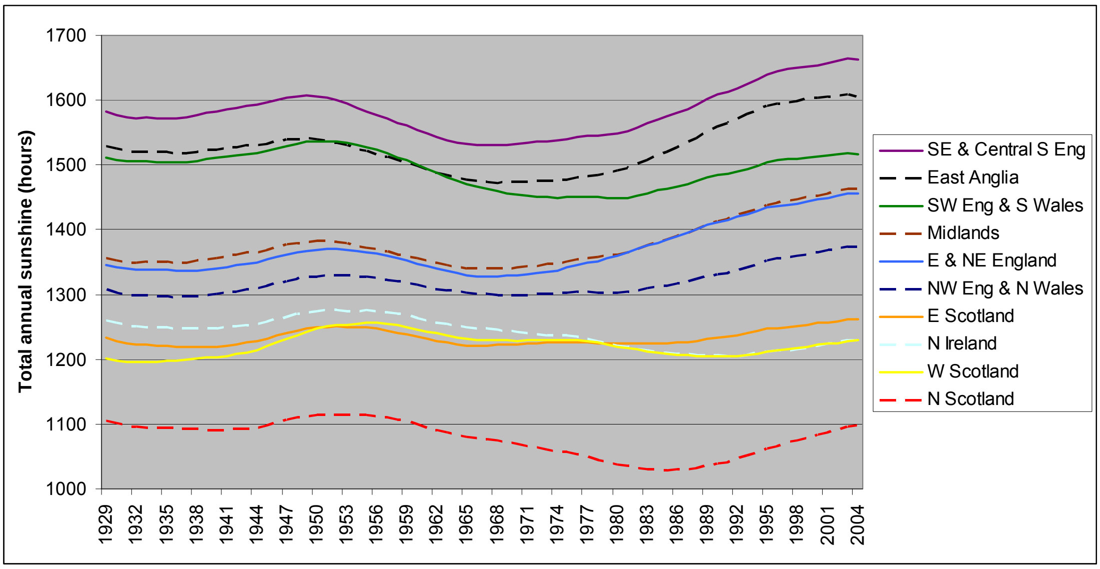
Winter sunshine has decreased in western Scotland, which ties in with the increase in precipitation (Map 10). Map 10 also shows that the greatest increase in sunshine has occurred in parts of northern England, notably in and downwind (i.e. northeast) of major conurbations, supporting an influence of the Clean Air Acts (Lee, 1998).

Table 12: Change in total sunshine duration by district from 1929 to 2004 (%)

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	-5.6	0.5	-4.4	5.4	-2.5	1.1	-2.3	-5.8	-2.1	-8.7
Summer	-3.1	1.1	1.9	3.9	1.8	4.4	1.1	-1.5	1.1	-4.1
Autumn	-3.0	4.5	8.3	8.9	*11.5*	*12.1*	9.3	2.2	*11.3*	0.0
Winter	-13.4	-0.7	-1.1	**27.1**	**18.4**	**23.5**	**20.8**	-3.2	*12.3*	-1.6
Annual	*-5.6*	1.2	0.2	7.8	3.7	6.8	3.7	-2.6	3.2	-5.0

The differences between the districts can be clearly seen in Figure 15, with Scotland and Northern Ireland showing different patterns of change over time to the English districts, which have had fairly rapid increases in sunshine during the last 30 years. The sunniest year of the series occurred in 2003.

Figure 15: Kernel smoothed annual sunshine hours by district, 1929 – 2004.



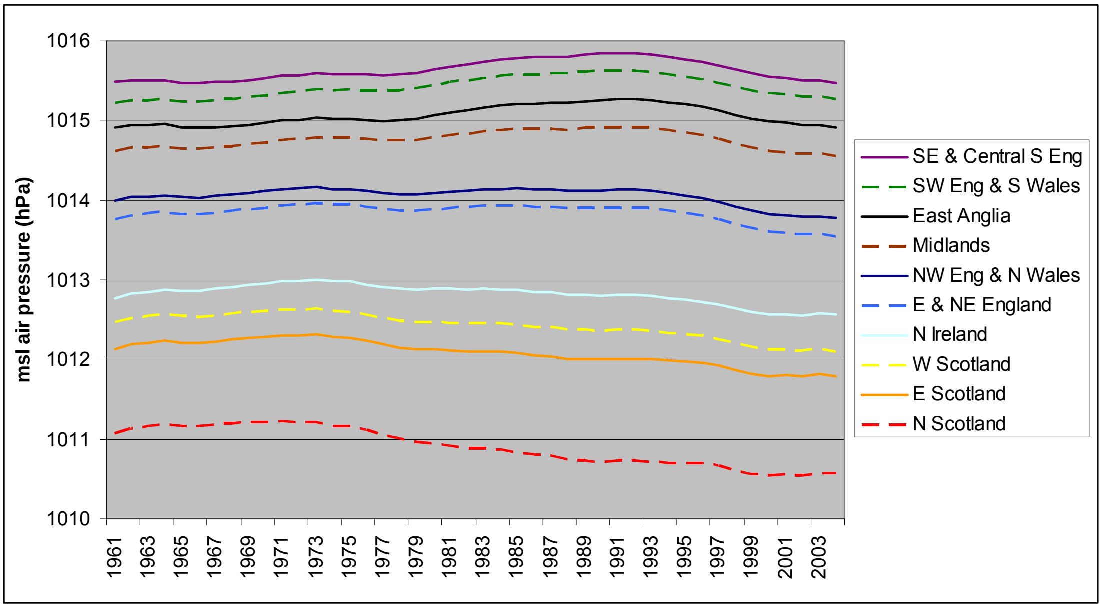
4.5 Mean sea level pressure

There have been no significant trends for mean sea level pressure since 1961 (Table 13), but there are some interesting patterns of change, especially in the winter when there is a strong latitudinal differentiation between decreasing values in North Scotland to increasing values in southern England (Map 11). This is also reflected in the annual changes. Figure 16 shows that the difference between the districts occurred from the late 1970's to the early 1990's, when pressure increased in southern England but decreased in Scotland.

Table 13: Change in mean sea level pressure by district (hPa), 1961-2004

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	0.2	0.5	0.5	0.7	0.7	0.9	1.0	0.9	0.9	0.7
Summer	-0.4	-0.4	-0.6	-0.6	-0.7	-0.7	-0.6	-0.7	-0.7	-0.7
Autumn	-0.5	-0.6	-0.9	-0.9	-1.1	-1.0	-1.0	-1.1	-1.1	-1.0
Winter	-2.0	-1.1	-0.6	0.3	0.8	1.4	1.7	2.5	2.3	0.5
Annual	-0.8	-0.5	-0.5	-0.2	-0.2	0.0	0.1	0.2	0.1	-0.3

Figure 16: Kernel smoothed annual mean sea level pressure by district, 1961-2004



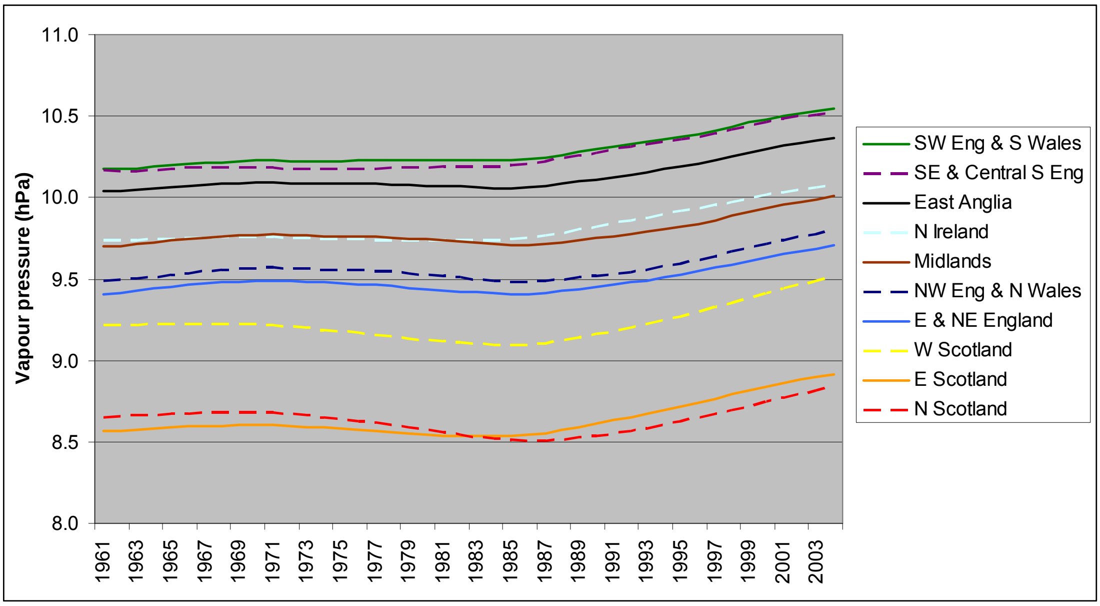
4.6 Vapour pressure

There has been a steady increase in vapour pressure for the UK, with an increased rate of change since the late 1980's (Figure 17). Table 14 and Map 12 show that Scotland has seen a strong increase in the summer months, while for England, Wales and Northern Ireland, there have been marked increases in all seasons except for the autumn. The winter increases in southern England are quite high but are only significant at the 10% level. Overall, southern England has had the greatest change, with an annual increase of 0.5 hPa which is significant at the 1% level.

Table 14: Change in vapour pressure by district (hPa), 1961 to spring 2005

	Scot-land N	Scot-land E	Scot-land W	England E & NE	England NW & Wales N	Mid-lands	East Anglia	England SW & Wales S	England SE & Central S	N Ireland
Spring	0.09	0.37	0.32	0.38	0.37	0.44	*0.50*	*0.53*	0.49	0.47
Summer	0.42	**0.73**	*0.55*	0.39	*0.45*	0.35	0.48	*0.47*	*0.55*	*0.58*
Autumn	0.01	0.18	0.05	0.01	0.00	0.00	-0.08	0.15	0.07	0.15
Winter	0.12	0.34	0.38	0.49	0.45	0.55	0.60	0.64	0.69	0.48
Annual	0.13	**0.37**	0.28	*0.28*	*0.28*	*0.30*	*0.34*	**0.41**	**0.42**	**0.38**

Figure 17: Kernel smoothed annual average vapour pressure by district, 1961-2004



4.7 Relationship between the variables

This section explores the correlation between the monthly values of the climate variables covered in this study. Table 15 shows the values of the correlation coefficient, r, between pairs of climate variables for the monthly values of each season from 1961-2004. Values are given for the four countries, England, Scotland, Wales and Northern Ireland, but they were also calculated for each of the ten climate districts.

Table 15: Correlation coefficient, r, between pairs of climate variables, based on monthly values for the period 1961-2004, and divided in season and country.

Spring	**Tmean & precip**	**Tmax & precip**	**Tmean & vapour pressure**	**Tmean & snow cover**	**Tmin & sun**	**Tmax & sun**	**MSLP & precip**	**Sun & precip**
N Ireland	-0.25	-0.32	0.95	-0.67	0.44	0.72	-0.74	-0.38
England	-0.16	-0.24	0.95	-0.71	0.64	0.84	-0.84	-0.39
Wales	-0.23	-0.31	0.94	-0.72	0.57	0.80	-0.73	-0.45
Scotland	-0.33	-0.40	0.95	-0.80	0.57	0.79	-0.67	-0.56
Summer								
N Ireland	-0.30	-0.45	0.92	n/a	-0.12	0.48	-0.83	-0.50
England	-0.29	-0.44	0.88	n/a	0.18	0.66	-0.80	-0.68
Wales	-0.29	-0.43	0.89	n/a	0.13	0.65	-0.79	-0.63
Scotland	-0.24	-0.39	0.93	n/a	-0.08	0.47	-0.81	-0.63
Autumn								
N Ireland	-0.13	-0.16	0.98	-0.55	0.63	0.77	-0.74	-0.27
England	-0.15	-0.19	0.98	-0.61	0.72	0.85	-0.86	-0.29
Wales	-0.21	-0.25	0.98	-0.62	0.69	0.84	-0.78	-0.40
Scotland	-0.14	-0.16	0.98	-0.68	0.71	0.83	-0.69	-0.33
Winter								
N Ireland	0.20	0.21	0.95	-0.64	-0.44	-0.22	-0.73	-0.30
England	0.34	0.33	0.95	-0.83	-0.16	0.05	-0.79	-0.19
Wales	0.50	0.53	0.97	-0.83	-0.48	-0.35	-0.66	-0.40
Scotland	0.45	0.48	0.95	-0.85	-0.41	-0.24	-0.65	-0.39

Temperature and precipitation are positively correlated in the winter, especially with maximum temperature for West Scotland (r=0.54) and Wales (r = 0.53). In the other seasons, the

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correlation between temperature and precipitation is negative. There is quite a strong positive correlation between maximum temperature and sunshine, especially in the spring and autumn, with values of r up to 0.85. Minimum temperature is negatively correlated with sunshine in the winter, and positively correlated in spring and autumn, but with lower values of r than for maximum temperature. There is a strong positive relationship between sunshine and diurnal temperature range.

There is a negative relationship between sunshine and precipitation in all seasons, which is at its strongest in the summer (r = 0.68 for England), as well as the spring in Scotland. Mean sea level pressure is also negatively correlated with precipitation, with the strongest relationship being for England in autumn (r = 0.86). Mean sea level pressure and sunshine are positively correlated, especially in the summer, with values of r up to 0.65 (SW England).

As expected, temperature is very strongly related to vapour pressure (positive) and snow cover (negative).

Discussion and Conclusion

An analysis of monthly and annual gridded datasets over the UK for a range of climate variables has been made, showing spatial and temporal patterns of change. Results have been shown seasonally for the 10 climate districts of the UK, and cover the 1961-2004 period, with some key variables going back to 1914.

The results are in general agreement with previous studies, but the use of a full network of observing stations together with techniques for generating gridded datasets enables the results to cover the whole of the UK with more spatial detail.

As expected, the most significant trends (at the 1% level) are for increasing temperature, with mean temperature increases varying from over 0.8 °C for the Midlands and East Anglia since 1914, down to 0.4 °C in North Scotland. However, there was virtually no trend in mean temperature between 1914 and 1987, and it is only since 1987 that the temperature has notably started to increase. The winter is the only season which has not seen significant increases during the 1914 – 2004 period. Increases in minimum temperature have been greater than those for maximum temperature, with a consequent decrease in diurnal temperature range.

There has been no significant change in annual precipitation since 1914. However, some of the seasonal changes are significant at the 5% level, especially the decrease in summer precipitation, and the 22% increase in spring precipitation in West Scotland. Since 1961, winter precipitation has increased dramatically for the west of the UK, associated with an upward trend in the winter North Atlantic Oscillation which causes stronger and more frequent westerly flow over the UK (Hurrell, 1995). Accordingly, changes in winter mean sea level pressure since 1961 have a strong latitudinal component with decreases in the north of the UK and increases in the south. The increases in days of heavy rain and the greatest annual 5-days precipitation amounts suggest a tendency for an increasing likelihood for extreme heavy rainfall events.

Winter and autumn sunshine has increased very significantly for northern, central and south-east England since 1929, which is likely to be linked to reduced air pollution brought about by the Clean Air Acts. Most of the increase has taken place since the late 1960's. North Scotland has had a 6% decrease in annual sunshine, which is significant at the 5% level.

It is clear from these results that the climate of the UK is already changing, and many of these changes are in line with predicted changes for the future. It is important to continue to monitor the climate so that climate models can be verified and put into context, and climatologies kept up to date. The changes which have taken place are already having impacts on many aspects of society, and these impacts need to be studied further so that the impacts of future changes can be planned for, mitigated, or taken advantage of. In particular, this study has indicated that there may be increasing possibilities for agriculture further north in the UK, with an extension of the growing season of 39 days in North and East Scotland since 1961, and a 20% increase in growing degree days. There has been a significant reduction in the length of winter cold spells, and their associated impacts, but the 15% reduction in heating degree days over central and eastern England has not been reflected in reduced energy demand. There has been a significant lengthening of summer heat-waves in central and eastern England, which may have impacts for human and animal health.

There are some fairly strong inter-relationships between the climate variables. These links will be explored further, together with further possible causes for the observed changes such as atmospheric circulation patterns. The changes will also be put into the context of predictions for future climate change.

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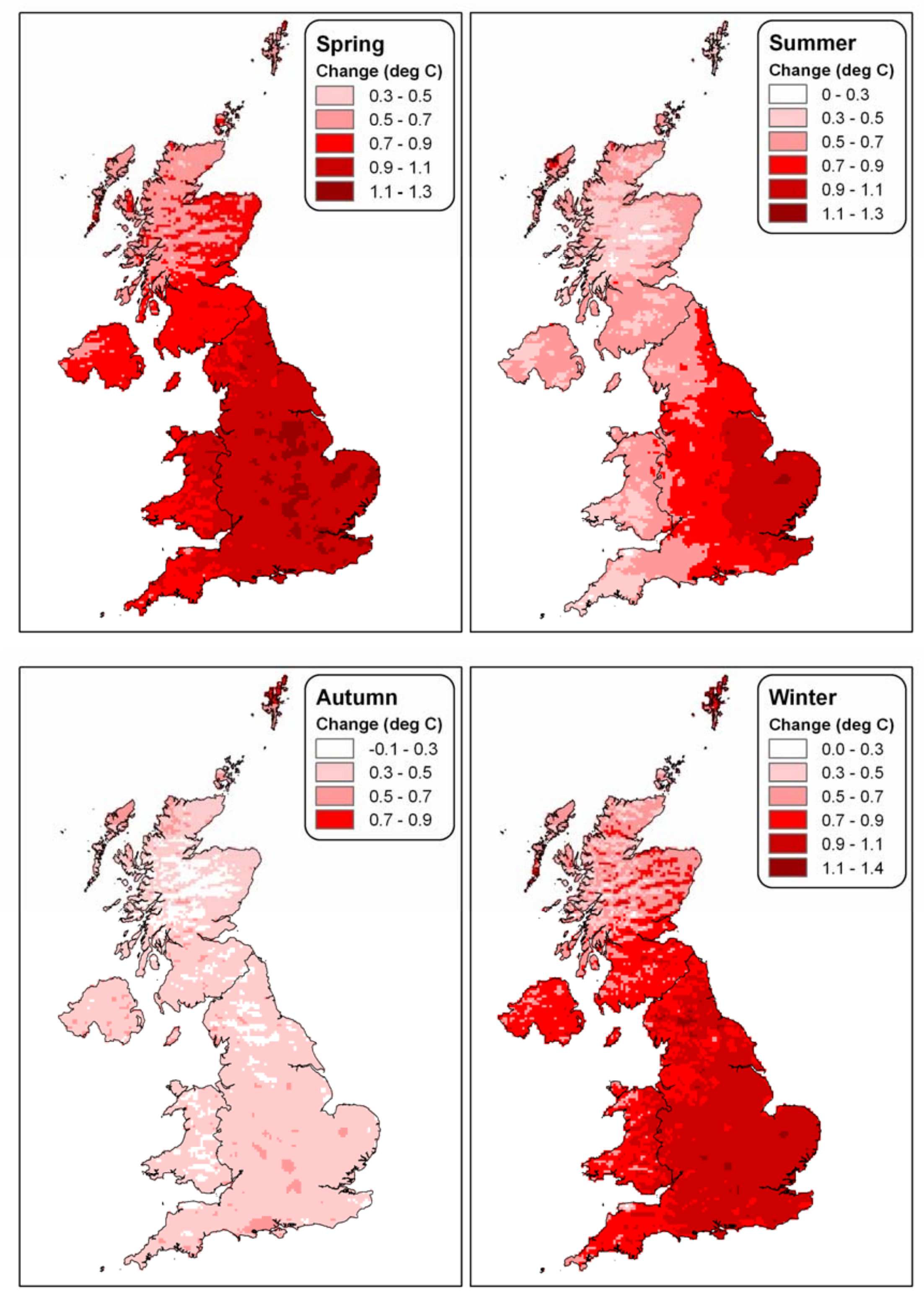
Appendix 1

Map 1: Mean temperature change (°C) from the 1961-1990 average to 1991-2004; a) spring, b) summer, c) autumn, d) winter.



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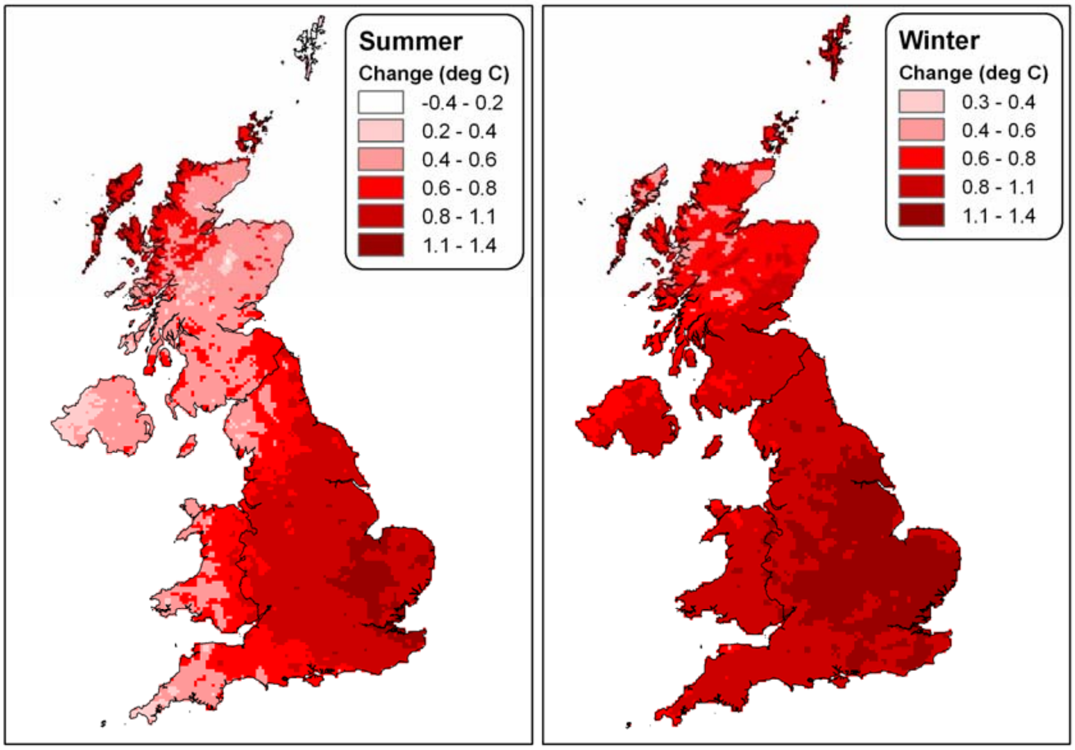
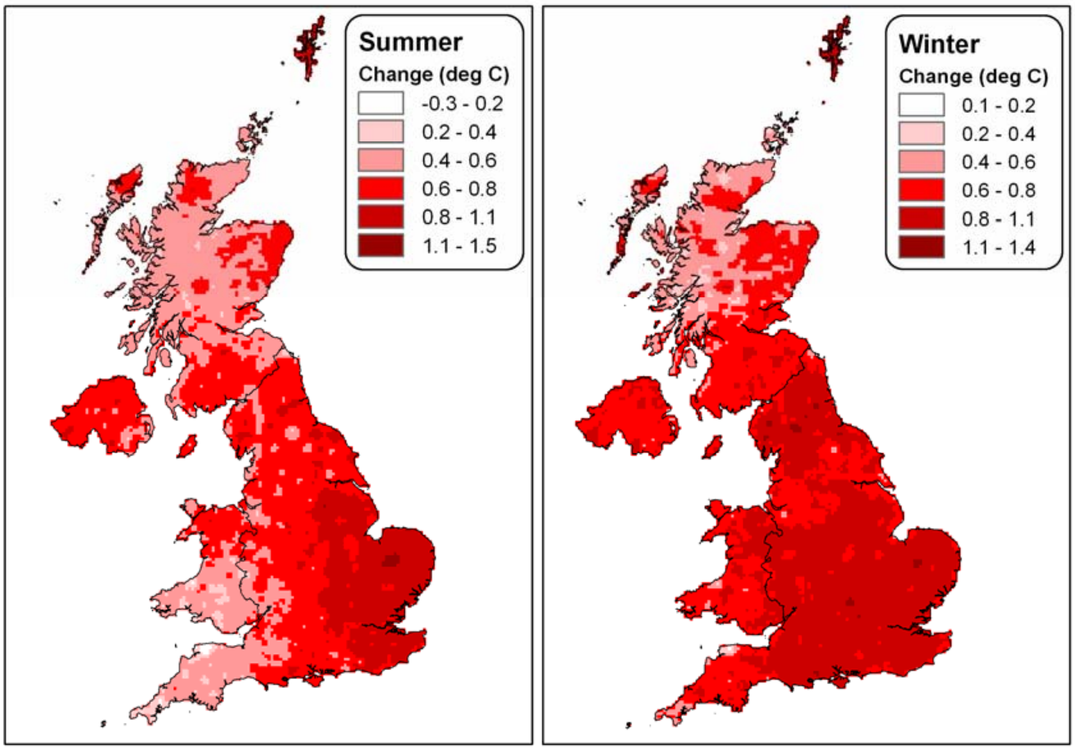
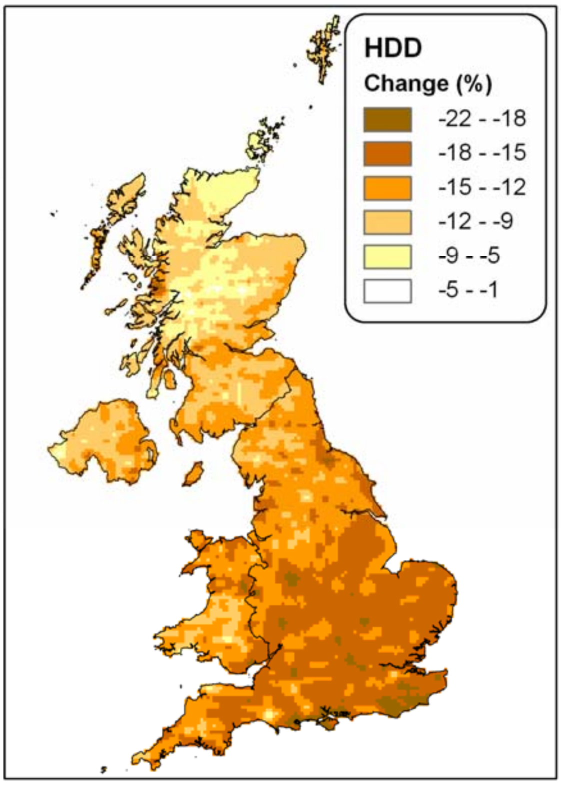
Map 2: 24-hour maximum temperature changes (°C) from the 1961-1990 average to 1991-2004; a) summer, b) winter.



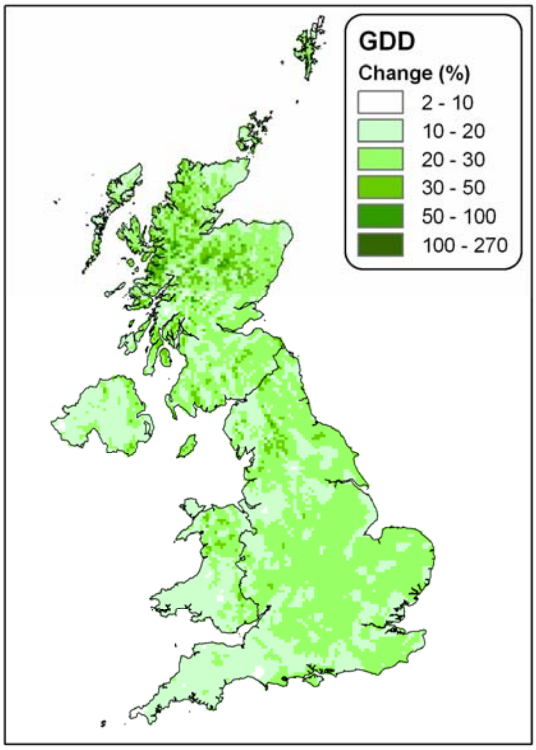
Map 3: 24-hour minimum temperature changes (°C) from the 1961-1990 average to 1991-2004; a) summer, b) winter.

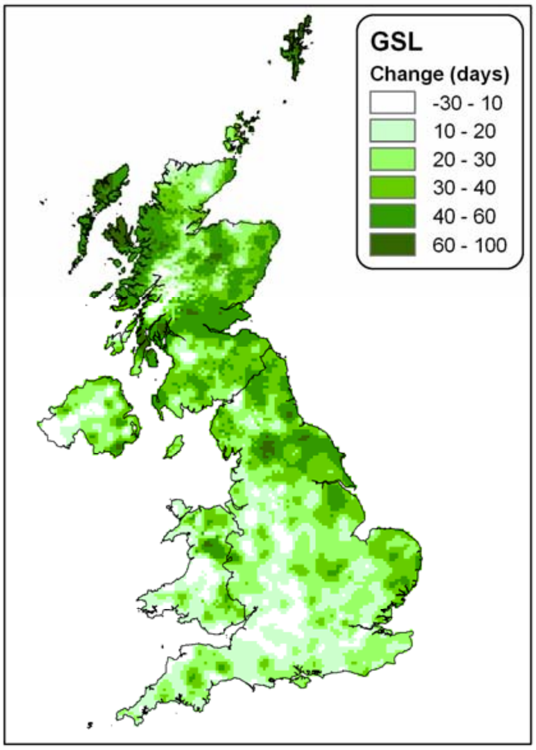


Map 4: Gridded trends for heating degree days (HDD), showing the percentage change from 1961 to 2003.

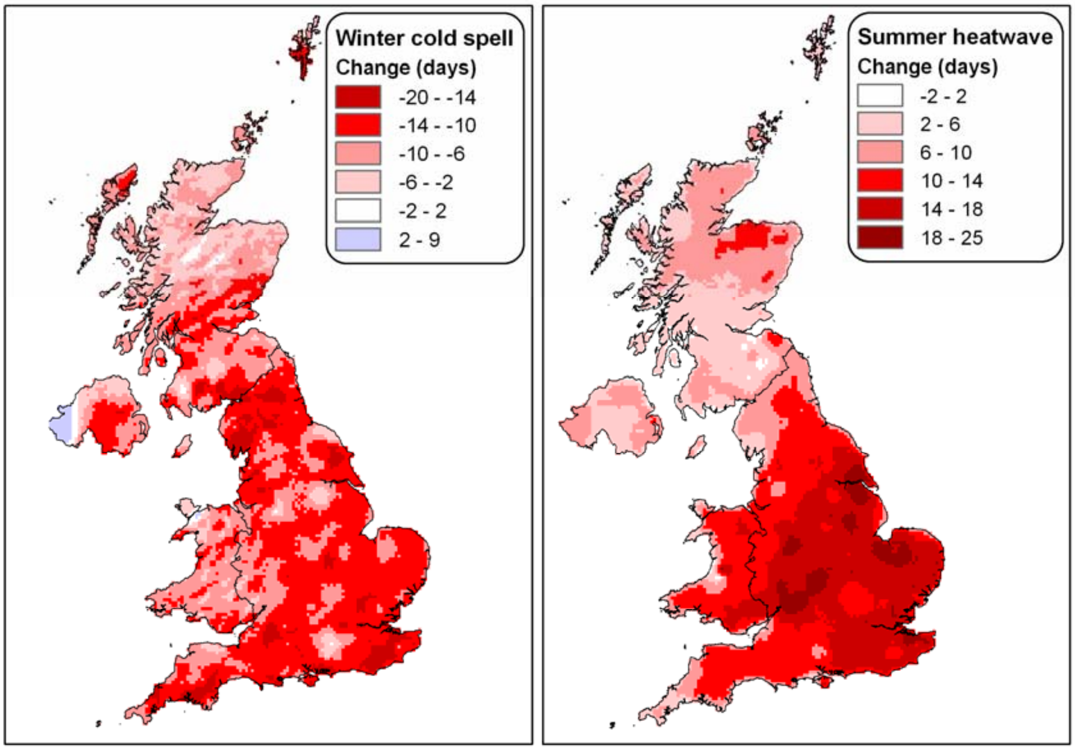


Map 5: Gridded trends for growing degree days (GDD) as a percentage, and growing season length (GSL) in days, showing the change from 1961 to 2003.

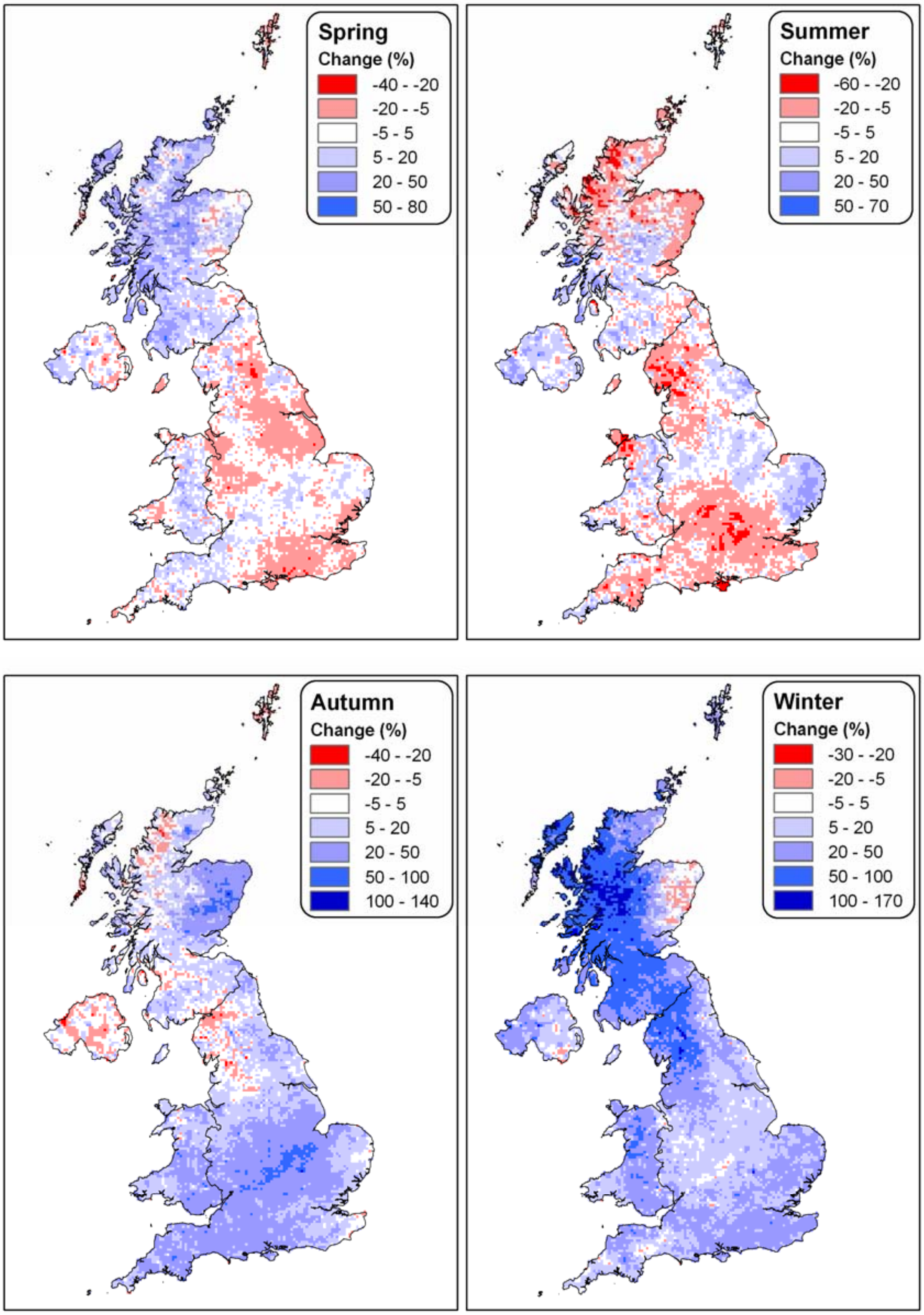




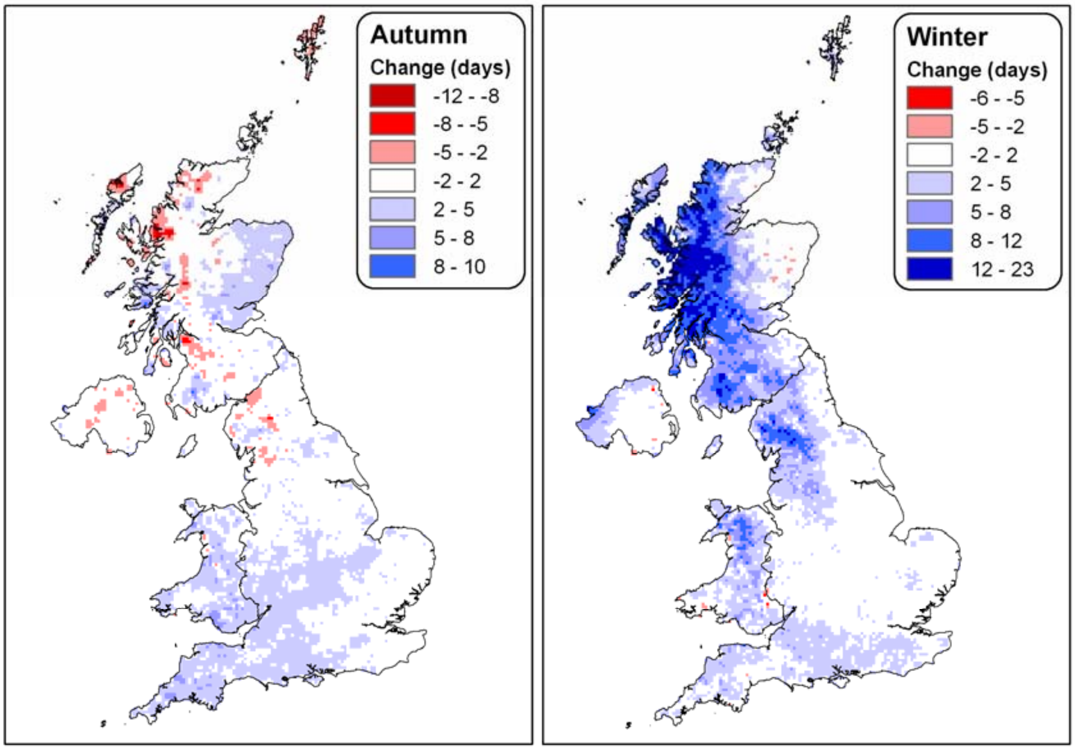
Map 6: Gridded trends for winter half-year cold spell duration and summer half-year heat wave duration, showing the change (in days) from1961 to 2003



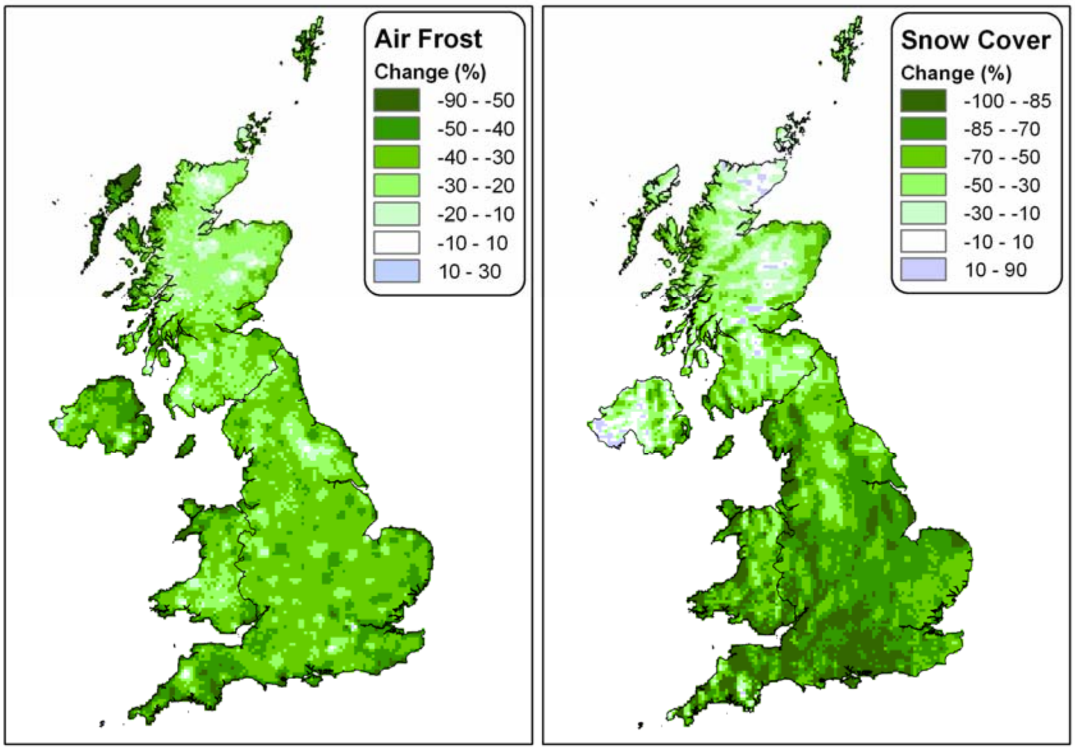
Map 7: Precipitation gridded trends, showing the percentage change from 1961 to 2004; a) spring, b) summer, c) autumn, d) winter.



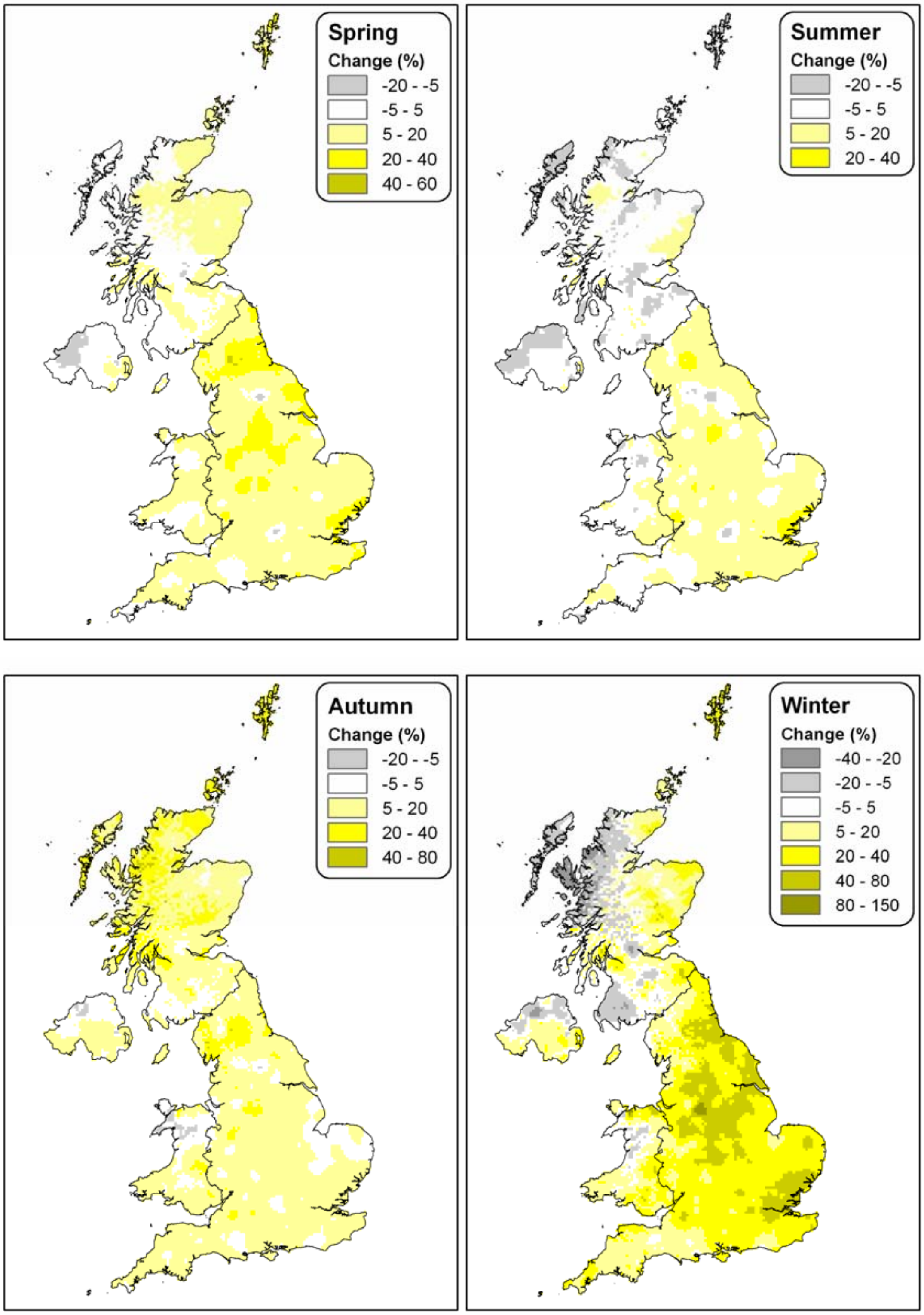
Map 8: Gridded trends for days of heavy rain ≥ 10 mm, showing the change (in days) from 1961 to 2004; a) autumn, b) winter



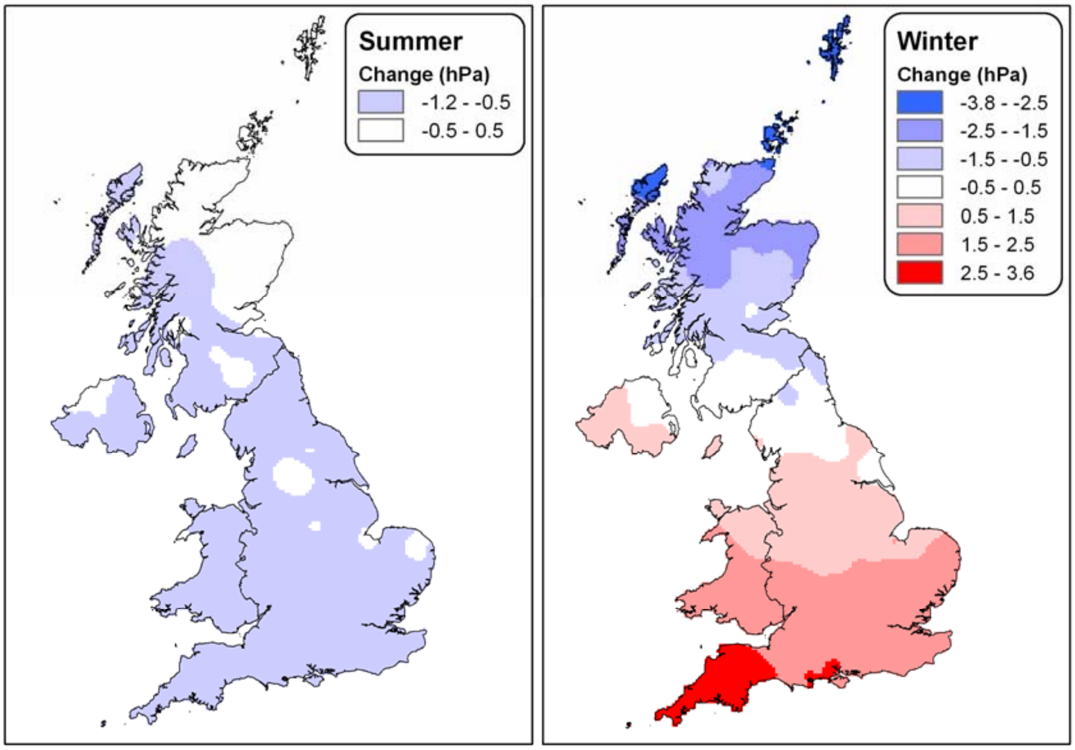
Map 9: Gridded trends for days of air frost and days of snow cover, showing the percentage change from 1961/62 to 2004/05.



Map 10: Sunshine gridded trends, showing the percentage change from 1961 to 2004; a) spring, b) summer, c) autumn, d) winter.



Map 11: Gridded trends for mean sea level pressure, showing the change (in hPa) from 1961 to 2004; a) summer, b) winter.



Map 12: Vapour pressure gridded trends, showing the change (in hPa) from 1961 to 2004; a) summer, b) winter.