Precipitation variability across the UK: Observations and model simulations

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Chapters

Abstract

Acronyms

AVG7	Regional rainfall series generated from Met Office gridded data, using 7 grid boxes per region (corresponding to the locations of the 7 sites per region used to generate the HadUKP series)
AVGR	Regional rainfall series generated from Met Office gridded data, using all of the grid boxes within a region
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSEMBLES	A European project which ran from 2004-2009, aimed at understanding uncertainty in climate projections using ensemble runs from global and regional climate models.
ERA-40	This ECMWF reanalysis dataset covers the period 1958-2002
HadUKP	Hadley United Kingdom precipitation series
IPCC	Intergovernmental Panel on Climate Change
MOHC07d	New daily rainfall series generated from Met Office Hadley Centre daily gridded rainfall data, extending to 2007
MOHC06m	New monthly rainfall series generated from Met Office Hadley Centre monthly gridded rainfall data, extending to 2006
NCIC	National Climate Information Centre (UK Met Office)

Abstract

A new UK precipitation series is developed at daily to annual timescales, based on gridded data from the Met Office Hadley Centre and a long-running precipitation series for the UK maintained by the Met Office and the UEA Climatic Research Unit (hereafter the HadUKP series), using denser spatial sampling. Error estimates are derived for the new series and for sampling errors associated with the HadUKP series. The new precipitation series is analysed to determine trends in extreme precipitation across the UK and assess regional variations. Climate model integrations from the ENSEMBLES project are used to determine which models are the best performing at simulating the geographical distribution of UK precipitation. The three best performing models are identified, and used to analyse how well precipitation is handled when associated with different atmospheric circulation types, and the predictions of changes in UK precipitation in the future associated with the A1B climate change scenario from the IPCC Fourth Assessment Report. The model simulations of the distribution of convective and large scale components of precipitation are assessed alongside those of mean and extreme precipitation.

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1. Introduction

1.1 Implications of increased precipitation variability and extremes

Extremes of precipitation have large impacts on human society and on wildlife (e.g. Meehl et al., 2000), including large scale negative impacts arising from droughts and flooding, as well as some positive impacts (e.g. blossoming of wildlife in arid areas following unusual heavy rainfall events). Examples in the UK in the previous two decades have included the summer drought in 1995, which had particularly severe impacts in Yorkshire and led to enquiries into how water companies handled the drought (Bakker, 2000), the flooding in York during the exceptionally wet autumn of 2000, and the flooding in Boscastle on the 16th August 2004, which was caused by intense convective rainfall. The flooding in June and July 2007 was caused primarily by frontal rainfall, associated with a persistent slow moving Rossby wave pattern which resulted in slow moving upper troughs promoting slow moving depressions and persistent frontal rainfall across the British Isles (Blackburn et al., 2008). Impacts included the inundation of numerous homes with water, forcing many people to evacuate, and the flooding of a sewage plant in the Gloucester area which resulted in approximately 350,000 people having to be provided with emergency water supplies (Standing, 2008). The UK Environment Agency calculated that the average cost of the 2007 floods to households was between £23,000 and £30,000 per flooded home, and that businesses incurred an average cost between £75,000 and £112,000 per flooded business, and that infrastructure and critical services were significantly hit (Environment Agency, 2011), and heavy insurance payouts were required. Many parts of Cumbria, particularly around Carlisle, were heavily hit by flooding during January 2005 and again near Cockermouth in November 2009, as a result of persistent moist south-westerly regimes. Such flood events can have significant psychological and health impacts and lead to conflicts between home owners and insurance and construction companies (Carroll et al., 2010).

Extreme falls of precipitation lead to increased flooding, which increases the need for increased financial investment in flood defences (Fowler et al., 2005). The UK Environment Agency (Environment Agency, 2011) is concerned that unless funding into flood defences increases then the mean annual costs of flood damage could rise by 60% by 2035 as a result of climate change and increasing human activity in flood-prone areas. Instead of just assessing changes in mean precipitation at a global and national level, there is a considerable need to assess regional changes in extreme precipitation and the resulting regional impacts (Hegerl et al., 2004, Tebaldi et al., 2006), which are important to stakeholders and impact assessments (e.g. Negri et al., 2005). It should also look at extremes that occur regularly enough for occurrences to arise during most years.

In the future, global warming caused by anthropogenic emission of greenhouse gases is expected to lead to increases in precipitation variability and extreme heavy rainfall events (e.g. Trenberth et al., 2007), even in some areas where mean precipitation is projected to decline (Fowler and Ekström, 2009, Frei et al., 2006), and climate models have consistently produced this result (Meehl et al., 2007). In physical terms, the Clausius-Clapeyron relationship suggests that the water holding capacity of the atmosphere increases by approximately 7% per degree Kelvin increase (Trenberth et al., 2003) which also implies an increase in mean rainfall intensity of at least that value, and there is also significant evidence that an enhanced hydrological cycle may occur (Fowler and Kilsby, 2007). When assessing recent extreme weather events and whether or not extremes are increasing in line with climate model projections, it is inappropriate to blame individual extreme weather events on anthropogenic global warming. Instead research on the subject should focus on ways of determining changes in exceedence of thresholds over a significant period of time, and the statistical significance of such changes, to assess whether observed changes can be explained by natural variability alone.

1.2 UK rainfall series

It is important to maintain up-to-date and homogeneous rainfall records over a long period in order to be able to determine recent trends in rainfall. The Hadley Centre United Kingdom Precipitation series (HadUKP), maintained by the UK Met Office and the Climatic Research Unit at the University of East Anglia, produces daily, monthly, seasonal and annual rainfall records for all regions of the UK, and monthly, seasonal and annual England and Wales values that extend back as far as 1766. The monthly data for England and Wales was originally devised by Wigley et al. (1984), who also developed monthly series for the five constituent regions of England and Wales extending back to 1873, and this series was updated further by Wigley and Jones (1987), Gregory et al. (1991), Jones and Conway (1997) and Alexander and Jones (2001). Gregory et al. (1991) added a further series for Scotland and Northern Ireland extending back to 1931, while daily series have been developed for all regions dating back to 1931. However, the homogeneity and reliability of the records is limited by sparse station coverage during the earlier years of the record, and the records rely upon the use of up to seven well-spaced rainfall sites in each region, which may not give the best representation of the "true" areal mean (e.g. bias towards the drier parts of a region). More details on these rainfall series are given in Chapter 3.

Hence, Chapter 4 discusses the generation of a new rainfall series for the UK regions based on 5km gridded data from the Met Office (Perry and Hollis, 2005a and Perry and Hollis, 2005b). The gridded data was generated for 36 climate variables, stemming from data from a comprehensive network of weather sites across the UK. Thus, the series based on the Met Office Hadley Centre gridded data (hereafter MOHC) is based on a far more extensive network of stations than the HadUKP series, which uses a maximum of seven stations per region. The main downside of this method is the reliance on interpolation, which is necessary to generate values for individual grid boxes in cases where station coverage is incomplete and thus values have to be interpolated for grid boxes which are not covered by observations within the vicinity of the grid boxes. However, the analysis in Chapter 4, which explores standard error estimates based on regressions between the two series and limited spatial coverage associated with the HadUKP series, suggests that it provides a more definitive record of mean regional daily, monthly, seasonal and annual precipitation across the UK than the HadUKP series.

The Met Office also maintains its own monthly rainfall series for the UK and constituent regions (using different regional boundaries to those used in the HadUKP series) based on the 5km grids, extending back to 1914, which are available at http://www.metoffice.gov.uk/climate/uk/datasets/ and are used for the Met Office's monthly climate summaries for the UK.

1.3 Climate model simulations of precipitation

Climate models form our main basis for forecasting changes in precipitation in the future under different rates of anthropogenic global warming. However, at present many of the key mechanisms behind rainfall generation are poorly handled by the models due to their vast complexity, including topographical influences. The reliability of model outputs is dependent on the reliability of the parameters that are input into the models, for the outputs are only likely to give accurate results if accurate assumptions are made about the behaviour of the atmosphere in the parameterisations that are adopted. Clouds and radiation are particularly difficult to handle as they vary considerably temporally and spatially and thus measurements of individual points may not be representative of the areal mean (Pincus et al., 2008) and model resolution is too limited to capture some of the local variation. Climate models consistently produce a "drizzle effect", with too high a frequency of light rainfall events and underestimation of extreme rainfall. The models also have significant problems handling convective precipitation, since for example parameterisation of convective events has to simulate the build up of convective available potential energy and the caps that inhibit convection, and the diurnal cycle of convective clouds (Trenberth et al., 2003) and as a result most cloud models have convective precipitation starting too early in the day, underestimate interactions with phenomena that typically develop during the day such as sea breezes and as a result, underestimate the intensity of severe convective rainfall.

Regional climate models nested within global climate models are capable of simulating climate variables at a regional level, unlike the general outputs from global climate models, and can be run at fine time steps and help to maintain physical consistency with regional climatic influences (Huntingford et al., 2003). On the other hand, they are constrained by the reliability of the global climate models and still have resolution limitations, as well as being computationally expensive.

An alternative downscaling approach for climate models is statistical modelling, relating predictor variables to station-scale parameters, such as by using synoptic climatology, which is usually less computationally expensive (Haugen and Ivensen, 2008) but this approach is limited by the reliability of the relationships between the predictor variables and the station-scale parameters and the issue that relationships do not always remain constant with time, particularly in a changing climate. There is a need for verification of the reliability of climate model simulations and one common method of helping verification is by judging their simulation of past and present weather, compared with observed data. Hence, Chapter 6 assesses the reliability of eight well-established regional climate models driven by the ERA-40 reanalysis (which provides a more accurate representation of past conditions than when a global climate model is used as the driving model), and explore how well they simulate convective as opposed to large scale precipitation. Using RCMs driven by ERA-40 provides output that indicates the best that models can currently do. The comparison with observations is a necessary, but not sufficient, test of a model's reliability, since a warmer global and regional climate may alter some of the key feedback processes that form the basis for accurate simulation of past climates.

In Chapter 7, the analysis then assesses the reliability of the three best performing models at handling precipitation under different atmospheric circulation types, and the projections for changes into the future, and notes changes in anomalies that arise when ECHAM-r5 or HadCM3 are used as the driving model instead of the ERA-40 reanalysis. This enables a comparison to be made between the reliability of ECHAM-r5 and HadCM3 as driving models. Verifying model accuracy using comparisons with past and present climate and extrapolating into the future has the downside that accurate simulation of past and present climatic conditions does not guarantee accurate simulation of future conditions as atmospheric variables are likely to change as climate changes. However, we can hope to be able to make increasingly accurate forecasts of changes in future climate using the understanding that we have, particularly where different models give consistent signals despite different underlying assumptions. One recurring issue is that the signal for changes in precipitation is less consistent than that for a rise in the mean global temperature associated with anthropogenic greenhouse gas emissions (e.g. Pall et al., 2007) and show greater and more uncertain regional variation in terms of sign and magnitude.

1.4 Changes in atmospheric circulation

Changes in atmospheric circulation have significant impacts upon UK precipitation, with a strong association between a strongly positive phase of the North Atlantic Oscillation (NAO), reflecting a steep gradient between low pressure over Iceland and high pressure over the Azores, strengthened westerlies and mild wet winters over north-western Europe (e.g. Wilby et al., 1997, Osborn et al., 2000). Much of the increase in winter precipitation totals and extremes across the UK during the twentieth century can be explained by changes in the NAO (Gillett et al., 2003). Many studies also suggest that an increasingly positive NAO is likely in association with global warming (e.g. Yin, 2005) though the relationship is not clear-cut, for example there is currently a theory that reduced Arctic sea ice levels may actually increase the frequency of cold, blocked winters in the Northern Hemisphere (Petukhov and Semenov, 2010), which may have contributed to the recent cold winters of 2005/06, 2009/10 and 2010/11 over much of Eurasia.

During summer, precipitation across the UK is correlated most strongly with cyclonicity, with a trend towards more blocked summers and, consequently, warmer drier weather across the UK during the twentieth century (Trenberth et al., 2007). Many climate model simulations predict more anticyclonic, drier summers across the UK under enhanced greenhouse conditions, though the signal for reduced precipitation in summer is consistently weaker than the signal for increased precipitation in winter, and the twentieth century trend towards drier summers has reversed since 2000 across the UK (Hopkins et al., 2010).

Due to the uncertainties surrounding the expected changes in atmospheric circulation, and the need to distinguish long-term precipitation trends from what may turn out to be short-term natural variability in atmospheric circulation, it may be useful to consider how accurately climate models simulate UK precipitation under different synoptic patterns. Thus, in Chapter 7, the accuracy of precipitation simulation of HadRM3, RACMO2 and HIRHAM5 (the three best performing models out of the models covered in the performance analysis in Chapter 6) is assessed for ten different circulation types, using the classification system of Prof H.H. Lamb (Jenkinson and Collison, 1977), assessing whether patterns in mean and extreme rainfall are accurately simulated.

The results of this analysis may help to more specifically identify the problems that climate models have in simulating precipitation across the UK, with a view to extending this to other regions, as specific factors such as coastal influences in regions facing the wind and orographic enhancement can be studied more specifically.
For example, the simulation of the distribution of precipitation in westerly and south-westerly flows gives an indication of how well the models simulate orographic enhancement in the west and “rain shadow” in the east, while extreme precipitation indices indicate how accurately the models handle intense orographic rainfall events such as the floods in Cumbria in November 2009.

1.5 Thesis outline

Chapter 2 covers the history of the HadUKP series for the UK regions, taking note of problems with updating the series and maintaining homogeneity, and the history of the more recent 5km gridded rainfall series maintained by the National Climate Information Centre (NCIC) of the UK Met Office which is used as a basis for most of the analysis of past UK precipitation. **Chapter 3** reviews the current literature on the range of topics covered in the thesis, expanding upon the concepts introduced in the Introduction and summing up the current challenges that face researchers in this field.

Chapter 4 documents and discusses the generation of a new regional UK rainfall series covering daily to annual timescales based on the NCIC gridded data, alternative methods of generating the regional figures and derivation of associated error estimates based on regression and spatial degrees of freedom. **Chapter 5** extends this by discussing changes in UK precipitation at a regional and national level for daily to annual timescales based on the new regional dataset, and assesses the statistical significance of any changes.

Chapter 6 deals with climate model simulations of precipitation, assessing the reliability of eight regional climate models (RCMs) at handling the geographical distribution of mean and extreme UK precipitation, and the distribution of convective precipitation and the projected fraction of convective precipitation as a proportion of the total precipitation, and the correlations with observed values. This is extended in **Chapter 7** to cover the reliability of handling UK precipitation under different synoptic patterns (based on the classifications of Lamb, 1972) for the three models that were shown to be the most accurate in the preceding chapter.

Projected changes in mean, extreme and convective precipitation in the future under the A1B scenario (from the IPCC Fourth Assessment Report) are also assessed in the chapter. **Chapter 8** sums up the results and gives some conclusions and discussion of possible future work that can arise from the work discussed in the thesis.

2. History of the HadUKP and NCIC series

2.1 Development and extension of a homogeneous UK rainfall series

Work has been underway since the early 20th century to establish a homogeneous series of rainfall records across the UK. It is very useful to have an easily accessible homogeneous precipitation series, as such a series can be manipulated to determine trends in precipitation amounts and variability, and assist research in a number of areas. In recent decades most of this work has been carried out by the UK Met Office and the Climatic Research Unit at the University of East Anglia.

2.1.1 The development of a homogeneous England and Wales rainfall series

The first significant contributions stemmed from G.J.Symons (Wigley et al., 1984) who played a major role in setting up the British Rainfall Organisation and the journal *British Rainfall*. Symons collected together a set of rainfall records, mostly provided by amateur observers, from the 18th and 19th centuries. Nicholas and Glasspoole extended this work in the 1920s and 1930s, developing an England and Wales precipitation series extending from 1727 to 1931, which was subsequently published in *British Rainfall* (see Nicholas and Glasspoole, 1931). This series formed the basis of the England and Wales series that is currently being maintained by the UK Met Office. However, the quality of some of their records was somewhat suspect, and there were periods, notably in the 18th century, when they used a sparse station network, with fewer stations than in the analysis conducted by G.J.Symons (Wigley at al., 1984). In addition, much of the early rainfall data held by the Met Office was only in the form of monthly totals and so could not account for the September 1752 calendar change (Jones and Conway, 1997).

In the 1980s, researchers at the Climatic Research Unit of the University of East Anglia and the UK Met Office worked upon establishing and updating a homogeneous set of precipitation records for the UK. Wigley et al. (1984) developed an updated monthly England and Wales rainfall series using observations from a small network of stations, extending previous work by Nicholas and Glasspoole (1931) and by Tabony (1981), and using the following five constituent regions (see Fig 2.1):

1. North-west England and south Wales (NWE),
2. North-east England (NEE),
3. Central and eastern England (CEE),
4. South-west England and south Wales (SWE),
5. South-east England (SSE).

Each regional series was derived from up to seven stations in each region, and extends back to 1873 for monthly data and 1931 for daily data. The national series was arrived at using weighted averages of the regions, determined by regression analysis (Jones and Conway, 1997). This is a preferable method to that of Nicholas and Glasspoole (1931), who instead used fractions of station averages over the period, which complicates the analysis as the area-average fraction has to be converted back to millimetres using an area-average normal. The use of percentages of long-term averages, however, can be useful in association with data manipulation and derivation of conclusions from the data. Wigley et al. (1984) concluded that there were insufficient station data available between 1727 and 1765, as not all of the regions had at least one gauge available (Jones and Conway, 1997) and thus the revised England and Wales rainfall series extends back to 1766. Subsequently, tentative corrections have been made to estimate values for the period 1727-1765 (Jones and Briffa, 2006) but these are not included in the official England and Wales rainfall series.

2.1.2 Development of a regional rainfall series, in conjunction with the maintenance and updating of the national series

Wigley and Jones (1987) followed up their earlier work on the monthly rainfall series in Wigley et al. (1984), using the set of regions for England and Wales to develop a daily regional rainfall series spanning the period 1931-1985. The regional series relied upon seven well-spaced stations within each region, generating an unweighted regional average. The regional series were not extended before 1931 due to the lack of daily rain gauge data in the network in the earlier years of the England and Wales record. Thus, there is scope for further work involving extending the regional series further back, using extensive digitisation of available data, but it would have to involve more complex statistical methodology to account for the sparser network of stations, and would not be as reliable as the later data.

The national series was updated to the period 1766-1985, continuing with the use of a weighted average of the England and Wales regions to obtain the national data. The England and Wales series gives a good approximation of England and Wales rainfall, with statistically significant correlations with the observed values from numerous long-standing weather stations (Croxton et al., 2006). The daily regional series were then extended by Gregory et al. (1991) to include regions for Scotland and Northern Ireland (see Fig 2.1):

1. South-west and south Scotland (SS)
2. North-west and north Scotland (NS)
3. Eastern Scotland (ES)
4. Northern Ireland (NI).

Again, the Scotland and Northern Ireland regional networks were defined using seven well-spaced stations for each region, as with the England and Wales network. There was difficulty in setting up a representative north Scotland network due to the sparse station network. There was a UK Met Office Scotland series available at the time, so Gregory et al. (1991) used regression of the three Scottish regions against the Met Office's rainfall series. A similar analysis was used for the Northern Ireland series which was also regressed against a series maintained by the Met Office.

These UK rainfall series were updated to 1995 by Jones and Conway (1997). By this time, many of the gauges used in the analysis by Wigley et al. (1984) were no longer operating and thus replacement gauges had to be used in the updated series. For the regional series, which are based on unweighted regional averages, the monthly precipitation totals were multiplied by the ratio of the 1961-90 average of the replacement gauge to the gauge that it was replacing. This was to approximate perfect homogeneity as closely as possible, for otherwise the use of replacement gauges may significantly affect the results due to the fact that precipitation can vary widely over small geographical areas.

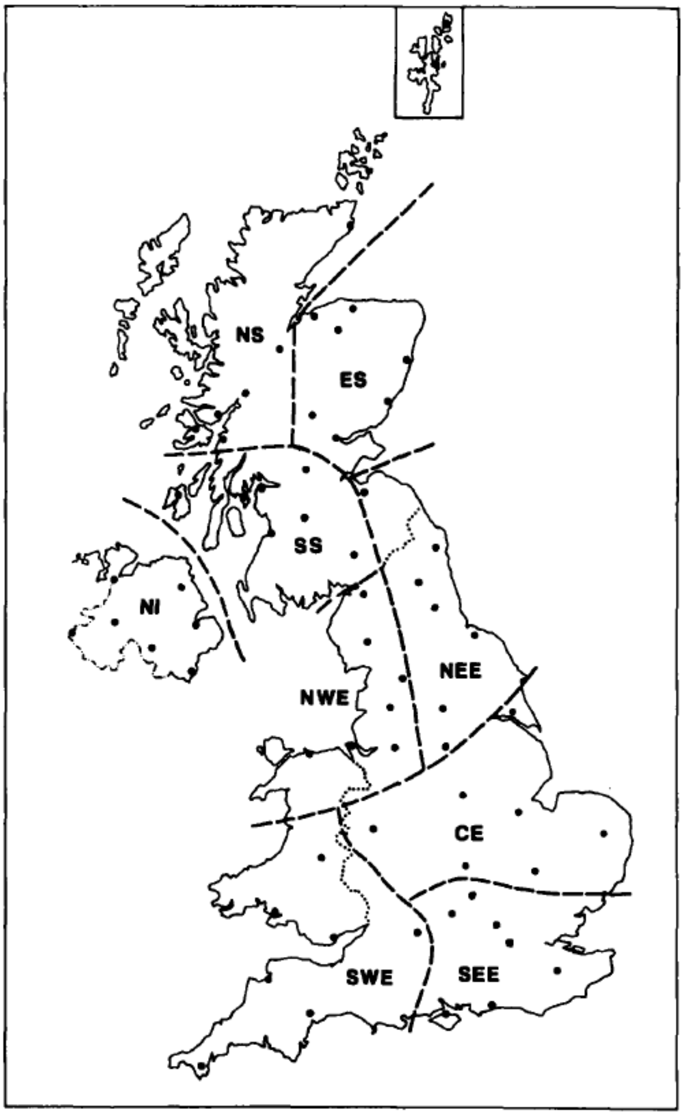


Fig 2.1 UK regions (Gregory et al., 1991)

2.1.3 Updating of the series in near real-time

Alexander and Jones (2001) documented the methods used at present to enable the updating of the series in real-time, enabling the data to be kept up-to-date more easily. The method used is to extract daily precipitation values from the Met Office MIDAS data bank, and to scale the daily precipitation totals from each station by the ratio of the regional monthly normal to the stations' monthly normal, summing them to reach a regional total (Alexander and Jones, 2001). All selected stations have 1961-90 averages and can send national climate messages once or twice per day. The monthly results obtained by these new methods are closely correlated to the series arrived at by Jones and Conway (1997).

However, the daily values, when derived this way, are less closely correlated with the Jones and Conway (1997) series as they are more sensitive to the number of stations in each region (Jones et al., 1997, Alexander and Jones, 2001). In both cases northern Scotland was the region with the greatest discrepancies, due to the high spatial variability of precipitation totals and fewer gauges in this region. Thus, the uncertainties associated with the real-time Met Office UK precipitation dataset, and potential inhomogeneities with respect to the Climatic Research Unit dataset, are higher for the more sparsely populated regions of northern and western Britain than for the densely populated south-east of England. This suggests that more analysis and tests are needed to confirm the homogeneity of the two series with respect to daily precipitation data. As of 2010 this method of updating the series was still in use (e.g. see Kennedy and Parker, 2010).

2.2 Generation of Met Office gridded data

In recent years the UK Met Office has developed daily, monthly and annual sets of gridded 5km by 5km data for 36 climate variables (Perry and Hollis, 2005b), using geographical information systems (GIS) to create gridded datasets from available station data. The gridded data stems from the Met Office's database of climate statistics which in turn is developed from readings from the network of weather stations maintained by the Met Office across the UK. The software used was ESRI ArcView, which allows regular gridded data to be created from irregularly spaced point data such as a network of weather stations. The effects of topographical and geographical variables, which can generate local anomalies, can be offset by using multiple regression techniques or by normalising with respect to long-term averages such as 1961-90 or 1971-2000.

For interpolation of the results, the Met Office chose inverse distance-weighted interpolation IDW (Perry and Hollis, 2005a) as it is easy to implement, provides realistic looking results and can be applied to a large range of climate variables. They rejected kriging as while it is considered to give more optimal results, it over-smooths the surface, and is computer-intensive. The Met Office considered splines likely to create unrealistically smooth surfaces due to the range of variables covered by their work, and thus rejected the spline method.

A custom method of developing IDW-based interpolation was devised, including an option to not go to infinity when a station and grid point coincide, and an adjustment for variations in station density, but for precipitation this method produced higher root mean square error values than the standard IDW method. Earlier studies, including studies covering the UK and also studies covering other regions such as Canada, had used either kriging or IDW for the generation of gridded precipitation data. Although the Met Office used interpolation methods for missing station data for most variables, for rainfall, any stations with missing data in a month were not used for gridding monthly values due to the high variability of daily rainfall. However, the UK has a dense station network for rainfall over the period 1961-2000, and thus this did not significantly affect the results.

The Met Office had previously developed 1km by 1km gridded averages for the UK (Perry and Hollis, 2005a) and the 5km by 5km gridded data for many of the variables were normalised with respect to the 1961-90 averages, including the rainfall. However, regression was also used in all cases to generate the grids because of the broad spatial trends that can be found even in the normalised data, due to variability of atmospheric circulation and associated weather patterns across the UK.

As pointed out by Perry and Hollis (2005a), this methodology for providing the gridded data is not perfect, for instance there may be significant scope for error in the more sparsely populated regions of the UK such as northern Scotland, much as in the analysis of Alexander and Jones (2001).   More variables could be added to the analysis, such as wind and humidity. Geographically weighted regression (Brundson et al., 2001), although computationally expensive, takes into account the relationship between rainfall and altitude, and may warrant further investigation as this method could potentially improve the reliability of the results. More details on the Met Office datasets can be found in Perry and Hollis (2005a) and Perry and Hollis (2005b).

2.3 A new rainfall series using updated Met Office gridded data

In 2008, the Met Office developed a revised 5km gridded daily rainfall dataset for the UK which extended from 1958 to 2007, using improved algorithms and corrections for errors in the previous version that extended from 1958 to 2002, including anomalies in the attribution of daily rainfall totals (e.g. a shift from attributing 24 hour 0900-0900 rainfall to the previous day to attributing it to the current day).   A separate monthly gridded dataset has been developed extending from 1914 to 2006. Differences between the daily and monthly datasets are assessed in Chapter 4. In Chapter 4, the Met Office gridded rainfall data are used to develop a new regional rainfall series for the UK, which has the advantage of being based on a far more comprehensive network of rainfall stations than the original HadUKP series. The rainfall series is then extended back as far as the HadUKP series extends using regressions against the HadUKP series.

3. Literature Review

3.1 Introduction

This literature review summarises the state of research on the subjects that are covered in this thesis. Section 3.2 covers the basics of precipitation formation and the atmospheric processes that govern precipitation distribution and amounts, including atmospheric moisture, the Clausius-Clapeyron equation and the distinction between convective and large-scale precipitation. Section 3.3 covers past changes in mean precipitation and extreme precipitation over time, focusing on the UK and covering the four seasons individually, and discusses ways of assessing changes in precipitation. Section 3.4 covers factors that influence precipitation variability, focusing especially on atmospheric circulation, and to a lesser extent oceanic circulation, temperature trends and the urban heat island effect. Section 3.5 covers climate model simulations of precipitation, the current projections into the future based on climate change scenarios stemming from the IPCC reports, and the main deficiencies that current climate models have in simulating clouds and precipitation.

3.2 Introduction to precipitation variability

3.2.1 Formation of precipitation

Precipitation forms when a parcel of air rises, cools and expands, and condenses to form clouds, and the cloud droplets grow sufficiently large to cause precipitation (e.g. rain, hail, snow, graupel) to fall from the cloud (Trenberth et al., 2003). There are many mechanisms that cause parcels of air to rise. Baroclinic instabilities arise due to the interaction of different airmasses, especially over the mid-latitude oceans, resulting in frontal depressions, associated with warm fronts (warm air rising over colder, denser air) and cold fronts (cold air undercutting comparably warm air), both of which cause parcels of air to rise, and these result in organised areas of precipitation. Convective instabilities arise from inequal heating of the atmosphere, such as solar heating over land, and cold airmasses flowing over comparatively warm oceans and lakes, as commonly occurs in the wake of cold fronts associated with mid-latitude depressions. Evaporation over oceans exceeds precipitation (Quante and Matthias, 2006) and there is thus a net transport of water from the oceans to the continents via the atmosphere.

Although global evaporation and global precipitation approximately balance each other out, evaporation alone cannot account for falls of moderate or heavy precipitation as it is continuous and subject to availability of moisture, and thus moderate or heavy precipitation arises from the convergence of moisture that arises via transport within the global atmospheric circulation (Trenberth et al., 2003). Water deposited by precipitation over the continents is returned to the oceans via rivers and surface runoff, completing the global hydrological cycle.

3.2.2 Atmospheric moisture

The availability of moisture in the atmosphere is essential for the generation of precipitation, and a limiting factor on the rate of precipitation. The characteristics, and in particular rate, of precipitation, are as important as the amounts, for example steady moderate rain soaks into the soil more efficiently than short-lived, heavy rainfall events which can cause significant surface runoff. In climate model simulations it is important to simulate both the characteristics of the precipitation and the correct reasons for those characteristics, otherwise such model simulations will inaccurately represent precipitation.

Many sources, such as Trenberth and Shea (2005) suggest increases in potential evapotranspiration under a warmer climate, which could potentially lead to more severe droughts in the absence of precipitation, and the Clausius-Clapeyron equation, discussed in Section 3.2.3, supports an increase in the water-holding capacity of the atmosphere at higher temperatures. Dai et al. (2004), using the Palmer Drought Severity Index, suggest that increased temperatures may already be causing increased drought across many areas of the Northern Hemisphere due to these factors. The PDSI does not take into account numerous factors such as water vapour, wind and radiation (Trenberth et al., 2007), but a refined version of the PDSI used by van der Schrier et al. (2010) suggests that the Penman (1948) type methods of assessing potential evapotranspiration do not give significantly different results. Measuring recent changes in evapotranspiration has also been complicated by decreases in solar radiation, as a consequence of increased cloud cover and/or increased aerosol content of the atmosphere, resulting in reductions in pan evaporation (Dai et al., 2004), although the extent of this “global dimming” process has reduced over the last two decades (Huntington, 2006), and shown reversal in some regions (Wild, 2009) and is primarily concentrated in urban areas (Alpert et al., 2005).

A decline in the proportion of winter precipitation falling as snow, although leading to increased precipitation due to rain being more efficient, may also lead to a reduced snowpack and thus reduced water resources from snowmelt in summer (Trenberth et al., 2007), for example an earlier melt of the snowpack reduces albedo and increases absorption of solar radiation by the soils, promoting reductions in soil moisture (Wetherald and Manabe, 2002).

In 2002 the drought in parts of the USA, especially Colorado, was rendered particularly severe by the lack of snow in the preceding winter, reducing imports of meltwater from melting snowfields on high ground and soil moisture. The findings of Huntington (2006) suggest that there has already been a trend, averaged globally, towards a more intense hydrological cycle, including greater evapotranspiration. Increased evaporation over oceans may lead to increased precipitation over land masses, particularly areas adjacent to windward coasts, due to increased imports of water vapour from the oceans (Wang, 2005). Trenberth et al. (2007) note an increase in cloud cover and water vapour over oceanic areas over the previous 30 years, which promotes a higher frequency of intense rainfall events.

Water vapour is expected to increase in a warmer climate, due to the ability of the atmosphere to hold more water at higher temperatures (again see Section 3.2.3 on the Clausius-Clapeyron equation), assuming constant relative humidity, although the current generation of climate models indicate some regional changes in mean relative humidity (Wright and Sobel, 2010). Climate model-based analysis has consistently produced results suggesting an increase in water vapour (e.g. Soden et al, 2002). Trenberth et al. (2003) argue that increased moisture should increase rainfall rates by generating more latent heat which is converted to kinetic energy, invigorating storms, thereby increasing the moisture supply further via oceanic evaporation. Willett et al. (2007) and Willett et al. (2008) found significant increases in specific humidity in recent decades over the globe, but no statistically significant trends in relative humidity, with the findings of Willett et al. (2007), based on Hadley climate model simulations, suggesting a strong link with anthropogenic forcing.

3.2.3 The Clausius-Clapeyron equation

The expected change in water-holding capacity of the atmosphere associated with an increase in global temperature, described by the Clausius-Clapeyron equation, is approximately 7% K^{-1}. The Clausius-Clapeyron equation can be expressed as:

$$de_s/e_s = LdT/RT^2$$

where e_s is the saturation vapour pressure at temperature T, L is the latent heat of vapourisation, and R is the universal gas constant (Trenberth et al., 2003).

Due to the nonlinearity of the Clausius-Clapeyron equation, saturation vapour pressure shows only small increases with temperature when temperatures are low, but large increases with temperature when temperatures are high (Wetherald and Manabe, 2002). Thus, although higher temperature rises are projected in higher latitudes, the Clausius-Clapeyron equation suggests significantly greater increases in available moisture amounts at lower latitudes. Also, increased precipitation and temperatures may have the effect of increased evapotranspiration but reduced sensible heat transfer (Wetherald and Manabe, 2002, Trenberth and Shea, 2005).

There is some disagreement over whether temperature increases will result in the full 7% increase in mean precipitation per increase in degree Kelvin, e.g. Huntingdon (2006) and Allen and Ingram (2002) suggest an increase of 3.4% per degree Kelvin at low latitudes, though closer to 7% at high latitudes. Constraints on energy availability, especially the ability of the troposphere to radiate away latent heat caused by precipitation, are examples of possible limiting factors. Pall et al. (2007) suggest that mid-latitudes may see changes that are most consistent with the Clausius-Clapeyron equation, though this result is dependent on the accuracy of simulations from HadCM3 and may need to be tested with a wider range of climate models (see Section 3.3). Richter and Xie (2008) argue that a change of 2% per degree Kelvin is more likely, primarily because many climate models project an increase in relative humidity in a warmer world and, due to the land warming faster than the oceans, surface stability increases (thus reducing the generation of precipitation over the oceans).

It is important to differentiate changes that result from the Clausius-Clapeyron equation from changes that are caused by shifts in atmospheric circulation. For example, Lenderink and Meijgaard (2008) analysed the relationship between temperatures and precipitation extremes for De Bilt in Holland, and found that at high temperatures, hourly precipitation extremes increased at twice the rate that would be expected from the Clausius-Clapeyron equation. However, this was probably strongly associated with atmospheric circulation (e.g. the hottest weather in summer in north-western Europe tends to arise from anticyclonic/southerly types, which also promote a high incidence of heavy convective precipitation, particularly when Atlantic systems push eastwards against well-established hot continental air), and so is probably not representative of the changes that we can expect due to increases in global and regional temperatures.

3.2.4 Convective vs. large scale precipitation

Moderate or heavy precipitation does not occur directly as a result of moisture from evaporation, but rather as a result of transport and convergence of areas of low-level moisture. Trenberth et al. (2003) hypothesise that areas of precipitation probably draw in moisture from a region of radius 3-5 times larger than the area in which precipitation is occurring. In convective cells most moisture used up by precipitation is resident in the atmosphere at the time of the initiation of the storm, whereas in depressions, especially hurricanes, a greater proportion of the moisture stems from surface evaporation. Convergence of moisture has also shown an increase in recent decades over oceans and at high latitudes (Meehl et al., 2007).

The diurnal cycle of precipitation is also important (Trenberth et al., 2003), measured in terms of the timing and duration of precipitation events as a function of the time of day. Most climate models are poor at simulating diurnal precipitation cycles, for example the European Centre for Medium-Range Weather Forecasting (ECMWF) simulates a noon maximum in convection over land, coinciding with the time of maximum heating, when in reality convection tends to peak three or four hours later. Premature generation of convection can have knock-on effects upon other atmospheric processes.

The categorisation of precipitation into “convective” and “large scale” is also problematic. Most convective parameterisation schemes in models use prescribed convective entrainment/detrainment rates (Wang et al., 2007) which often err on the low side, as low simulated entrainment/detrainment rates typically result in convection being initiated too early in the model outputs. Stratiform precipitation is generally simulated separately using condensation parameterisation schemes (Song and Yu, 2004). It is also complicated by the fact that many precipitation events combine the two, e.g. convective cells and squall lines occurring along a cold front, in conjunction with steady precipitation from stratiform clouds. Research into precipitation in the tropics suggests that stratiform precipitation can also occur within regimes where clouds and precipitation form exclusively through atmospheric convection (Houze, 1997, and Houze, 2004) for when the vigorous updraughts and downdraughts associated with mature convective cells weaken, areas of stratiform cloud and steady precipitation result, in contrast to the sharp updraughts and downdraughts and intense precipitation associated with younger convective cells. Correspondingly, attempts to separate precipitation events into convective and large scale components using satellite data have proven problematic; for example, Hand (2005) notes that Meteosat cannot detect convective clouds underneath a veil of extensive upper-level cloud, and so his analysis on the occurrence of convective events across the UK focused on the occurrence of “sunshine and showers” conditions, which are commonly associated with post-frontal airmasses in the mid-latitudes. Research is ongoing into enabling more robust parameterisation of convective and stratiform precipitation into cloud models, and Sui et al. (2007) note that ice microphysics dominates in regions of predominantly stratiform forcing while water microphysics dominates in regions of predominantly convective forcing, but segregation of convective and large-scale precipitation remains a problematic area for climate models (Pincus et al., 2008).

3.3 Past and present extreme precipitation across the UK

3.3.1 Distribution and seasonal cycles of mean and extreme precipitation across the UK

The distribution of precipitation across the UK varies according to the time of year, although there is considerable month-on-month variability either side of the long-term average. Western Britain experiences a strong seasonal cycle in precipitation, with wet autumns and winters and relatively dry springs and summers, while eastern Britain is relatively dry throughout the year and only experiences a modest seasonal cycle (Wigley and Jones, 1987). Northern and western Scotland experience the greatest seasonal variation in precipitation totals across the UK as a whole (Gregory et al., 1991) while within England and Wales it is the south-west that has the strongest seasonal cycle (Wigley and Jones, 1987). Extreme precipitation also shows strong seasonal variation in north-western Britain, with a maximum in autumn and winter, caused mostly by frontal rainfall generated via Atlantic depressions, although convective events can also occur particularly along western coastal fringes (Maraun et al., 2008). The reverse occurs in East Anglia, where extreme precipitation events are substantially more common in summer than in winter due to occasional intense convective events, even though mean precipitation amounts show very little seasonal variation across the region. Central parts of the UK, especially the Midlands, experience a small annual cycle in extreme precipitation because the contributions from the predominantly frontal extreme events in winter are similar to those from the predominantly convective extreme events in summer (Maraun et al., 2008).

Although East Anglia and the south-east has the highest incidence of extreme convective rainfall, the frequency of “sunshine and showers” conditions featuring short-lived convective rainfall with sunny intervals in between is highest in upland and western parts of Britain, especially but not exclusively in autumn and winter (Hand, 2005), which suggests that convective precipitation may occur less frequently in the east than in the west, but that particularly in southern England, when it does occur in the east it tends to be more intense.

3.3.2 Methods of assessing changes in extreme precipitation

Although the general principle of assessing changes in occurrence above given thresholds is consistent across studies on the subject, there are many different methods of assessing changes in extreme precipitation, with associated advantages and disadvantages. For example, it can be useful to differentiate changes in the frequency and intensity of short-lived extreme events over a single day (often of convective origin), which trigger flash flooding, and sustained events over several days (such as a prolonged spell of heavy frontal rainfall) which can saturate the ground and lead to flooding, since it is possible that in a warmer world the frequency and intensity of those different types of event may change in different ways. Thus, many studies compare changes in extreme rainfall over differing timescales, such as 1, 2, 5 and/or 10 day events, e.g. Fowler and Kilsby (2003a and 2003b). Common statistical methods for assessing occurrences of extreme precipitation above a threshold level include return period analysis, frequency of occurrence above a certain amount over a given time period, and changes in the value of a given percentile of the distribution. Some studies use quantile based analysis (e.g. Osborn et al., 2000), in which case it is more appropriate to divide precipitation into equal amount quantiles rather than equal frequency quantiles to avoid biasing the results towards contributions from the highest quantiles, though this does contain the issue that the highest quantiles correspond to the lowest proportion of the total raindays and vice versa.

Changes in extreme precipitation can be assessed as an average over large regions, or at individual points, e.g. Fowler et al. (2005) directly compared the pros and cons of regional frequency analysis vs. individual grid box analysis when using gridded precipitation data. Regional frequency analysis has the advantages of relying upon a wider range of data and producing stronger and more homogeneous results but has the disadvantages of masking small-scale spatial variations in precipitation changes. In addition, regional frequency analysis has the problem that observing sites tend to be biased towards the drier lowland parts of regions of variable topography, which means that it may mask differences in changes between lowland and upland regions (Burt and Holden, 2010).

3.3.3 Evidence of a trend towards drier summers

There has been a trend towards drier summers, mostly through a reduction in the frequency of wet days (Osborn et al., 2000), but there has also been a small contribution via a reduction in the mean wet-day amounts, though the decline in mean wet-day amounts may represent a return to early 20th century levels following an unusual phase of frequent intense events peaking in the 1960s. The record that Osborn et al. (2000) used only dates back as far as 1908, so unlike analysis on the HadUKP record this does not cover changes during the 19th century or between the 19th and 20th centuries. Thus, there is no evidence for an increase in frequency and/or intensity of extreme summer precipitation during the 1980s and 1990s. Wigley and Jones (1987) noted a trend towards drier summers between the 1960s and mid 1970s, with the summer of 1976 having been exceptionally dry. Gregory et al. (1991) noted no long-term trend in summer rainfall, but this was most likely influenced by the fact that the period of coverage extended up to 1989 and ended with the generally wet summers of 1985-1988. Further studies, notably Jones and Conway (1997) and Alexander and Jones (2001) have confirmed a general long-term reduction in high summer (July and August) precipitation across the UK, which is evident in all regions of England and Wales, Northern Ireland and northern and eastern Scotland, although Alexander and Jones (2001) did not find any trend in the number of consecutive dry days for July and August. The summer of 1995 was especially dry, comparably so to that of 1976. Correspondingly, when Perry and Hollis (2005a) compared the 1971-2000 reference period with the 1961-90 reference period, they found a nationwide decline in summer precipitation.

It is not a given that this trend towards drier summers will continue; already there is evidence that some of the trends in summer rainfall that became established during the late 20th century have reversed during the early years of the 21st century. For instance, Eden (2005) notes that July and August rainfall has increased over England and Wales since the turn of the century, following a succession of notably dry such months in the 1990s. Subsequently, May to July 2007 (UK Met Office, 2007) was the wettest May to July combination since the England and Wales precipitation series began in 1766, and the summers of 2008 and 2009 were also wet over much of the UK.

Maraun et al. (2008), updating the analysis by Osborn et al. (2000), noted that when the period 1900-2006 was considered, the decrease in heavy precipitation contribution noted in summer appears consistent with inter-decadal variability and the trend showed signs of a reversal since the beginning of the 21st century, even prior to the wet summers of 2007-09. Fig 3.1 suggests that despite recent wet summers, precipitation averaged over England and Wales has yet to recover to the levels seen during the 19th and late 18th centuries. Monthly summer precipitation over England and Wales dating back to 1766 is shown in Fig 3.1, and Fig 3.2 shows the values for Scotland back to 1931.

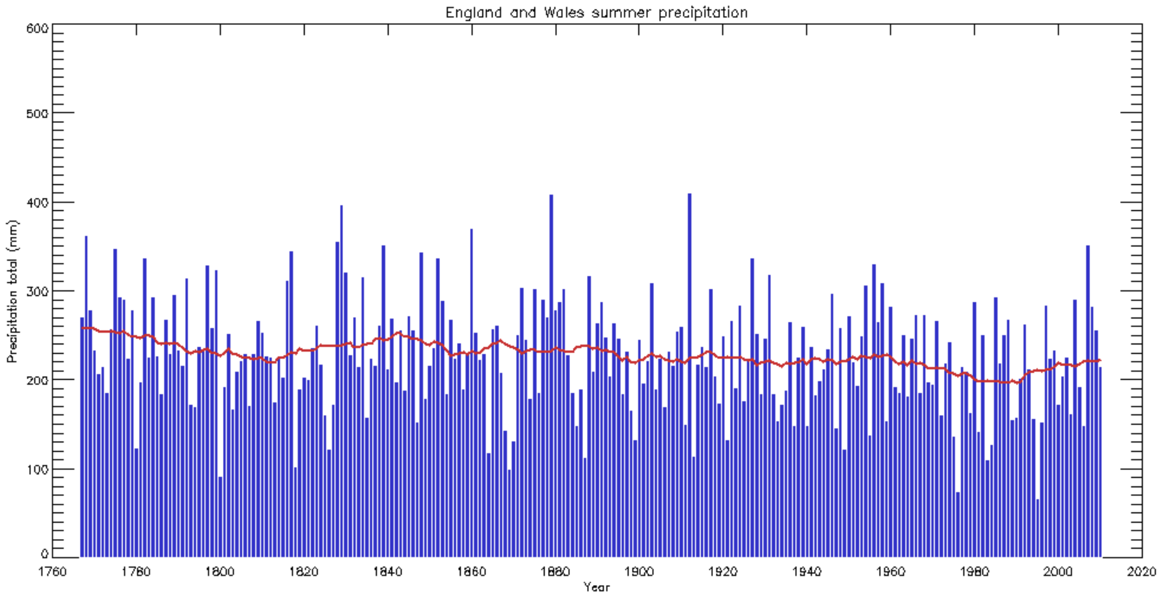


Fig 3.1. Summer (JJA) precipitation for England and Wales from the HadUKP dataset (1766-2010), fitted with a 101-point moving average.

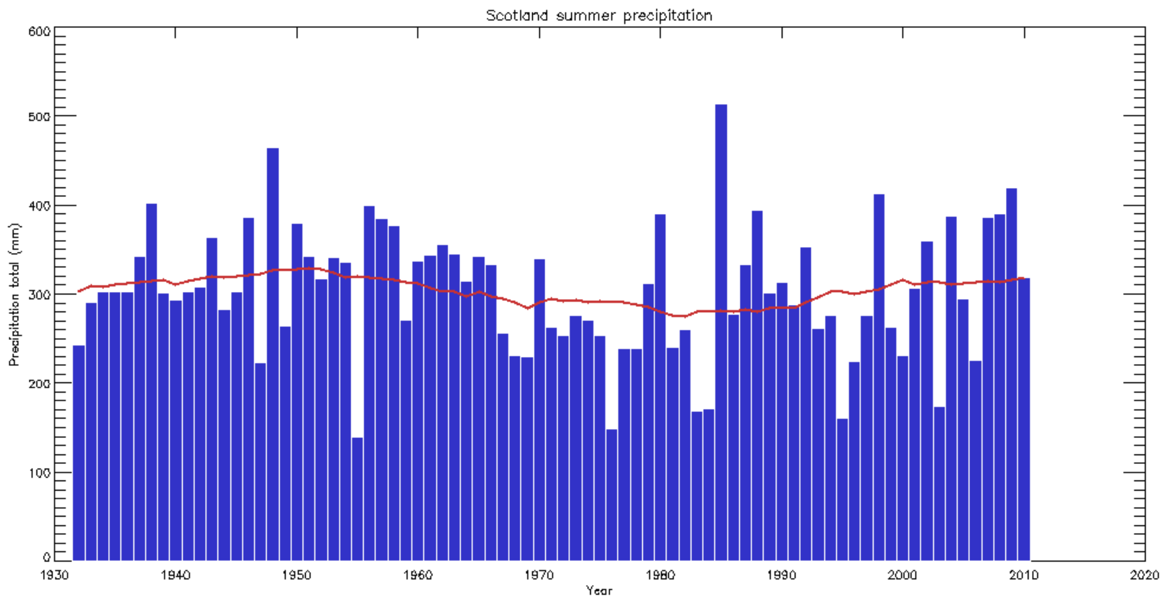


Fig 3.2. Summer (JJA) precipitation for Scotland from the HadUKP dataset (1931-2010), fitted with a 51-point moving average.

3.3.4 Evidence of a trend towards wetter winters

There is also considerable evidence of an increase in winter precipitation, associated with an increase in the frequency of wet days and the intensity of wet days in western Britain. For eastern Britain, the frequency of wet days has not increased, but the intensity of wet days has increased (Osborn et al., 2000). Wigley and Jones (1987) noted an increasing trend in winter precipitation. Gregory et al. (1991) also noted this trend, particularly pronounced for Scotland. Jones and Conway (1997) noted that for Scotland as a whole, between 1988/89 and 1994/95, only one winter (1990/91) did not produce an extreme high precipitation total. Western Scotland has seen the greatest increase in winter half-year precipitation, and in extreme events (Alexander and Jones, 2001), and the increases in winter precipitation are associated with an increasingly positive North Atlantic Oscillation (see section 3.4). In south-west Scotland, every year in the 1990s exceeded the 1931-99 average number of heavy precipitation days for the period October to March. The number of days per season with precipitation totals above the 95th percentile also showed a marked increase over the 1931-99 period (Alexander and Jones, 2001). It is questionable whether the increase in winter precipitation during the twentieth century and the high incidence of extreme wet winters during the 1990s represents a long-term trend or is down to natural variability, as UK winter precipitation has fallen during the first decade of the 21st century.

Perry and Hollis (2005a) compared the 1971-2000 reference period with the 1961-90 reference period, and noted a 10% increase in winter precipitation over north and west Scotland and north-west England, but little change in eastern Britain. The finding of no significant change in eastern Britain does not necessarily contradict the earlier findings, as the comparison of 30-year averages may potentially mask shorter-term changes in precipitation amounts. Perry and Hollis (2005b), in generating 5km grids of meteorological variables across the UK, noted an upward trend in rainfall intensity over the period, which was greatest in western Scotland. It appears that the variability of winter precipitation over the UK has increased in recent years, especially in western and northern Britain. Fig 3.3 and Fig 3.4 show the HadUKP winter precipitation totals for England and Wales and Scotland respectively.

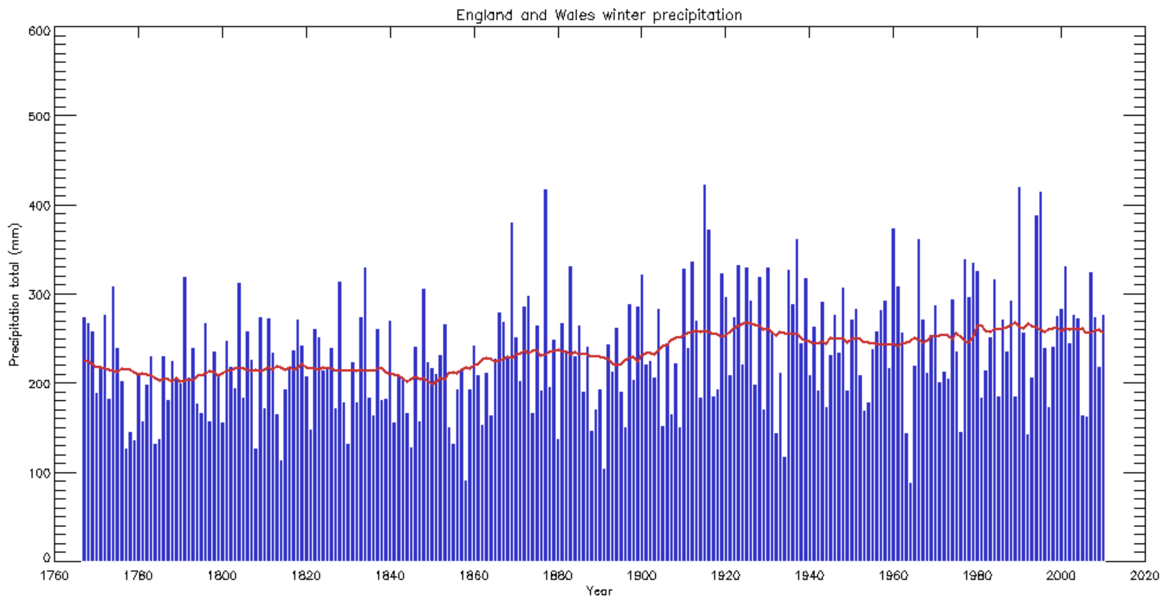


Fig 3.3. Winter (DJF) precipitation in millimetres for England and Wales from the HadUKP dataset (1766-2010), fitted with a 101-point moving average.

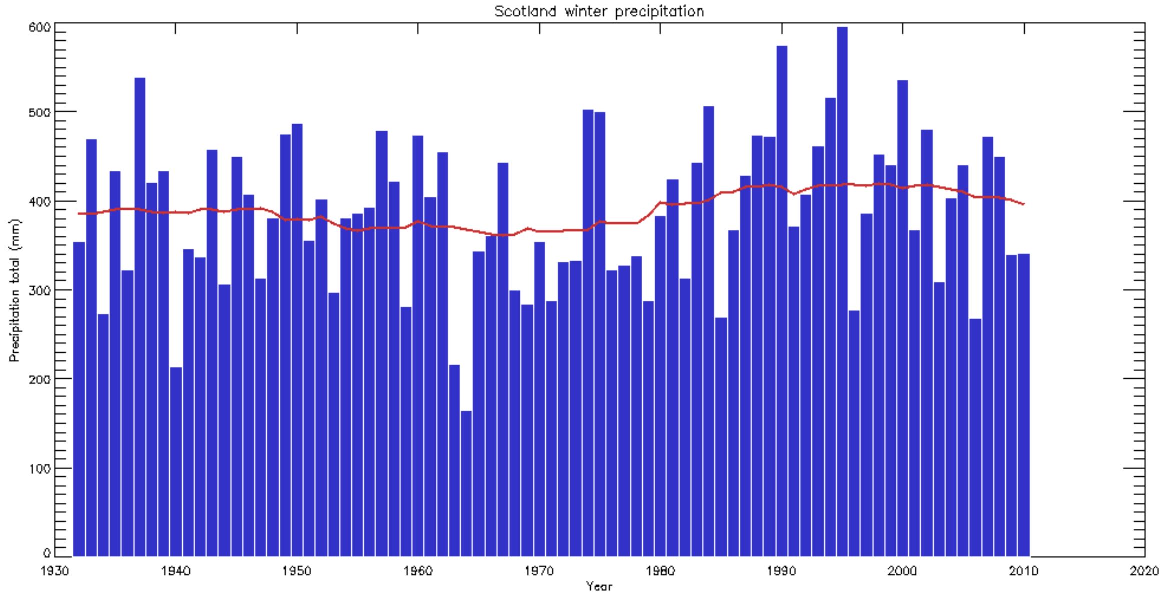


Fig 3.4. Winter (DJF) precipitation in millimetres for Scotland from the HadUKP dataset (1931-2010), fitted with a 51-point moving average.

3.3.5 Trends in spring and autumn precipitation

Trends in spring and autumn precipitation have not been as clear-cut as for winter and summer precipitation, with different papers yielding different results. Wigley and Jones (1987) noted a succession of wet springs in the late 1970s and 1980s, suggesting that the wetness of the preceding ten years exceeded what could be expected due to natural variability. Subsequent analysis has suggested that the succession of wet springs over England and Wales was just a temporary feature, but that spring precipitation has shown a pronounced upward trend in Scotland. Jones and Conway (1997) note that the increase in precipitation over Scotland has been concentrated in the November-April period, and that the wetter springs may be associated with a bias towards a more positive North Atlantic Oscillation, much as is the case with the wetter winters. The Aprils of 1998 and 2000 were both exceptionally wet, especially in north-east England, and the three month period April to June in the north-east region was the record wettest in records dating back to 1931, for both 1998 and 2000 (Alexander and Jones, 2001). April 2000 was the wettest April over England and Wales since records began in 1766.

Osborn et al. (2000) noted an increase in mean wet day amounts over Scotland, Northern Ireland and eastern England during the spring quarter, resulting in increases in total precipitation over Scotland and Northern Ireland. However, for eastern England the increase in mean wet day amounts has been offset by a reduction in the frequency of wet days. In contrast, northern England, south-west England and south Wales showed a decline in mean wet day amounts. Thus, while there is a clear trend towards wetter springs in Scotland and Northern Ireland, and an increase in the frequency of extreme precipitation events, the evidence for trends over England and Wales is far less conclusive.

For autumn there is even less evidence of any long-term changes in precipitation totals, although the data presented by Jones and Conway (1997) suggests that there was a temporary period of anomalously high precipitation totals in Scotland in the 1980s, followed by a return to precipitation amounts close to the long-term average in the 1990s. Osborn et al. (2000) suggests that there has been an increase in the frequency of high-intensity events in northern Scotland and central and eastern England, but a decline in northern England and the far south-east of England. Autumn 2000 was the wettest autumn since records began in 1766 over England and Wales, and October 2000 was the wettest since 1903, assisted by an exceptional fall of 40mm over England and Wales as a whole on the 29th (Alexander and Jones, 2001). However, there is not yet enough evidence to suggest that this was part of a long-term change in patterns of UK precipitation variability.

3.3.6 Trends in annual precipitation and the winter-summer ratio

There is no significant long-term trend in annual precipitation over England and Wales, as the increase in mean winter precipitation has been approximately cancelled out by a decrease in summer precipitation (Osborn et al., 2000). However, there has been an upward trend in annual precipitation in Scotland in recent years; the increased wetness of the winter half-year has been so marked that it has more than outweighed the trend towards drier summers. The analysis by Osborn et al. (2000) suggests that the bias towards extreme rainfall events has not increased significantly on annual timescales, with increases in winter being offset by decreases in summer. The frequency of wet days appears to have declined slightly over much of England and Wales. There may also be spatial differences, e.g. Fowler and Kilsby (2003a, 2003b) produced a similar result from analysis of growth curves (curves showing the growth in annual maximum precipitation totals over given time periods) focusing on 1, 2, 5 and 10-day extreme precipitation events over the period 1961-2000, finding a significant increase over much of Scotland and northern England, especially eastern Scotland, but a decrease over southern England. The greatest changes occurred in spring and autumn, with general increases at 1 and 2-day durations especially in the north and west and at 5 and 10-day durations in the north and west in autumn, and in eastern England in spring. This contradicts the findings of Osborn et al. (2000), which emphasised summer and winter as the seasons of greatest change, but decreased summer extremes and increased winter extremes were again strongly evident in Fowler and Kilsby (2003b).

The exceptionally wet period from April 2000 to March 2001 inclusive is noteworthy in the context of the long-term England and Wales rainfall series; Eden (2005) notes that the number of records that were broken over this period may have been a record. Again, further analysis of the precipitation patterns during the early years of the 21st century may help to determine whether this was an extreme consequence of natural variability, or part of a longer-term trend towards more extreme rainfall, whereupon the probability of extreme individual events such as the wet 2000/01 season increases. The frequency of winter thunderstorms across the UK showed a weak increase over the period 1961-1995 (Osborn et al., 2000) which suggests a possible link between the increase in extreme winter precipitation and convective influences. Summer thunder frequency has declined since the 1980s (Eden, 2005) which may be related to the decline in extreme summer precipitation across the UK.

The summer-winter ratio of precipitation has narrowed in most eastern parts of England (where most places have a maximum in summer and autumn) in recent years, due to a decline in mean summer precipitation and a decline in the emphasis on heavy precipitation events in contribution to the monthly and seasonal totals (Burt and Horton, 2007, Osborn and Hulme, 2002). Conversely in most upland and western regions, where orographic forcing plays a major role in the generation of heavy precipitation events and winters are generally wetter than summers, the summer-winter ratio has increased for the same reasons (winters becoming wetter and with more intense precipitation events, and summers drier with fewer intense events).

3.4 Variables that influence UK precipitation variability

3.4.1 Atmospheric circulation

Precipitation variability across the UK is strongly influenced by the strength of the prevailing westerly winds across north-western Europe, which is related to the North Atlantic Oscillation (NAO), particularly during the winter half-year. There are various indices used to determine the NAO but broadly speaking the NAO represents the pressure difference between the Azores region and Iceland (Jones et al., 1997), for example Hurrell (1995) used the difference of normalised pressures between Lisbon (Portugal) and Stykkisholmur (Iceland) as the measure of the NAO. Jones et al. (1997) instead used a set of pressure measurements from Gibraltar and Reykjavik. Some climatologists (e.g. Thompson et al., 2000) prefer to use the Northern Annular Mode (NAM), formerly known as the Arctic Oscillation (AO), which, in its positive state, features low pressure over the Arctic and northerly tracking depressions, and features high pressure over the Arctic and more southerly tracking depressions in its negative state.

Murphy and Washington (2001), in experimenting with different sea-level pressure difference indices to the NAO indices, suggested an especially strong link between UK precipitation and the pressure difference between Scotland and Madeira in September-April, which while not a useful substitute for the NAO, reflects the tendency for precipitation to be inversely correlated with atmospheric pressure over the UK and suggests that persistent blocking around Greenland may also be related to the occurrence of particularly wet summers. Ambaum et al. (2001) argued that the NAO is more physically relevant in terms of influence on Northern Hemisphere variability, but noted that their results did not exclude an annular-mode mechanism that could help to explain the NAO itself. The NAO and NAM are strongly positively correlated during the Northern Hemisphere winter (Trenberth et al., 2007).

Many papers have suggested a link between UK precipitation variability and the phase of the NAO (e.g. Hurrell, 1995, Jones and Conway, 1997, Osborn et al., 2000). A strongly positive winter NAO is associated with an anomalously high frequency of strong westerly and south-westerly winds across the UK and produces a greater frequency of intense precipitation events across the UK, especially in the north and west of the UK, though correlations are somewhat weaker for eastern Britain. Although there is also a general increase in precipitation totals across northern and western Britain associated with a strongly positive NAO (Osborn et al, 2000), an increase in wet day amounts is a consistent factor that is correlated with the NAO. According to Maraun et al. (2011), when considering the influences of wind direction, wind speed and vorticity (a measure of cyclonic curvature and shear), wind direction is generally the most dominant factor in influencing extreme precipitation events in central, eastern and southern England.

Wind speed is the most dominant factor in some western coastal areas (especially western Scotland) and vorticity is most dominant in other regions. This is consistent with the previous findings of Wigley and Jones (1987), who carried out an analysis comparing rainfall with the difference in pressure between 50 and 55N (indicating the strength of westerly winds over Britain), finding a strong correlation between the strength of the westerlies and precipitation over western Britain, most pronounced over north-west England but less strongly so over south-west England.

Similar results were obtained when the occurrence of days with a westerly Lamb type (Jones et al., 1993) were compared with precipitation. These results have been supported in subsequent studies comparing the NAO with UK precipitation, e.g. Wilby et al. (1997), Jones and Conway (1997) and Alexander and Jones (2001), with a strong suggestion that the positive correlations that Wigley and Jones (1987) found over north-west England apply to north-western Britain in general, including Northern Ireland (and possibly Southern Ireland also) and western Scotland.

Conway et al. (1996) used vorticity and analysed correlations with wet-day probability. In addition to high wet-day probabilities over western Scotland and north-west England in association with westerly flows, there was an indication of bias towards high wet-day probabilities in south-west England from southerly flows, and in north-east England from easterly flows, most likely associated with coastal influences. There was also a strong indication that flow strength is more strongly correlated with wet-day probability than wet-day amounts. In addition, Osborn et al. (1999), continuing this work, suggested a stronger correlation between airflow and wet-day probability than wet-day amounts, and a stronger correlation between precipitation amount and vorticity (and hence low pressure prevalence) than with airflow direction or strength. There was also little correlation between airflow direction or strength and high daily precipitation totals (e.g. 5mm or more).

Much of the recent increase in winter half-year precipitation totals and extremes, particularly in north-western Britain, can be explained by the trend towards a more positive NAO (Gillett et al., 2003, Gillett, 2005), The NAO was often strongly positive during the first four decades of the 20th century, followed by a downward trend between the 1940s and 1970s, and then a rapid upward trend since. The trend has been associated with a stratospheric cooling and deeper polar vortex, which may in itself be the main cause of the more positive NAM and NAO (Osborn, 2004, Meehl et al., 2007) and a stronger Icelandic Low (Hurrell et al., 1995). The corresponding strong positive trend in the NAM may explain approximately 50% of the recent winter warming over Eurasia, and 30% of the warming over the Northern Hemisphere as a whole (Thompson et al., 2001), accentuating the extent to which the Northern Hemisphere has warmed more than the Southern Hemisphere over December, January and February. Correspondingly, there has also been an increase in the strength of the polar vortex (Christiansen, 2003) and the density of cyclone activity between Greenland and Iceland (Schneidereit et al., 2007).

There is also considerable evidence that anthropogenic forcing may be a significant contributory factor to this trend (Thompson and Wallace, 2001). Other factors, such as perturbation of stratospheric ozone, changes in ocean circulation and changes in solar activity, may also have contributed to the change (Christiansen, 2003). The storm track over the north Atlantic and Pacific has increased in intensity and displaced poleward since the 1970s (Chang and Fu, 2002, Harnik and Chang, 2003, Wang et al., 2006), with a decrease in the frequency of mid-latitude depressions and increase in the frequency of high-latitude depressions, and the change has been especially strong during January, February and March (Wang et al., 2006). The trend towards a northward shift and strengthening of the winter storm track over the North Atlantic is also reproduced in climate model predictions of 21st century climate assuming a large degree of anthropogenic forcing (Yin, 2005), as is the weakening of the storm track, as well as northward displacement, during the summer months leading to hotter drier summers over Europe. According to Gillett et al. (2003) and Gillett (2005), the recent trends in the NAO, while reproduced in most climate models, have far exceeded the model predictions so far in terms of sea-level pressure changes, even when non-anthropogenic factors in climate change are taken into account. One possible implication of this is that the climate models may underestimate the impacts of increased greenhouse gas concentrations on atmospheric circulation.

The impact of higher sea surface temperatures on atmospheric circulation may be one factor that the climate models underestimate (Chang and Fu, 2002). An alternative possible conclusion from Gillett's observations may simply be that only some of the recent changes in the NAO are forced by mechanisms simulated by current climate models (Miller et al., 2006), while the remainder may stem from unforced variability and/or forcings that are not picked up by current climate models. Osborn (2004) also reached a similar conclusion, noting that only the most sensitive models that simulate the greatest variability can reproduce the recent degree of change, and thus that anthropogenic influences may only be a small contributor to the recent trend. The state of the stratosphere, as well as sea surface temperatures, may have a significant impact on the state of the NAO, as noted by Parker at al. (2007) who showed that models reproduce the state of the NAO with significantly greater accuracy when they are coupled to the stratosphere.

There are other possible complicating factors, e.g. there is currently a theory that the reduced Arctic sea ice extent associated with a warmer world may lead to greater high latitude blocking and thus a greater incidence of strongly negative winter NAO (Petukhov and Semenov, 2010). It is also not fully clear whether the recently-enhanced North Atlantic storm track intensity exceeds that of the early twentieth century (Trenberth et al., 2007). There is also considerable uncertainty over the extent of the magnitude of increase of the intensity of the storm track, though more prominent over the Pacific than over the North Atlantic towards Europe (Trenberth et al., 2007). Analysis by Wang et al. (2008) suggests that the increased winter storminess in the North Sea area during the early 1990s was indeed unprecedented in records dating back to the 1880s, exceeding the period of high storminess around 1905, but the increased spring storminess was not unprecedented, and there was a decrease in storminess during summer and autumn. However, following the exceptional winter storminess of the early 1990s, the 2000s have seen winter storminess in the North Sea area decline to levels close to the long-term mean. Correspondingly, there is also tentative evidence of a decline in the frequency and duration of Atlantic blocking episodes (Barriopedro et al., 2006, Trenberth et al., 2007), with particularly strong confidence of a positive link between Atlantic blocking episodes and a negative phase of the NAO, and hence reduced Atlantic blocking during the winter and in March over the previous three decades.

In summer there has been a trend towards increased incidence of anticyclonic flow over Europe in July and August since the 1960s, which has contributed to warmer drier summers in this region (Trenberth et al., 2007, Linderholm et al., 2009) although this trend has been less prominent in June, which also displays a different spatial signature during positive and negative NAO months to July and August (Folland et al., 2009). The high summer (July/August) NAO shows a different pattern to the winter NAO with positive summer NAO generally associated with a jetstream tracking SW-NE through the eastern Atlantic, promoting increased high pressure development across western Europe and hotter drier sunnier conditions, with increased easterlies across central Europe and advection of hot continental air into England (Folland et al., 2009). The typical pattern associated with negative high summer NAO features a jet tracking NW-SE across the eastern Atlantic and north-western Europe, prevalence of low pressure over north-western Europe and comparatively cool cloudy wet conditions over the British Isles.

Conversely, there is a weaker positive relationship between a positive summer NAO and wet summers across southern Europe, albeit only small in the Mediterranean where summers are usually very dry (Linderholm et al., 2009). The summertime NAM is also important, and shows a positive correlation with the NAM of the preceding winter, which may be connected to the lower snow cover typically associated with Eurasian springs and summers following positive NAO winters, leading to a stronger thermal contrast between the cold Arctic Ocean and warm continents (Ogi et al., 2004). A positive NAM is associated with a relatively northerly storm track, and the positive NAM of Summer 2003 contributed to the heat and drought across much of Europe (Ogi et al., 2005) while a negative NAM defaults the storm track over towards the UK with high pressure at high latitudes. The NAM also shows persistence between consecutive months in winter and summer, but not in spring and early autumn. More research is needed in this area, as previous studies have tended to focus on relationships with the winter NAO, and thus there are far fewer studies covering the summer NAO and NAM, and in particular the late spring and June NAO signals have yet to be studied in depth.

3.4.2 Oceanic circulation and temperature trends

There is considerable uncertainty surrounding changes in the Atlantic Meridional Overturning Circulation (MOC) in response to projected climate change, in particular resulting from the melting of the Greenland ice sheet, and an increase in precipitation at high latitudes (Allen and Ingram, 2002). The MOC is a significant contributor to the mild winters experienced over north-west Europe (Christensen et al., 2007). Most models predict that the MOC will weaken to some extent over the course of the 21st century (Meehl et al., 2007) which may offset the warming associated with rising global temperatures over regions adjacent to the North Atlantic such as north-west Europe, due to reduced meridional heat flux, and also, potentially, affect changes in precipitation amounts and precipitation variability.

However, despite the large uncertainties, model simulations consistently suggest that there is no significant likelihood of a large reduction in, or complete shutdown of, the MOC, and that if such an event does occur it is likely to take many decades or even centuries. Even in the simulations that project a large change to the MOC, the results consistently suggest no overall cooling in north-west Europe due to the cooling effects of a MOC shutdown being more than offset by the radiative forcing that initially caused the MOC shutdown (Meehl et al., 2007). However, the issue of changes in ocean circulation, and particularly the MOC, adds further uncertainty to projections of changes in precipitation variability.

Mean global temperatures have risen appreciably over the previous 100 years, with an acceleration of the warming since around 1975. The HadCRUT3 global temperature reconstruction for 1906-2005 suggests a warming of 0.74C (with confidence limits of +/- 0.18C) over this 100-year period (Trenberth et al., 2007), and that most of the warming is “very likely” (i.e. at the 95% confidence level) due to the increasing concentration of greenhouse gases down to anthropogenic influences. Although there is some uncertainty as to how much of the 20th century warming has been caused by human activity, and as to how much warming can be expected over the 21st century, there are strong indications that the globe is set to warm further during the course of the 21st century, most likely with a rise of between 2 and 4C, but with some of the extreme scenarios suggesting a rise as low as 1.1C under the lowest emissions scenario, or as high as 6.4C under the highest emissions/climate sensitivity scenario. The uncertainty range is dependent on the extent to which humans reduce their greenhouse gas emissions over the next 100 years in addition to the extent of influence of human activity upon atmospheric processes and the extent of climate sensitivity.

Such warming of the climate may trigger changes in precipitation patterns and atmospheric circulation, especially at mid to high latitudes, contributing to changes in precipitation variability across the UK. Intense and significant precipitation events cause increased runoff (Qian et al., 2006), which can lead to increased risk of flooding (Fowler et al., 2007) and runoff is projected to increase during the 21st century (Huntington, 2006).

3.4.3 Urbanisation and increased aerosol concentrations in the atmosphere

At a local level, the urban heat island effect can change the characteristics of precipitation in and downwind of urban areas, causing increases of 5-25% in summer precipitation (Trenberth et al., 2007). The warmth of cities compared with surrounding areas encourages a greater tendency for pools of warm air to rise, and this encourages excess convection over cities on days when the atmosphere is mildly unstable (Dixon and Mote, 2003). Buildings help to disturb airflows and generate convergence (Changnon and Westcott, 2002), and cities tend to reduce mean horizontal wind speeds on days of high synoptic flow (strong pressure gradient), and increase wind speeds on days of weak synoptic flow (Dixon and Mote, 2003). Cloud microphysics are also important, and human activity can have an effect on cloud microphysics through input of aerosols into the atmosphere. Pollutants emitted into the atmosphere from industry and transport increases availability of cloud condensation nuclei (Diem and Brown, 2003). Thus, there is a significant risk that increased urbanisation could cause increased incidence of extreme precipitation events within and downwind of the urbanised areas. Other land use changes can also affect precipitation, such as deforestation (Trenberth et al., 2007).

Menon et al. (2002) note that light-absorbing aerosols can generate excess local heat, which in turn affects the generation of clouds and precipitation. They can also affect convective precipitation through absorbing solar radiation and thus reduce the extent of solar heating of the ground, with considerable uncertainty surrounding the effects of this on precipitation over land due to the mostly regional nature of aerosol outputs (Trenberth et al., 2007). There are very few studies relating to the effects of urbanisation and aerosols specifically on precipitation across the UK.

3.5 Model simulations of precipitation changes under climate change scenarios

3.5.1 Reliability of climate models in projecting precipitation changes

Many attempts to derive results from climate change scenarios have been conducted via simulation of a steady-state doubling and/or tripling of atmospheric carbon dioxide concentrations in the atmosphere, using a base concentration of 300ppm, increased to an equilibrium level of 600ppm or 900ppm (e.g. Mearns et al., 1995, Hennessy et al., 1997). However, due to significant increases in computing power in the 1990s, more recent model simulations have often simulated time-dependent transient responses to a gradual increase in greenhouse gas concentrations (Conway, 1998). This gives a more realistic simulation of changes in greenhouse gas concentrations over time. However, some subsequent studies have still relied upon steady-state simulation of doubled and tripled carbon dioxide concentrations, e.g. Barnett et al. (2006) and Hegerl et al. (2004).

While most climate model simulations produce strongly defined temperature trends at a regional and global level, trends in precipitation are less well defined (Conway, 1998, Groisman et al., 1999, Wilby and Wigley, 2000, Yonetani and Gordon, 2001, Lal et al., 2002, Meehl et al., 2007), giving greater uncertainty over likely precipitation changes over the 21st century under a scenario of a warming planet and increased greenhouse gases in the atmosphere. The complexity and scale of the processes involved in generation of precipitation, together with orographic forcing processes, are poorly represented by global climate models (e.g. Mearns et al., 1995, Osborn et al., 2000) although representation improves as model resolution is increased. Osborn and Hulme (1997) noted the difficulties in relating the area-mean output of global climate models to station outputs, concluding that more than three stations were needed to get an accurate estimate of the rainday frequency for a given area. However, there is hope that as climate models improve, stronger conclusions and more accurate predictions will be possible (Hennessy et al., 1997).

It is possible to correct for biases in climate model simulations by computing simulations of past climate, comparing with past observations and subtracting the differences from the model outputs, but one disadvantage of the bias correction method is that bias corrections based on certain regions may result in anomalous results in other regions (Fowler et al., 2007). Multi-model ensemble analysis (e.g. Meehl et al., 2007) and simulations run using different versions of the same model with adjusted parameters (Barnett et al., 2006) may help to determine the consistent trends shown by the models, but one issue with this is that the actual conditions may not be close to the mean of the model simulations (Raisanen, 2005), which is a common issue generally with the use of ensembles-based analysis.

However, despite the large uncertainties involved, climate model based studies of precipitation under enhanced greenhouse gas conditions have consistently suggested that increases in precipitation variability are likely, with a weaker signal for increases in mean precipitation amounts (e.g. Lal et al., 2002, Groisman et al., 2005, Pall et al., 2007, Pall et al., 2011). Pall et al. (2007) note that increases in precipitation intensity was one of the earliest consistent climate model results under a scenario of enhanced greenhouse gas concentrations. Improvements are needed in the simulation of convective storm initiation, cloud condensation nuclei, convective available potential energy, caps on convection, and the diurnal cycle of convection (Trenberth et al., 2003).

3.5.2 Climate model simulation of precipitation

The accuracy of climate model simulations of precipitation is limited by poor simulation of atmospheric processes including cloud microphysics, convection, boundary layer processes and atmospheric circulation (Dai, 2006). Climate models tend to overestimate moderate precipitation events but underestimate severe precipitation events, yet conversely they overestimate the contribution that arises from convective precipitation as opposed to stratiform precipitation, an issue that was well known in the 1990s also (Osborn and Hulme, 1998). A contributory factor to this is the simulation of regular convection, firing convection too early, whereas in reality convection often encounters a cap which temporarily prevents convective storm activity, but can lead to severe storms late on as the convection eventually overcomes the cap (Trenberth et al., 2003, and Dai, 2006).

Sea surface temperatures are also poorly estimated in some regions, notably around the Pacific. A major problem is that systematic biases creep into the climate model simulations, especially with regards air-sea interactions, as small errors can develop into large systematic biases due to positive feedbacks (Dai, 2006).

The main area of uncertainty in climate model simulation of precipitation is in cloud and radiation simulation. Clouds and radiation are difficult to verify in forecast accuracy analysis as they are temporally and spatially variable and thus measurements of individual points are not necessarily representative of the area mean (Pincus et al., 2008). The analysis of Pincus et al. (2008), using performance metrics for climate models comparing with actual observations over the period 1991-2001, suggests that the climate models are not very proficient at predicting radiation, clouds or precipitation. These results are open to question due to the difficulty in verifying the correspondence of observations to the area-average climatology, especially in the cases of clouds and radiation. However, there was stronger agreement between primary and secondary observational data than the observational data and the model projections, which suggests that the models still have serious issues in modelling those factors. Soden et al. (2006) found that clouds were a source of positive feedbacks in a survey of the feedbacks in 14 of the models used for the IPCC report, but that the extent of the feedbacks varied considerably for different models, highlighting the uncertainty in cloud modelling.

Osborn and Hulme (1998) suggested that models that include evaporation of falling precipitation produce more intense daily precipitation in summer (and closer to observed values) than those that do not. The use of raw output from global climate models alone gives limited confidence in simulations of regional precipitation trends and variability, and changes due to future climate change, because of weaknesses in the simulation of physical processes and coarse model resolution (Haugen and Iversen, 2008). Thus, downscaling methods are widely used to help bridge the gap between the limited-resolution outputs from global climate models and station-scale climate characteristics (Hundecha et al., 2008).

Prior to the first decade of the 21st century, downscaling approaches to climate model simulations have traditionally been differentiated into two downscaling methods, dynamic downscaling, using regional climate models that are nested within global climate models) and statistical downscaling, finding and applying statistical relationships between predictor variables and station-scale parameters (Wilby and Wigley, 1997, Maraun et al., 2010). The downscaling approach interpolates regional-scale predictor variables to station-scale meteorological series. Statistical downscaling can take the form of simple regression using linear and nonlinear relationships between predictor variables and station-scale parameters (Wilby and Wigley, 1997). The parameters are tied to the simulations from global climate models (Haugen and Iversen, 2008). Bilinear modelling is also possible, where the respective covariances of the global circulation and local weather variables are linked in bilinear fashion. An alternative method is to relate station-scale parameters to synoptic scale climatology, and condition expected station-scale variables, such as precipitation at an individual site, on the prevailing synoptic scale features that are projected by global climate models, using conditional probability distributions (Wilby and Wigley, 1997). Stochastic weather generators can also be used, simulating the probability of climate variables occurring conditional on their occurrence on a previous day, and noting the differences that may occur under a different future climate (UKCP09, 2010). Using comparisons with existing climate data, stochastic generators can be used to test the reliability of relationships with predictor variables (Wilby and Wigley, 1997), and can be used to help assess likely changes in extremes (UKCP09, 2010). Such statistical methods of downscaling have the advantage that they are not computationally expensive (Haugen and Iversen, 2008) and thus a large range of climate scenarios can be analysed at low cost. However, weather generators have the limitation of assuming that relationships between predictor variables and station-scale parameters will remain constant as climate changes, which may not always be the case (Huntingford et al., 2003, UKCP09, 2010). They also lack a physical basis, instead “learning” the behaviour of weather from observed weather data and using it in statistical relationships (UKCP09, 2010).

Dynamical downscaling methods typically generate a regional climate model nested within a global climate model, and use the global climate model to set the time-varying boundary conditions (Wilby and Wigley, 1997, Murphy, 2000). Such models are limited by the reliability of the outputs from the global climate model, and are computationally expensive. However, they help to maintain physical consistency (Huntingford et al., 2003) and can simulate small-scale parameters such as orographic enhancement of rainfall (Wilby and Wigley, 1997). Regional climate models are run at fine time-steps, simulating changes over long periods of time, e.g. 30 minute time-steps over hundreds of years, while disseminated data outputs usually appear as aggregated daily estimates for particular time slices, including estimates of the past and predictions of the future (Rivington et al., 2008). Regional climate models aim to represent climate at the regional scale and can pick out general regional characteristics, but due to limited resolution they cannot provide simulated conditions that are identical to individual locations within each grid box, which is especially likely to generate anomalies in regions of large topographical variability (Rivington et al., 2008).

In recent years the distinctions between these methods have become less clear as there are increasing amounts of research into ways of combining these methods, aiming to combine the advantages and address the disadvantages of the individual methods. For example, the UKCP09 (UK Climate Projections) project used a stochastic weather generator where statistical measures were perturbed using probabilistic projections based on a climate model ensemble, a method which aimed to reduce the extent of the aforementioned downsides of using weather generators, while at the same time overcoming the issue of poor regional simulations caused by low RCM resolution when purely dynamical downscaling is used. Another way of combining these methods is correcting data from gridded RCM outputs using the relationships between variables simulated by the RCM and observed data, and using the corrected RCM data as the basis for statistical downscaling, which is acquiring increasing attention as a promising approach (Maraun et al., 2010).

3.5.3 The evolution of the Met Office Hadley Centre models

Many studies have used climate models produced by the Hadley Centre at the UK Met Office. Early versions of the first global climate model produced by the Met Office, based on simulations of a doubled carbon dioxide scenario, were first developed in the late 1980s (Gregory and Mitchell, 1995) and provided a broadly accurate simulation of the control climate, though with an unrealistic bias towards extreme cold events in winter and high incidence of moderate precipitation events. The results suggested a decrease in wet-day frequency but an increase in wet-day intensity, a result consistent with more recent model simulation results.

The Second Hadley Centre Coupled Model (HadCM2), developed by the Hadley Centre at the Met Office in the late 1990s (see Johns et al., 1997), when integrated with increased greenhouse gas concentrations, predicts an increase in extreme precipitation events during winter, and also an increase in extreme precipitation events in northern Britain in summer, but not southern Britain (Osborn et al., 2000). The HadCM2 model is capable of simulating gradual increases in atmospheric greenhouse gas concentrations rather than being limited to the simplistic doubled carbon dioxide scenario. However, Wilby and Wigley (2000) note that HadCM2 tends to overestimate the relationship between precipitation and humidity, particularly in summer, and thus, potentially, the impacts of anthropogenic climate forcing on precipitation, and the model also underestimates the strength of the westerlies over north-western Europe (Johns et al., 1997).

The Met Office subsequently released a third coupled model (HadCM3), described in Johns et al. (2003), which contained substantial improvements to simulation of oceanic and atmospheric components, such that artificial flux adjustments were not needed, unlike with HadCM3. HadCM3 also simulates climate over a period of 2000 years. The analysis of Johns et al. (2003) suggest that HadCM3 is generally realistic at simulating global climate, and more so than HadCM2, but still contains some deficiencies, such as an underestimation of the gradient between the Azores High and Icelandic Low, and thus anomalously weak wintertime westerlies over north-western Europe, more so than for HadCM3. In addition, there was a bias towards high pressure over the Arctic, especially in winter.

The HadRM2 and HadRM3 models stem from a development of a nested climate modelling system at the Hadley Centre where output from a global climate model is used as boundary conditions to drive a regional climate model (Buonomo, 2007). The HadRM2 climate model was driven by “one-way nesting” using prior outputs from the global climate model HadCM2 (Murphy, 2000) and when its simulated correlations between predictor variables and precipitation were assessed, they proved to be unrealistically high and did not always match the correlations found in reality. HadRM2 also overestimates precipitation totals over European land areas, and across the UK, especially over high ground and in East Anglia, but handles extreme precipitation quite well except in south-west England in summer (Jones and Reid, 2001).

The HadRM3 climate model simulates too many occurrences of small precipitation events leading to an underestimation of the number of dry days, as well as changes in surface temperatures and cloud-surface interactions, and also underestimated the magnitude of the largest precipitation event at all grid boxes (Rivington et al., 2008). The “drizzle effect” results from the attempts by the model to simulate the spatial occurrence of light rain by the model. The use of 30 years of hindcasting may not be a long enough timespan to pick out extreme events with longer return periods, but it is clear that the model underestimates the most extreme precipitation events. Huntingford et al. (2003) found a similar tendency for the HadRM2 model to overestimate moderate precipitation events, but also found that it simulated the extreme precipitation events well, comparing the RCM output with observations from the period 1961-1990. Unlike HadRM2, which underestimates precipitation in upland and western parts of Britain, HadRM3 overestimates precipitation in those areas (Buonomo, 2007). The HadRM3 and HadCM3 models were both used in the ENSEMBLES project. Following HadCM3 the Met Office released HadGEM1, which contains significant changes to its formulation of atmospheric dynamics and resolution of sea ice processes, and higher resolution than HadCM3 (Johns et al., 2006). HadGEM1 has been shown to improve significantly on HadCM3’s cloud microphysics simulations but still gives too strong a hydrological cycle and underestimates precipitation to the north of Scotland. The HadGEM2 model (Collins et al., 2008) also significantly improved the overall climate simulation relative to HadGEM1, though retaining issues with the simulation of ENSO and the Indian monsoon that are to be addressed by HadGEM3.

3.5.4 ENSEMBLES regional climate models

The ENSEMBLES project (see Section 6.2) aimed to generate probabilistic projections of temperature and precipitation changes over the 21st century, assess the likely impacts of climate change, gain a clearer picture of the feedback processes within the climate system and provide high-resolution climate observation datasets for Europe which can be used to validate climate model performance. Model runs are available for thirteen RCMs driven by the ERA-40 reanalysis, for comparison with observed data, and future projections are available from the same RCM integrations driven by associated global climate models. Outputs from eight of those RCMs are analysed in Chapter 6 for purposes of validation, determining which three are the most accurate at simulating precipitation across the UK, and outputs from the three most accurate models are analysed in Chapter 7.

To produce probabilistic projections of future climate, Christensen et al. (2010) provided weightings based on assessments of the individual models' reliability, using six different metrics covering temperatures and precipitation across Europe, comparing ERA-40 driven runs with observations, and using three different mathematical methods to obtain the total weights. These weights were used to generate the weighted model ensembles. In addition, Kjellstrom et al. (2010) used a "skill scores" method of assessing the models' reliability, using comparisons with temperature and precipitation. These results are open to some question as ensemble weighting is subjective and the results are sensitive to the choice of metrics (Lenderink, 2010).

The KNMI-RACMO2 model was developed by the Royal Netherlands Meteorological Institute (KNMI), and version 2.1 was used in ENSEMBLES. The model verification analysis by Christensen et al. (2010) and Kjellstrom et al. (2010) both had RACMO2 ranked as the best-performing model. An analysis of five selected models' performance at handling the timing, distribution and intensity of the west African monsoon suggested that RACMO2 provided the best overall representation (van der Linden and Mitchell, 2009). However, for some individual indices of temperature and precipitation RACMO2 was outperformed by some of the other models, and it performed less well in summer and autumn than in winter and spring. RACMO2 also has a warm dry bias in eastern Europe in summer (Christensen et al., 2007).

The HadRM3 model (see Section 3.5.3), produced by the Met Office Hadley Centre, was run with three sensitivity levels, the HC-Q0 (normal sensitivity), HC-Q3 (low sensitivity) and HC-Q16 (high sensitivity). In Chapters 6 and 7 outputs from the HC-Q16 version are used. The HC-Q16 version of HadRM3 performed second-best according to Kjellstrom et al. (2010) but did not rank as highly in the weights derived by Christensen et al. (2010). The DMI-HIRHAM5 model extended from earlier HIRHAM models, conducted by the Danish climate institute (DMI) and the Potsdam Research Unit of the Alfred Wegener Institute Foundation for Polar and Marine Research. HIRHAM5 did not perform well in the ENSEMBLES model weighting tests, overestimated summer and winter precipitation over the Alps (Christensen et al., 2010) and heavily overestimated precipitation amounts in coastal parts of West Africa during the monsoon season (van der Linden and Mitchell, 2009). The RACMO2, HadRM3 and HIRHAM5 models are used in the analysis in Chapter 7.

Outputs from five other ENSEMBLES models are also analysed in Chapter 6; the MetNO-HIRHAM, CLM, SMHI-RCA (hereafter RCA), INM-RCA3 (hereafter RCA3) and REMO. HIRHAM was run by the Norwegian Meteorological Institute and is an earlier version of the HIRHAM model used to develop DMI-HIRHAM5 (Christensen et al., 2010), and did not rank among the better-performing models in the ENSEMBLES analysis. CLM was run by the Swiss Federal Institute of Technology, and also did not perform better than most of the other models, and overestimates precipitation over the Alps. The Rossby Centre (RCA) model was run by two institutes, the Swedish Meteorological and Hydrological Institute (SMHI) and the Community Climate Change Consortium for Ireland (C4I), and REMO was run by the Max-Planck Institute for Meteorology. The performance of RCA and REMO was variable according to the metrics used by Kjellstrom et al. (2010), ranking among the best models by some measures and among the worst models by other measures, and Christensen et al. (2007) noted that SMHI-RCA performs better over eastern Europe than RACMO2. SMHI-RCA handles the monsoon over West Africa quite well but prematurely initiates the Sahel rainy season (van der Linden and Mitchell, 2009).

3.5.5 Projections of changes in precipitation variability

Global simulations of precipitation variability consistently suggest an increase in precipitation variability associated with 21st century climate projections (e.g. Yonetani and Gordon, 2001), with more intense convective precipitation at low latitudes, and greater contributions from more intense frontal precipitation at high latitudes. For example, Pall et al. (2007) found near-uniform increases in contribution from the upper 50 percentiles of precipitation events at high latitudes, but a strong bias towards increases from the uppermost percentiles at low latitudes, which is consistent with increased intensity of convective events. Earlier studies, including those by Mearns et al. (1995) and Hennessy et al. (1997) produced similar results, though Hennessy et al. (1997) suggested a decrease in the intensity of non-convective events at low latitudes. Groisman et al. (2005) suggested that an increase in extreme precipitation events in the mid-latitudes is likely under enhanced greenhouse conditions, and suggested that this is consistent with changes in precipitation over the previous half-century (a conclusion also reached by Groisman et al., 2004). For the UK, these conclusions may suggest a greater contribution from increased intensity of frontal precipitation in the north, and more emphasis on increased intensity of convective events further south. The results also supported the use of the Clausius-Clapeyron equation to predict future changes in extreme precipitation, noting that the Clausius-Clapeyron equation provides a better estimate of changes in extremes than the changes in mean precipitation.

A detailed multi-model analysis of expected trends in global precipitation over the 21st century is discussed by Meehl et al. (2007), which suggested increased precipitation to the north of Britain, but reduced precipitation to the south, particularly over Spain, which is consistent with predictions of an increasing bias towards positive North Atlantic Oscillation values (e.g. Yin, 2005). Similarly, there is a signal for reduced runoff and reduced soil moisture over most of central and southern Europe, but an increase in runoff for northern Britain and Scandinavia. The sign of change is consistent, but the degree of change is subject to considerable uncertainty. Raisanen (2005) and Yonetani and Gordon (2001) suggest an increase in both wet and dry extremes across the globe, with dry extremes increasing most in areas where mean precipitation declines, and wet extremes increasing most in areas where mean precipitation increases, but with the issue that the signal for precipitation variability change is weak compared with model-to-model variation, so more work is needed on improving climate models in order to produce a more consistent set of results.

Over the UK, results have been mixed, though with a general consensus of increases in extreme winter precipitation, especially in northern and western Britain (e.g. Hundecha and Bardossy, 2008), consistent with the projections of a northward shift in the track of Atlantic depressions (Raisanen and Joelsson, 2001). For example Jones and Reid (2001), using a regional model derived from HadCM2, found projections of an increase in heavy precipitation events in Scotland for all four seasons, and for southern England during winter, and an overall increase in convective precipitation across the UK. An ensemble of the HadRM3H model (a European high resolution model derived from HadCM3) produced an increase of 20-30% in winter precipitation across north-west England and a decrease in summer precipitation of as much as 50% (Fowler et al., 2007).

Some studies, e.g. Christensen and Christensen (2004) and Palmer and Raisanen (2002) have suggested that there may be an increase in heavy summer rainfall events across the UK despite a decline in mean summer precipitation, and a trend towards enhanced storm track activity associated with higher precipitation from mid-latitude depressions. Christensen et al. (2007) note a general trend among atmosphere-ocean global climate models to simulate increased precipitation north of 55N, especially in winter, but also decreased precipitation south of 55N, especially in summer. In addition, the two most relevant physical signals to UK precipitation consistently picked out by the models for summer climate change (changes in land-sea temperature contrast and specific humidity, and sea-level pressure change) are of opposite sign (Rowell and Jones, 2006). The increased moisture content of maritime air, consistent with the Clausius-Clapeyron equation, suggests increased precipitation, but the predicted trend towards reduced strength of the summer westerlies suggests reduced precipitation.

Although there is considerable uncertainty due to deficiencies in climate models, there is a consistent implication that UK precipitation amounts and variability are likely to increase during the boreal winter, with a trend towards higher wet-day amounts, and large increases in the frequency of extremes above specified thresholds, though much smaller increases in the magnitude of extreme events. The signals for changes in summer precipitation are less clear-cut, with tentative suggestions of a reduction in wet days but an increase in intense rainfall events, though there is limited evidence to suggest that this is already occurring across the UK, with a decline in extreme heavy precipitation during the summers of the late twentieth century (Osborn et al., 2000) and a recovery during the first decade of the twenty-first century.

3.6 Aims and objectives

The current literature on precipitation variability (Section 3.3) suggests that there has been an increase in winter precipitation and a decrease in summer precipitation across the British Isles, but with uncertainty over whether these trends are primarily the result of natural variability or are signs of long-term climate change. The HadUKP series (see Chapter 2) gives a long-standing rainfall record covering the UK regions with strong efforts made to ensure homogeneity but the use of seven sites per region may introduce bias, e.g. bias towards the drier parts of a region with variable topography.

The first objective is to extract regional average precipitation values at daily to annual timescales using the Met Office Hadley Centre gridded data, and develop a new homogeneous rainfall series for the UK regions. The aim of this is to overcome the shortcomings of using seven well-spaced sites per region as per the HadUKP series, using values based on a denser network of sites. The likely error bounds associated with the new series will be estimated and compared with estimated error bounds stemming from basing regional values on the outputs from seven sites per region.

The second aim is to provide an analysis of the new rainfall series, at daily to annual timescales and at a regional level, to determine recent trends in mean and extreme rainfall for each of the four meteorological seasons, and to assess whether any of the trends are statistically significant. This work will also build on the statistical analysis carried out by previous papers relating to the HadUKP series, from Wigley et al. (1984) to Alexander and Jones (2001); for more information on these see Section 2.1. This aims to help towards determining whether the observed trends in precipitation across the UK (particularly the increase in winter and decrease in summer) are statistically distinguishable from natural variability.

The literature on climate model analysis (Section 3.5) suggests that the current generation of climate models have problems with precipitation simulation, e.g. the “drizzle effect” where models produce too many small precipitation events. The third objective is thus to produce an analysis of the reliability of individual regional climate models at simulating precipitation across the UK. Similar analysis has previously been done at a Europe-wide level, but the aim here is to perform an in-depth analysis of the strengths and weaknesses of the individual models at simulating the distribution and magnitude of mean and extreme precipitation across the UK, and identify which models appear to be the most accurate regarding precipitation.

The models' simulation of convective as opposed to large scale precipitation (Section 3.2.4), and simulation of precipitation under different atmospheric circulation types, have not been thoroughly explored in the scientific literature and thus one objective is to examine those, with the aim of improving our understanding of the main strengths and weaknesses of current regional climate models.

4. Generation of new monthly and daily UK precipitation series using the Met Office 5km gridded data and the HadUKP precipitation series

4.1 Generation of a regional dataset via the 5km data in the same format as the original HadUKP dataset

This chapter discusses the production of a new UK daily, monthly, seasonal and annual rainfall dataset, in the same format as the HadUKP series, based on the Met Office gridded data from Perry and Hollis (2005a, 2005b). The project began with the use of an earlier version of the dataset spanning 1958-2002, but the Met Office subsequently updated the dataset to address some errors (such as incorrect attribution of daily precipitation at individual sites due to a move towards attributing the previous 24 hours' precipitation from 0900-0900 to the current day rather than the previous day, and some issues with missing data) and provide a full 50-year period for analysis. Masks were generated by the Met Office, corresponding to each of the UK regions from Gregory et al. (1991), enabling the gridded data to be divided up into each of the corresponding regions.

This chapter explores the viability of different methods of producing regional averages based on the gridded data as well as providing regression values and error estimates for the values. The remainder of Section 4.1 covers the methods of averaging the gridded data over a region to produce a mean value, the generation of the new series and correlations between the new MOHC values and the HadUKP values. Section 4.2 specifically covers the generation of the monthly data, and the percentage of daily values that come out within 0.5mm and 1mm of the respective HadUKP values. Section 4.3 covers the regressions between the MOHC and HadUKP series, with the aim of extending the MOHC datasets back before 1958 for daily data and 1914 for monthly data, using regressions against the HadUKP series. Section 4.4 covers the generation of error estimates, based on the regressions given in Section 4.3 and also based on spatial sampling (the limitations of using a limited number of sites to represent a region) and presents samples from the new series.

4.1.1 Methods of averaging the grid boxes to produce a mean value

Daily precipitation values have been extracted from the grids using two methods:
1. Taking an average of the grid boxes corresponding to the stations in a given region that were used to generate the HadUKP series (hereafter AVG7). For this method a set of eastings and northings for each station have been taken from those given by Jones and Conway (1997) and the closest corresponding grid boxes have been located. The associated weights given by Jones and Conway (1997) are not applied as they will have been taken into account in the generation of the grid boxes in MOHC07d.
2. Taking an average of all of the grid boxes within a region (hereafter AVGR).

The aim is to give as close as approximation as possible to the "true" areal values for the UK regions. AVG7 is more consistent with the original method used to generate the HadUKP series and correspondingly, values give a closer approximation to the original HadUKP series. AVGR gives a better representation of the "true" areal precipitation values due to being based on a significantly larger number of stations, reducing the extent of bias towards the drier parts of a region. The results from both methods are analysed but AVGR has been chosen as representing the "true" areal mean when producing the new series.

4.2 The national and regional rainfall series

4.2.1 Generation of the national series

To maintain consistency with the method used to generate national series (England & Wales, Scotland, Northern Ireland) the figures for England & Wales and Scotland are generated by summing weighted values for the constituent regions, using the weights given by Gregory et al. (1991). This method is compared with the method of simple averaging of all of the grid boxes within England & Wales, Scotland and Northern Ireland (Table 4.1 and Table 4.2), and the resulting daily precipitation values are regressed against the corresponding HadUKP values. The use of the weighted averaging method gives rise to considerably higher consistency and higher correlations. The period 1958-1997 is used to avoid issues with inhomogeneities in the HadUKP series since 1997 (see Section 4.3).

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.96	0.95	0.94	0.95	0.92	0.93	0.93	0.96	0.95	0.95	0.94	0.96	0.95
ES	0.99	0.98	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.98	0.98	0.99
SS	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
NWE	0.99	0.98	0.98	0.98	0.97	0.98	0.98	0.98	0.98	0.99	0.98	0.99	0.98
NEE	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99
SWE	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.99	0.99	0.99	0.99	0.99
CEE	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	0.99
SEE	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99
NI	0.98	0.98	0.98	0.98	0.98	0.98	0.97	0.98	0.99	0.99	0.98	0.98	0.98
S	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
EW	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
NI2	0.98	0.98	0.98	0.98	0.98	0.98	0.97	0.98	0.99	0.99	0.98	0.98	0.98
S2	0.99	0.98	0.98	0.97	0.98	0.98	0.97	0.99	0.99	0.98	0.98	0.98	0.98
EW2	0.99	0.98	0.98	0.99	0.98	0.98	0.97	0.98	0.98	0.98	0.98	0.99	0.98

Table 4.1. Correlations for the regions (MOHC07d vs HadUKP) for daily precipitation for each month of the year, plus all days of all months, using AVG7, covering the period 1958-1997. NI, S and EW refer to the values generated by applying the respective weights and NI2, S2 and EW2 refer to the values generated by unweighted averaging of all grid boxes.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.91	0.91	0.90	0.90	0.87	0.88	0.88	0.90	0.90	0.91	0.91	0.90	0.90
ES	0.96	0.95	0.94	0.96	0.96	0.96	0.96	0.96	0.97	0.97	0.95	0.95	0.95
SS	0.98	0.97	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.97	0.98	0.97
NWE	0.98	0.97	0.97	0.97	0.96	0.95	0.96	0.96	0.97	0.97	0.97	0.98	0.96
NEE	0.97	0.97	0.97	0.97	0.97	0.95	0.96	0.96	0.97	0.97	0.98	0.97	0.96
SWE	0.98	0.98	0.98	0.98	0.96	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.97
CEE	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.97	0.98	0.99	0.99	0.99	0.98
SEE	0.98	0.98	0.98	0.97	0.97	0.97	0.96	0.97	0.96	0.98	0.98	0.99	0.97
NI	0.97	0.98	0.98	0.97	0.97	0.98	0.96	0.98	0.98	0.98	0.98	0.98	0.97
S	0.98	0.98	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
EW	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
NI2	0.97	0.98	0.98	0.97	0.97	0.98	0.96	0.98	0.98	0.98	0.98	0.98	0.97
S2	0.96	0.96	0.95	0.96	0.95	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
EW2	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.98

Table 4.2. Correlations for the regions (MOHC07d vs HadUKP) for daily precipitation for each month of the year, plus all days of all months, using AVGR, covering the period 1958-1997. NI, S and EW refer to the values generated by applying the respective weights and NI2, S2 and EW2 refer to the values generated by unweighted averaging of all grid boxes.

For all statistical analysis of relationships between the datasets, days with both datasets giving regional precipitation totals of 0 have been removed from the calculations, due to the potential for those days to cause some bias in the results, e.g. overestimates of the correlation coefficients.

4.2.2 Monthly totals

Monthly totals can be generated either by summing the daily totals from MOHC07d, or by carrying out the same methodology on the monthly (1914-2006) version of the gridded data (hereafter MOHC06m). The two sets of results deviate (Table 4.3), particularly in the UK regions with variable topography, indicating that the two datasets use slightly different interpolation methods. Thus, in all subsequent analysis using monthly precipitation values, the values generated via MOHC06m are used. The seasonal and annual totals are generated by summing the monthly totals.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.95	0.97	0.97	0.96	0.95	0.95	0.92	0.96	0.94	0.95	0.95	0.94	0.91
ES	0.96	0.97	0.95	0.97	0.97	0.98	0.99	0.98	0.99	0.98	0.98	0.98	0.96
SS	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.98
NWE	0.99	0.99	0.98	0.98	0.98	0.97	0.98	0.99	0.98	0.98	0.99	0.98	0.96
NEE	0.98	0.98	0.99	0.98	0.98	0.98	0.97	0.98	0.98	0.98	0.99	0.98	0.96
SWE	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.96
CEE	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.97	0.99	0.99	0.99	0.99	0.98
SEE	0.99	0.99	0.99	0.99	0.99	0.99	0.97	0.98	0.99	0.99	0.99	0.99	0.98
NI	0.97	0.99	0.98	0.99	0.98	0.97	0.98	0.99	0.99	0.98	0.98	0.99	0.92
S	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.97
EW	1.00	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.99

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.97	0.98	0.97	0.96	0.96	0.95	0.93	0.96	0.95	0.94	0.95	0.95	0.93
ES	0.95	0.97	0.94	0.96	0.97	0.99	0.98	0.98	0.99	0.97	0.98	0.97	0.96
SS	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.98
NWE	0.99	0.99	0.98	0.99	0.99	0.97	0.99	0.98	0.98	0.98	0.99	0.99	0.97
NEE	0.98	0.97	0.99	0.98	0.99	0.99	0.97	0.98	0.99	0.99	0.99	0.99	0.98
SWE	0.99	0.99	0.98	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.95
CEE	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.99
SEE	0.99	0.99	0.99	0.99	0.99	0.99	0.97	0.98	0.99	0.99	0.99	0.99	0.98
NI	0.98	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.96
S	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.97
EW	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	0.99	0.99

Table 4.3. Correlations for the regions for monthly and seasonal monthly precipitation, between HadUKP and the MOHC06m values (top) and the aggregated MOHC07d daily values (bottom) covering the period for which sets of values are available up to and including 1997, using AVGR.

4.2.3 The percentage of daily regional values within 0.5mm and 1mm

This analysis compares the percentage of daily values within 0.5 and 1mm when comparing the newly generated values from the 5km dataset with those from the HadUKP dataset, in the same manner as the Alexander and Jones (2001) method of assessing the accuracy of the Met Office's alternative continuation of the HadUKP dataset. Pairs of values for which both MOHC07d and HadUKP are equal to zero have been removed as they would provide a positive bias in the percentage of values within 0.5mm and 1mm. Using AVG7 (Fig 4.1) gives the highest accordances, supporting the correlations results given earlier. For NS, 72% of all values are within 1mm and 55% are within 0.5mm, while other regions have 85% or more within 1mm and 69% or more within 0.5mm. This suggests that there is good accordance between the grid boxes corresponding to the HadUKP stations and the actual values from the stations.

Using AVGR (Fig 4.2), the results indicate lower accordance with the original HadUKP values, again consistent with the results of the correlations analysis. For NS, 56% of all values are within 1mm and 40% are within 0.5mm, while only EW, CEE and SEE have at least 85% of values within 1mm and 70% within 0.5mm. The consistently lower results for NS probably stem from the variable topography, sparse station network, and the fact that the region is wetter than the other UK regions (meaning that even if the percentage differentials are consistent with those of the other regions, absolute differences are greater due to greater absolute totals).

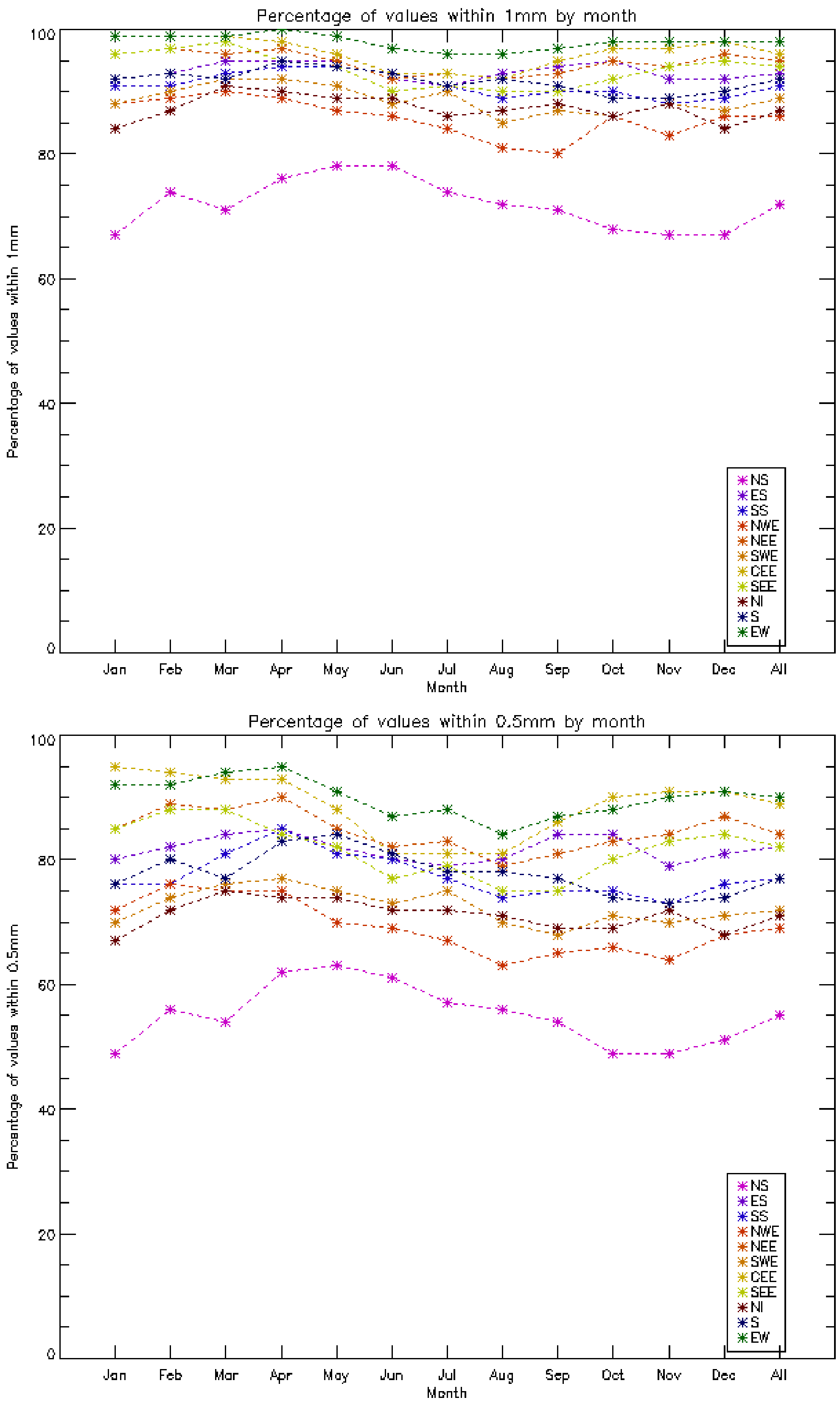
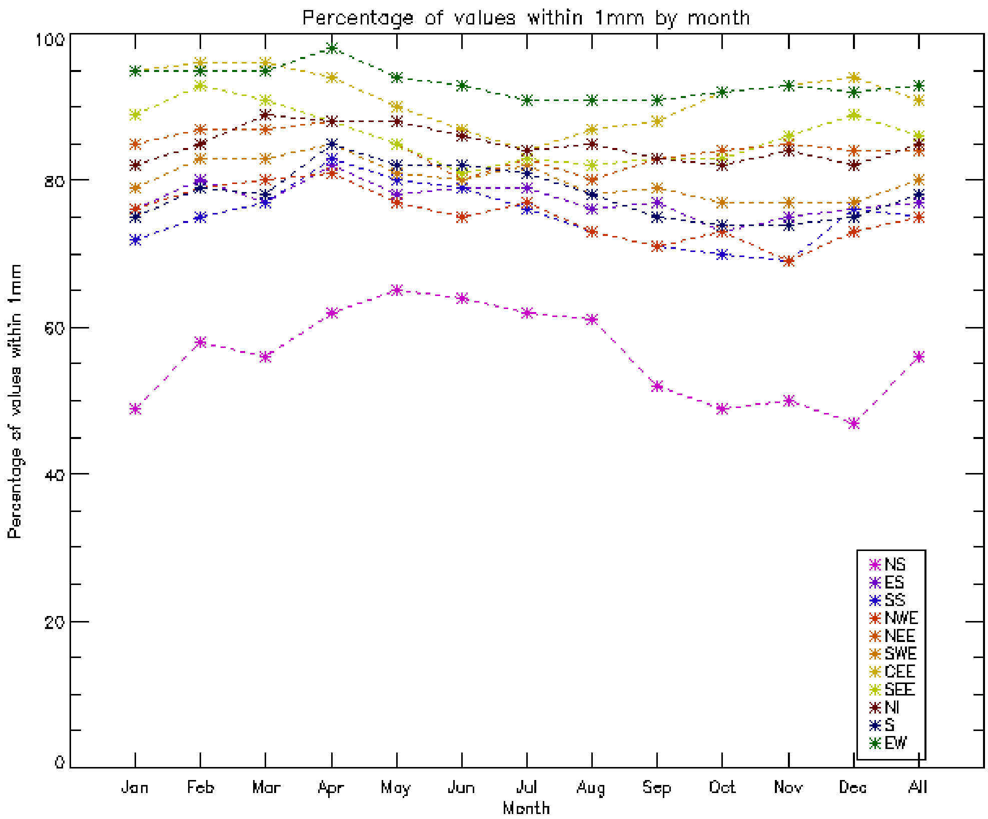


Fig 4.1. Percentage of daily values within 1mm (top) and 0.5mm (bottom) using AVG7 over the period 1958-1997, for each region, for each individual month of the year plus all days of all months, excluding dry days. NS (pink) shows less agreement between MOHC07d and HadUKP than the other regions.



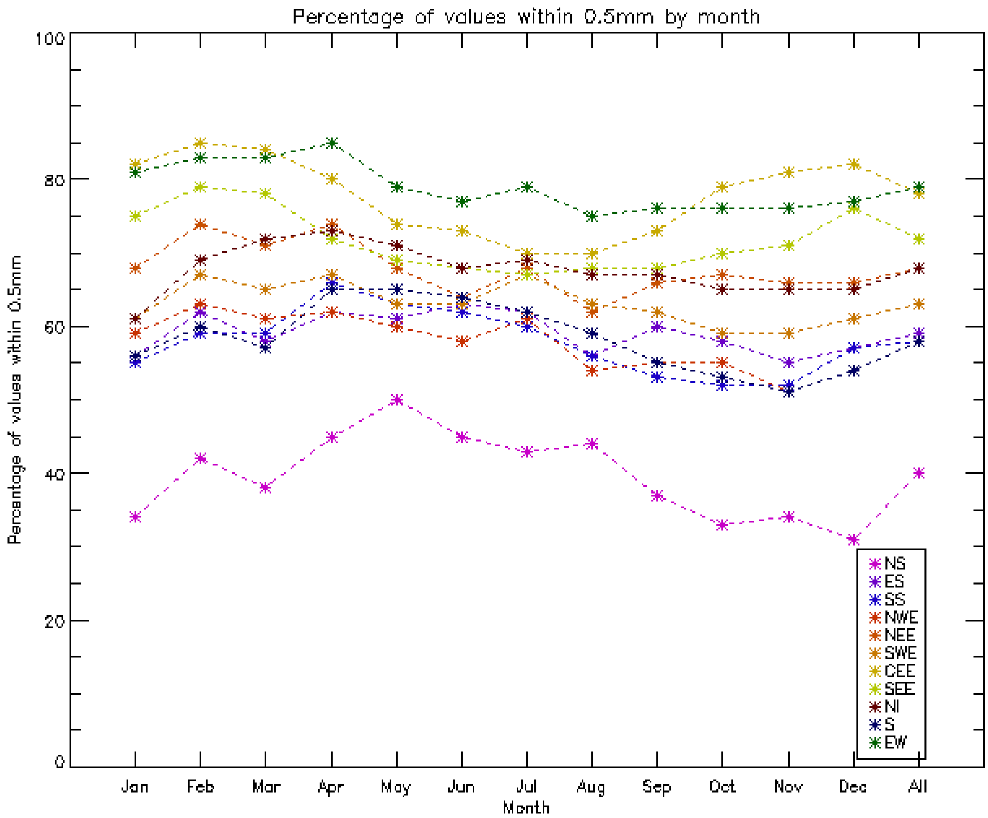
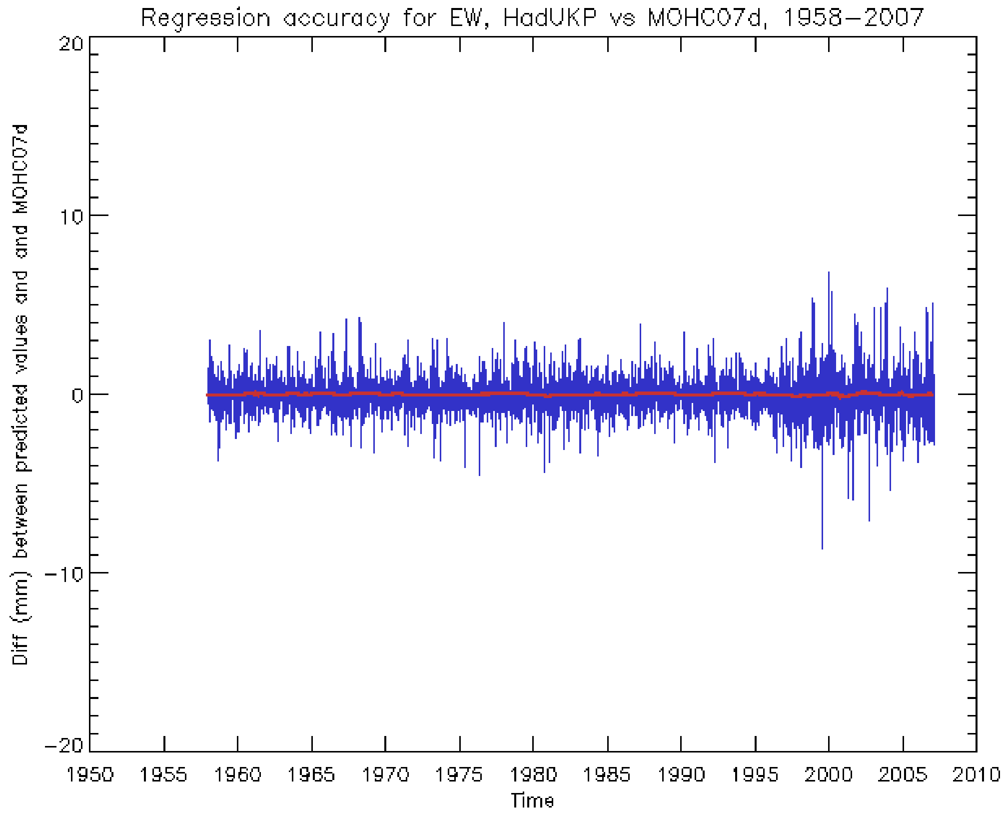


Fig 4.2. Percentage of daily values within 1mm (top) and 0.5mm (bottom) using AVGR over the period 1958-1997, for each region, for each individual month of the year plus all days of all months, excluding dry days. NS (pink) shows less agreement between MOHC07d and HadUKP than the other regions.

4.3 Regression analysis

In addition to providing daily, monthly, seasonal and annual rainfall values based on a combination of MOHC07d and MOHC06m, it is also desirable to extend the series back as far as HadUKP goes (in instances where HadUKP data extends further back than the Met Office gridded data). For this, regressions were generated of the form (MOHC07d = a(HadUKP)) and (MOHC06m = a(HadUKP)) for each of the regions, comparing the results from MOHC07d and MOHC06m with those from the original HadUKP dataset. The new series based on MOHC07d and MOHC06m are then extended back as far as HadUKP extends, using the values in the regressions. The regressions are based on the period 1958-1997 for daily values, 1914-1997 for monthly values for England and Wales and its constituent regions, and 1931-1997 for monthly values for Scotland, the Scottish regions and Northern Ireland (as monthly HadUKP data only exists back to 1931 outside of England and Wales). Intercepts for the regressions are fixed at zero, to avoid the unrealistic scenario of non-zero precipitation totals being given for days with zero precipitation in the HadUKP series (although this method also has imperfections, e.g. on days with sporadic precipitation, a complete areal coverage may result in a non-zero total, while HadUKP may return zero due to the precipitation missing the seven or fewer stations that were used to generate the HadUKP values).

The regressions only cover the periods up to and including 1997, rather than 2007, because the methodology for the generation of the HadUKP dataset was changed over to a real-time updating method used by the Met Office, detailed by Alexander and Jones (2001). The correlations between the daily rainfall totals generated from MOHC07d and the HadUKP values up to 1997 are significantly larger than those between the post-1997 method of generating the HadUKP series, as given by Alexander and Jones (2001), and the original method (Fig 4.3).



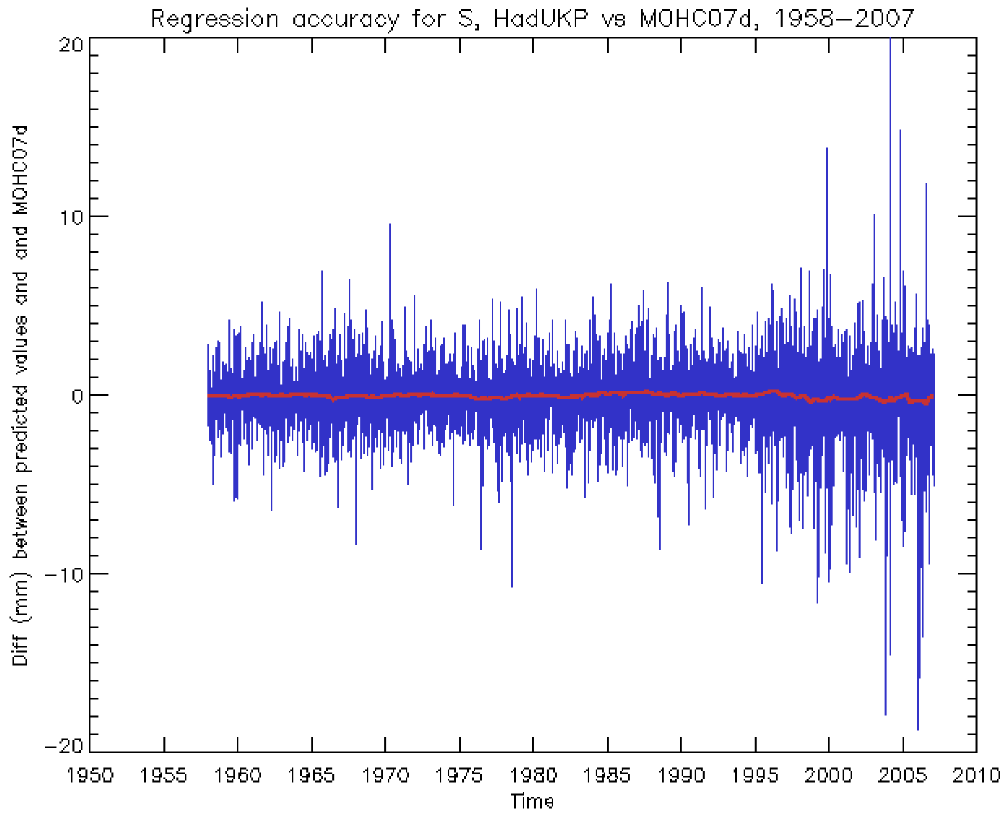


*Fig 4.3. Regression accuracy expressed as the difference between the regression gradient * HadUKP and MOHC07d, using AVGR, for England and Wales (top) and Scotland (bottom). There is a clear decline in accuracy after 1997.*

4.3.1 Regression results

The results of the regressions using AVG7 (Table 4.4) again suggest that the grid boxes of MOHC07d corresponding to the stations used to generate the HadUKP series are in strong accordance, though gradients of approximately 0.9 for SEE suggest that the MOHC07d grids give lower mean daily precipitation totals for the sites within SEE. The results using AVGR (Table 4.5) strongly suggest that both MOHC07d and MOHC06m produce significantly higher mean daily precipitation totals than HadUKP in regions that have variable topography. The difference is largest for the ES region, with gradients between October and March inclusive exceeding 1.3 for the daily data, and the gradient for April also exceeds 1.3 for the monthly data. The deviation from 1 is greatest during the winter months and smallest during the summer months. The statistics for NWE exhibit the same behaviour but the deviations from 1 are less extreme, ranging from 1.08 to 1.26 for the daily data. Results for monthly regressions (Table 4.6 and Table 4.7) are similar to those for daily regressions, though with some small differences, e.g. using AVGR, CEE and SEE do not come out substantially drier than in the HadUKP series, suggesting that the regressions and the increased precipitation in ES and NWE is even more marked.

This supports the hypothesis that the methodology of using seven well spaced stations across the region as per HadUKP has led to the stations in ES and NWE, and to a lesser extent SWE (which give gradients close to 1.1 for most months) being biased towards the drier parts of those regions. The results for ES and NWE strongly suggest topographical influences due to the bias being larger in the winter months, when orographic enhancement accounts for a larger proportion of the rainfall totals in upland areas. The SS and NS regions do not show this behaviour, with gradients consistently close to 1, suggesting that the seven sites chosen in those regions for HadUKP were representative of the region as a whole.

CEE and SEE are the only two regions to consistently produce gradients below 1, and the difference is larger when the AVG7 method was used. This implies that the use of the Met Office gridded data results in less precipitation being produced over the areas of CEE and SEE corresponding to the seven sites used in HadUKP, rather than those seven sites being unrepresentative of the regions as a whole.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	1.01	1.03	0.99	1.05	0.97	1.04	1.05	1.01	0.99	1.01	1.02	1.00	1.01
ES	1.05	1.03	1.03	1.06	1.04	1.03	1.06	1.06	1.03	1.05	1.03	1.02	1.04
SS	1.00	1.01	1.00	1.01	1.01	0.98	0.99	1.01	0.99	0.99	1.01	1.01	1.00
NWE	0.97	1.02	1.03	1.04	1.03	1.04	1.07	1.03	1.04	1.02	1.03	1.01	1.02
NEE	0.97	0.95	0.98	1.00	0.98	0.99	1.00	0.98	0.98	0.99	0.97	0.95	0.98
SWE	1.03	1.03	1.00	1.08	1.05	1.03	1.03	1.05	1.00	0.98	1.01	1.02	1.02
CEE	0.97	1.00	0.98	0.95	0.97	0.98	0.94	0.93	0.97	0.96	0.97	0.99	0.97
SEE	0.89	0.89	0.91	0.93	0.93	0.92	0.91	0.89	0.92	0.90	0.90	0.91	0.91
NI	1.07	1.06	1.04	1.01	1.05	0.99	0.99	1.01	1.01	1.00	1.02	1.08	1.03
S	1.03	1.04	1.03	1.05	1.03	1.04	1.05	1.04	1.02	1.03	1.03	1.03	1.03
EW	0.98	1.00	0.99	1.01	1.00	1.00	1.00	0.99	0.99	0.98	0.99	0.99	0.99

Table 4.4. Regression gradients of the form (MOHC07d = a[HadUKP]) for each region, using the period 1958 to 1997, using AVG7.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	1.06	1.10	1.03	1.01	0.98	1.01	0.93	0.96	0.98	1.01	1.07	1.05	1.02
ES	1.34	1.34	1.31	1.25	1.18	1.13	1.13	1.15	1.23	1.32	1.33	1.30	1.25
SS	1.03	1.02	1.03	1.05	1.04	1.01	1.01	1.03	1.00	1.01	1.01	1.03	1.02
NWE	1.20	1.26	1.24	1.21	1.14	1.08	1.10	1.13	1.16	1.17	1.20	1.22	1.18
NEE	1.01	1.02	1.01	1.00	0.98	0.98	0.99	0.99	1.02	1.01	0.99	1.01	1.00
SWE	1.06	1.06	1.04	1.06	1.07	1.06	1.03	1.08	1.09	1.06	1.06	1.07	1.06
CEE	0.98	0.98	0.96	0.95	0.91	0.96	0.92	0.92	0.96	0.97	0.98	0.98	0.95
SEE	0.95	0.95	0.95	0.93	0.89	0.92	0.90	0.89	0.95	0.93	0.94	0.95	0.93
NI	1.04	1.03	1.00	1.00	1.01	0.98	0.97	1.01	0.98	0.99	0.98	1.03	1.00
S	1.16	1.18	1.15	1.16	1.13	1.11	1.08	1.10	1.11	1.14	1.16	1.15	1.14
EW	1.07	1.08	1.06	1.06	1.04	1.04	1.03	1.04	1.06	1.07	1.07	1.07	1.06

Table 4.5. Regression gradients of the form (MOHC07d = a[HadUKP]) for each region, using the period 1958 to 1997, using AVGR.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.99	0.99	0.99	1.04	1.01	1.04	1.07	1.03	1.01	1.00	1.00	1.00	1.01
ES	1.03	1.02	1.02	1.07	1.02	1.03	1.06	1.03	1.01	1.03	1.02	1.02	1.03
SS	1.01	1.01	1.01	1.00	1.01	0.99	1.00	1.01	1.01	1.00	1.01	1.01	1.01
NWE	0.99	1.03	1.03	1.06	1.05	1.04	1.07	1.04	1.04	1.02	1.03	1.01	1.03
NEE	0.97	0.97	0.97	0.98	0.98	1.00	1.00	0.98	0.98	0.99	0.96	0.97	0.98
SWE	1.04	1.04	1.03	1.06	1.06	1.06	1.06	1.07	1.05	1.05	1.04	1.04	1.05
CEE	0.98	1.00	0.98	0.97	0.99	1.00	0.98	0.96	0.99	0.98	0.98	0.99	0.98
SEE	0.90	0.91	0.93	0.94	0.94	0.95	0.94	0.93	0.93	0.91	0.90	0.93	0.92
NI	1.05	1.03	1.00	1.02	1.02	0.98	0.98	0.99	1.01	1.00	1.02	1.06	1.01
S	1.01	1.01	1.01	1.04	1.02	1.02	1.04	1.02	1.01	1.01	1.01	1.01	1.02
EW	1.00	1.01	1.00	1.01	1.01	1.02	1.02	1.01	1.02	1.01	1.00	1.01	1.01

Table 4.6. Regression gradients of the form (MOHC06m = a[HadUKP]) for each region, using the period 1914 to 1997 for regions within England and Wales and 1931 to 1997 for the Scottish regions and Northern Ireland using AVG7.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	1.04	1.06	1.05	1.08	1.04	1.01	1.03	1.00	1.00	1.02	1.06	1.04	1.04
ES	1.38	1.37	1.37	1.32	1.23	1.19	1.18	1.18	1.25	1.33	1.34	1.36	1.30
SS	1.02	1.02	1.02	1.02	1.04	1.02	1.04	1.04	1.02	1.01	1.04	1.03	1.03
NWE	1.24	1.29	1.28	1.24	1.20	1.16	1.16	1.15	1.20	1.21	1.26	1.25	1.23
NEE	1.05	1.03	1.03	1.03	1.02	1.01	1.03	1.03	1.03	1.05	1.02	1.05	1.04
SWE	1.06	1.06	1.05	1.07	1.09	1.08	1.11	1.09	1.08	1.08	1.07	1.07	1.08
CEE	1.00	1.00	0.99	0.99	0.98	1.01	0.99	0.98	1.00	1.01	1.01	1.01	1.00
SEE	0.97	0.99	0.97	0.99	0.96	0.97	0.98	0.97	0.97	0.98	0.98	0.99	0.98
NI	1.03	1.03	0.99	0.99	1.01	0.96	0.98	0.98	0.98	0.98	0.98	1.02	0.99
S	1.13	1.13	1.13	1.14	1.12	1.08	1.09	1.08	1.08	1.11	1.13	1.12	1.12
EW	1.08	1.08	1.07	1.06	1.06	1.05	1.07	1.06	1.07	1.08	1.08	1.09	1.07

Table 4.7. Regression gradients of the form (MOHC06m = a[HadUKP]) for each region, using the period 1914 to 1997 for regions within England and Wales and 1931 to 1997 for the Scottish regions and Northern Ireland using AVGR.

4.4 Error estimates

4.4.1 Generation of error estimates for the regression values from daily to annual timescales

Error bars have been calculated based on the regressions for daily, monthly and seasonal timescales. The errors from regression are calculated using the standard equation

$$SE = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

These errors only apply to the years for which data are available for HadUKP but not MOHC07d (or MOHC06m for analysis of the monthly data), because the MOHC07d/MOHC06m values are accepted as “true” values for the areal mean. The standard errors have been scaled by multiplying by the mean precipitation total, and error estimates have been developed using both AVG7 and AVGR in the case of MOHC07d. Error bars have also been calculated for the gradients used for the regressions, for the method that takes the average of seven grid boxes with pairs of values that are equal to zero ignored.

The errors have been generated using least squares regression, based on calculating the least squares estimate of the variation either side of the regression lines.

$$y_i = ax_i$$

where y_i is the gradient of the line (it is assumed that any additional noise is normally distributed), and the standard error has been generated using the following equations:

$$\hat{a} = \frac{\sum x_i y_i}{\sum x_i^2}$$

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (\hat{a}x_i - y_i)^2$$

$$SE = \frac{\sigma}{\sqrt{\sum x_i^2}}$$

4.4.2 Results of error estimates

Daily error estimates (Fig 4.4) using AVG7 are below 1mm for all regions with the exceptions of NWE, where error estimates exceed 1mm in the case of August, and NS, where error estimates exceed 2.5mm during the winter half-year. Using AVGR the error estimates are consistently larger, approaching 3mm for NS during the winter half-year, but other regions consistently produce error estimates between 0.5mm and 1.5mm. The larger error estimates using AVGR are probably due to not maintain collocation. Mean standard error estimates for the monthly precipitation totals (Fig 4.5), using AVG7, are less than 10mm for all regions with the exception of NS, which produced error estimates closer to 15mm during the winter half-year. The estimated standard errors of the slopes in the regressions are less than 2mm in the case of all regions except NS, and were less than 1mm in the cases of CEE, SEE and EW. Using AVGR, error estimates are again slightly larger. Mean standard error estimates for the monthly precipitation values are again below 10mm for all regions except NS, where they exceed 20mm in the winter half-year. The estimated standard errors of the slopes in the regressions are below 2mm for CEE, SEE, NEE and EW, but exceeded 5mm for NS in January, July and September-December.

Seasonal and annual totals have larger error bars, with larger error bars for winter and autumn than for spring and summer, with NS again having a much larger error than the other regions. Daily error estimates for AVGR (Table 4.9) are below 2mm for all regions with the exception of NS which exceeded 2.5mm during the winter half-year. The Scottish regions consistently show greater seasonal variation in error magnitudes than the England and Wales regions, with a maximum in winter and minimum in summer, reflecting the greater precipitation amounts and variability in the Scottish regions in winter.

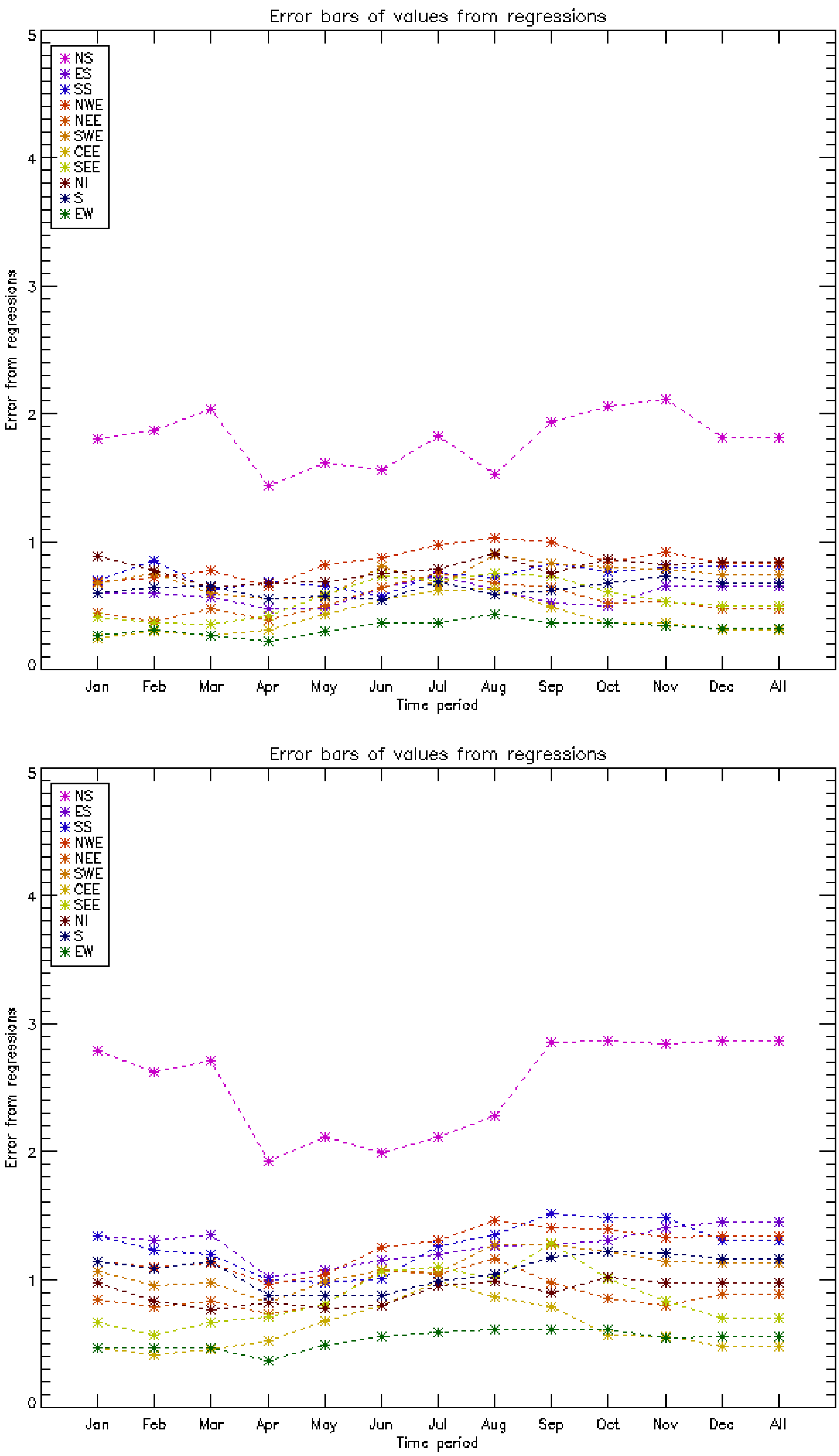
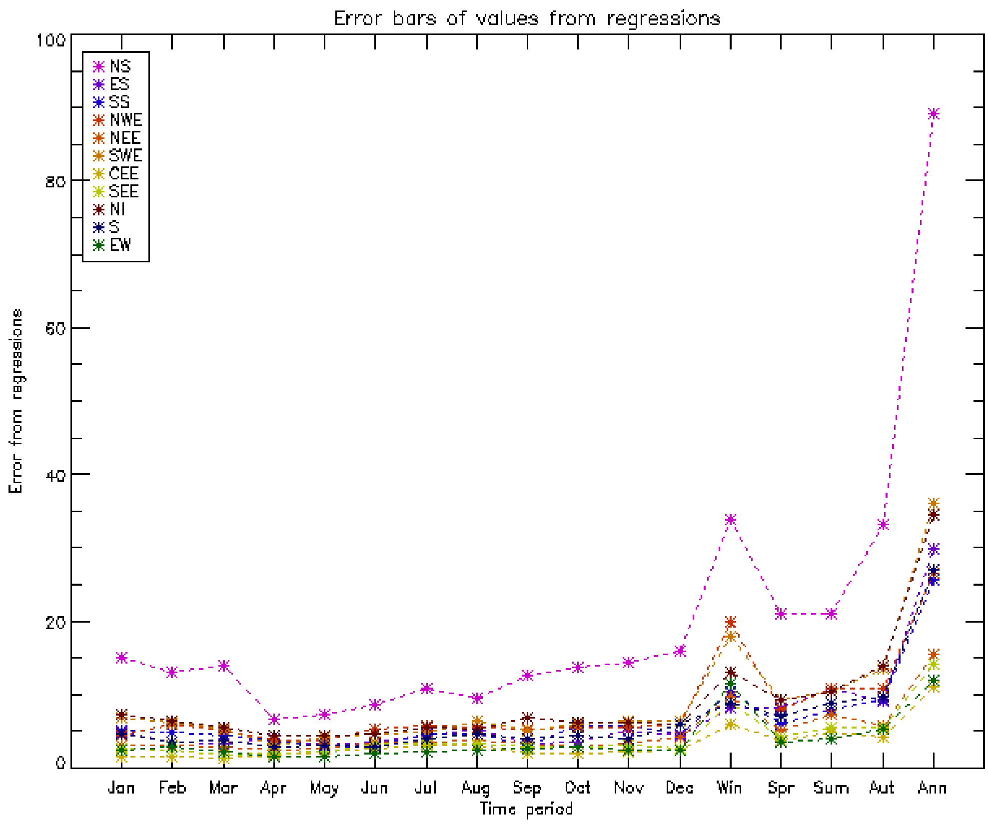


Fig 4.4. Error bar estimates (mm) of the regression values obtained by applying the regression gradients to HadUKP daily data, using AVG7 (top) and AVGR (bottom).



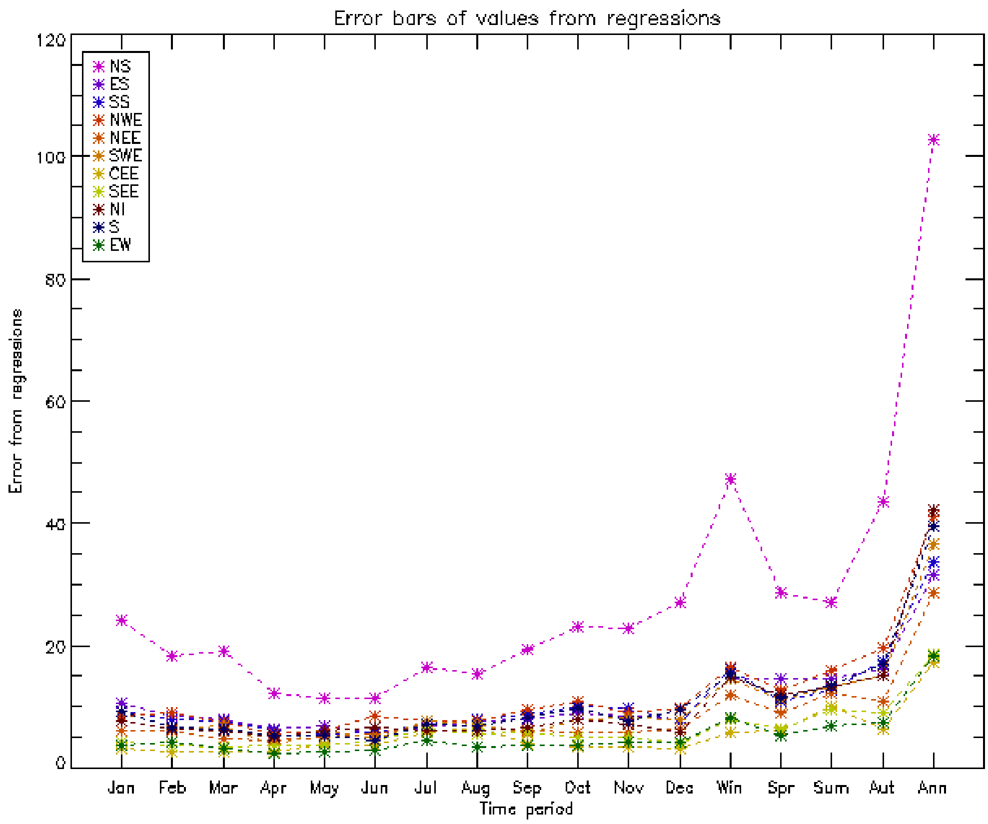


Fig 4.5. Error bar estimates of the regression values obtained by applying the regression gradients to HadUKP monthly data, using AVG7 (top) and AVGR (bottom).

The error bars for the gradients for daily precipitation values are smaller than those for the precipitation values. For daily precipitation values, error estimates are below 0.1mm for all regions, regardless of whether AVG7 or AVGR is used (Table 4.8 and Table 4.9 respectively). For monthly values, error estimates are below 2mm for all regions except NS when AVG7 is used (Table 4.10), with consistently higher values for NS, but the other topographically variable regions produce some higher values also when AVGR is used (Table 4.11). Again, the higher values using AVGR are probably due to not maintaining collocation with respect to the original HadUKP series.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.07	0.08	0.08	0.08	0.08	0.08
ES	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
SS	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.05	0.04	0.04	0.04	0.04
NWE	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
NEE	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.03	0.02	0.02	0.03	0.03
SWE	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03
CEE	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.01
SEE	0.02	0.02	0.02	0.02	0.03	0.04	0.04	0.03	0.04	0.03	0.02	0.02	0.02
NI	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
S	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03
EW	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table 4.8. Error estimates for the gradients for daily precipitation values from regressions based on MOHC07d, using AVG7.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
NS	0.07	0.07	0.07	0.04	0.04	0.05	0.05	0.05	0.07	0.08	0.08	0.08	0.08
ES	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
SS	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.03
NWE	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NEE	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
SWE	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
CEE	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
SEE	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.01	0.01
NI	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
S	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03
EW	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 4.9. Error estimates for the gradients for daily precipitation values from regressions based on MOHC07d, using AVGR.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
NS	4.44	2.99	3.31	1.91	2.07	2.74	3.90	2.72	4.25	4.39	4.38	5.17	74.54
ES	1.58	0.92	1.10	1.14	0.89	0.93	1.19	1.33	0.80	0.97	1.38	1.51	32.43
SS	1.56	1.07	1.20	1.02	0.76	1.03	1.62	1.18	0.91	1.66	1.60	1.41	25.57
NWE	1.19	1.12	1.13	0.99	0.97	1.22	1.60	1.36	1.25	1.30	1.40	1.56	23.57
NEE	0.85	0.69	0.63	0.56	0.60	0.69	0.87	0.89	0.68	0.71	0.80	1.12	14.49
SWE	1.80	1.15	1.10	0.73	1.00	0.98	1.10	1.52	1.12	1.45	1.55	1.61	32.94
CEE	0.44	0.33	0.27	0.44	0.50	0.52	0.78	0.79	0.42	0.46	0.56	0.58	9.15
SEE	0.63	0.43	0.31	0.45	0.54	0.64	0.80	0.74	0.54	0.53	0.65	0.59	10.47
NI	2.94	1.66	1.76	1.28	1.23	1.33	1.74	1.49	1.98	2.05	2.12	2.30	41.92
S	1.56	0.90	1.22	0.94	0.97	1.02	1.45	1.31	1.36	1.47	1.28	2.11	31.03
EW	0.68	0.58	0.46	0.38	0.42	0.43	0.62	0.66	0.60	0.73	0.62	0.68	11.55

Table 4.10. Error estimates for the gradients for monthly precipitation values from regressions based on MOHC06m, using AVG7.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
NS	7.12	4.17	4.54	3.56	3.19	3.59	5.88	4.35	6.51	7.35	6.93	8.73	85.92
ES	3.52	2.24	2.77	1.78	1.98	1.49	1.76	1.94	1.96	2.44	2.24	2.64	34.46
SS	2.81	1.78	2.08	1.65	1.52	1.89	2.53	2.02	2.53	2.95	2.73	2.28	33.46
NWE	2.32	1.72	1.69	1.49	1.58	1.97	2.13	1.94	2.25	2.56	2.32	2.56	36.50
NEE	1.73	1.35	1.07	1.08	1.20	1.11	1.73	1.61	1.30	1.45	1.47	1.77	26.67
SWE	2.05	1.21	1.40	0.91	1.42	1.00	1.76	1.70	1.22	1.94	1.98	2.04	33.27
CEE	0.89	0.56	0.51	0.63	0.93	0.74	1.40	1.62	0.80	0.79	0.92	0.75	14.18
SEE	1.02	0.64	0.62	0.86	0.86	0.90	1.53	1.27	1.10	0.98	1.03	0.86	13.81
NI	3.12	1.63	1.87	1.45	1.69	1.97	1.99	1.71	1.96	2.59	2.46	2.24	51.23
S	3.17	1.69	2.03	1.73	1.69	1.52	2.57	1.98	2.70	3.38	2.42	3.41	45.47
EW	1.06	0.86	0.69	0.65	0.68	0.68	1.23	0.92	0.82	0.98	1.09	1.14	17.88

Table 4.11. Error estimates for the gradients for monthly precipitation values from regressions based on MOHC06m, using AVGR.

4.4.3 Estimation of errors based on spatial degrees of freedom and inter-site correlations

Here, an alternative method of assessing errors is analysed, based on the limitations of using a limited number of sites across a region to give an approximation of the "true" areal mean. This method is then used to compare the standard errors associated with regressing the new MOHC series against the HadUKP series with those stemming from the use of a limited sample of stations to generate the HadUKP series. When using a finite number of sites to estimate an areal mean of a variable, the number of sites that are required to generate a certain level of reliability is dependent on the effective number of independent sites over the area, N_{eff}, which has been referred to as "spatial degrees of freedom" (Jones et al., 1997). The concept is that the mean of a small sample of independent points can be used to give a good approximation of a mean regional value, but if the points are co-dependent then the results may be less reliable as a result. The value of N_{eff} is dependent on the timescale used, as N_{eff} generally decreases as the timescale is increased. The concept of spatial degrees of freedom is explained in detail by Jones et al. (1997). The standard error of an areal average of precipitation is dependent on the standard deviation of the areal series, which in turn is dependent on the mean inter-site correlation (Wigley et al., 1984, Jones et al., 1997). Standard errors based on spatial degrees of freedom were calculated for each month for each region, separately for daily and monthly data, using the following formula from Jones et al. (1997):

$$SE^2 = \frac{\overline{S_i^2}\,\bar{r}(1-\bar{r})}{1+(n-1)\bar{r}}$$

where S_i^2 is the square of the mean single-site precipitation standard deviation, $\bar{r}$ is the mean inter-site correlation, and n is the number of sites used (in this case 7). The mean inter-site correlation was calculated in each case using the seven grid boxes per region that were compared within the gridded data, as the grid boxes correspond to locations of rain gauges that were used to generate the HadUKP precipitation series. The value of $\overline{S_i^2}$ was estimated using the following equation:

$$\overline{S_i^2} = \frac{\hat{S}^2 n}{1+(n-1)\bar{r}}$$

The value is only an estimate because the value of s, the "true" standard deviation of the areal series, was unavailable, so the grid-box standard deviation, $\hat{s}$, has been used instead, based on a 1961-90 reference period. Standard errors have been generated for daily, monthly, seasonal and annual values for MOHC07d. The mean inter-site correlations were plotted over different timescales, using 1, 5, 10, 20 day and month-long day periods using AVG7 (Fig 4.6). The timescale used shows a small positive relationship with $\bar{r}$, with the most consistent increase occurring when the time period used is increased beyond 20 days. Mean inter-site correlations generally range from 0.5 for EW and S to 0.8 for NI, SS and SEE, and the extent of spatial coverage is negatively related to the magnitude of the mean inter-site correlations due to regional variations in rainfall. NS comes out with relatively low values, probably due to the large topographical variation and the strong orographic forcing that characterises the region resulting in variation between the west and east. Using AVGR (Fig 4.8) mean inter-site correlations are very similar to those using AVG7, but there is no evidence of an increase in correlations as the time period is increased, presumably due to the extensive regional coverage.

Standard errors using AVG7 (Fig 4.7) increase as the time period is increased, with evidence of an approximately linear relationship, and errors are lower than the errors that result from regression as discussed in section 4.4.2. England and Wales and Scotland produce the smallest errors, due to the relatively low mean inter-site correlations being more than offset by the regions being based on a larger number of sites (35 and 21 respectively, as opposed to 7 sites for the other regions). NS, which also produced low mean inter-site correlations, correspondingly produces the highest standard errors. Using AVG7, the errors derived from the mean inter-site correlations are generally higher than those stemming from regressions derived using AVG7, except for Scotland and England and Wales, and are similar to those generated from regressions derived using AVGR. Using AVGR (Fig 4.9), errors are considerably smaller because of the increased sample size, and errors are below 2mm for all regions regardless of the timescale used, and remain below 1mm until the time period is increased beyond 10 days. The errors are considerably smaller than those stemming from the regressions generated using AVGR. Monthly mean inter-site correlations using MOHC06m are shown in Fig 4.10, and associated standard errors in Fig 4.11, and the results are very similar to those for monthly time periods using MOHC07d.

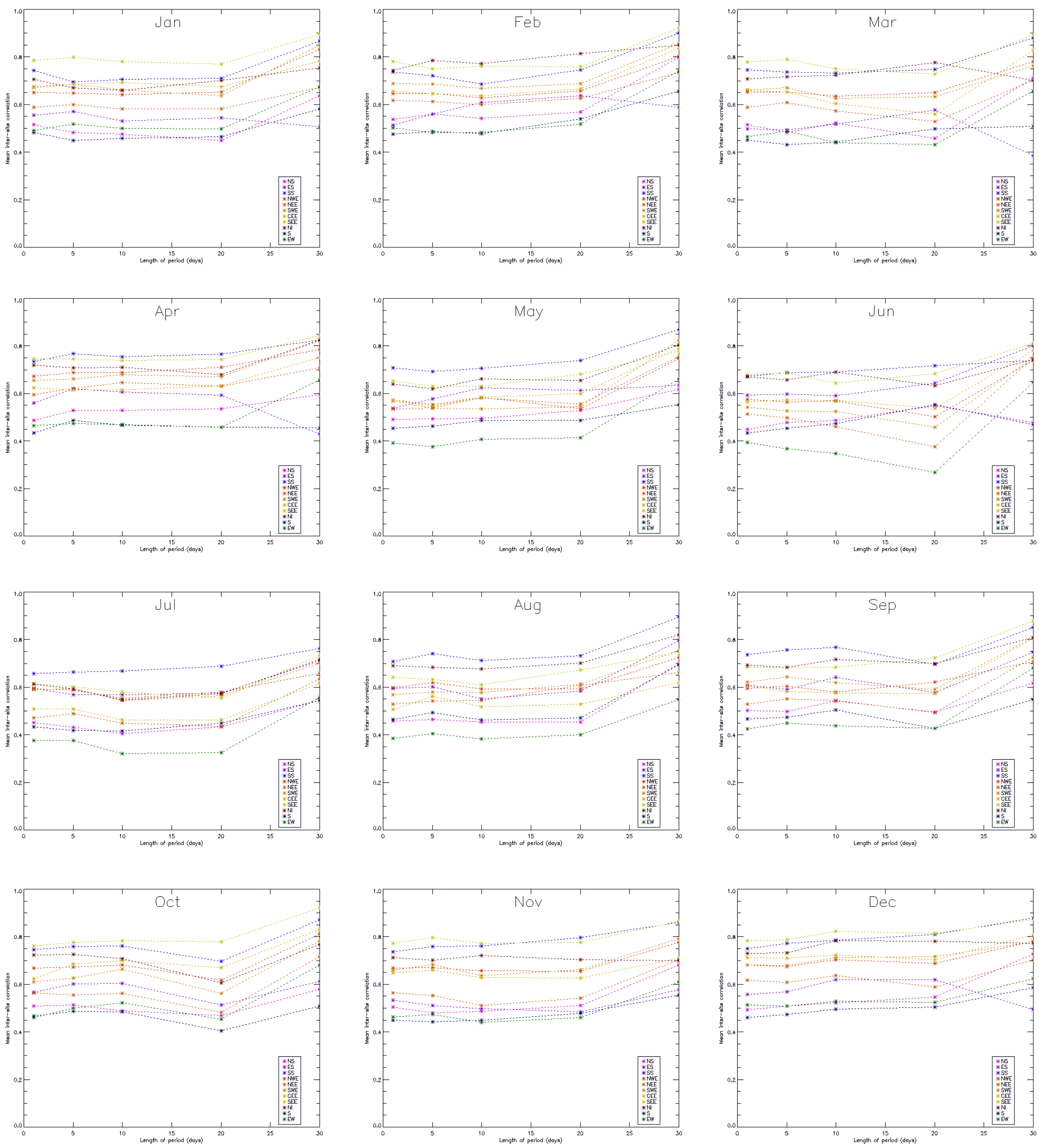


Fig 4.6. Mean inter-site correlations for each of the UK regions by month, for 1, 5, 10, 20 day and month-long periods, using AVG7.

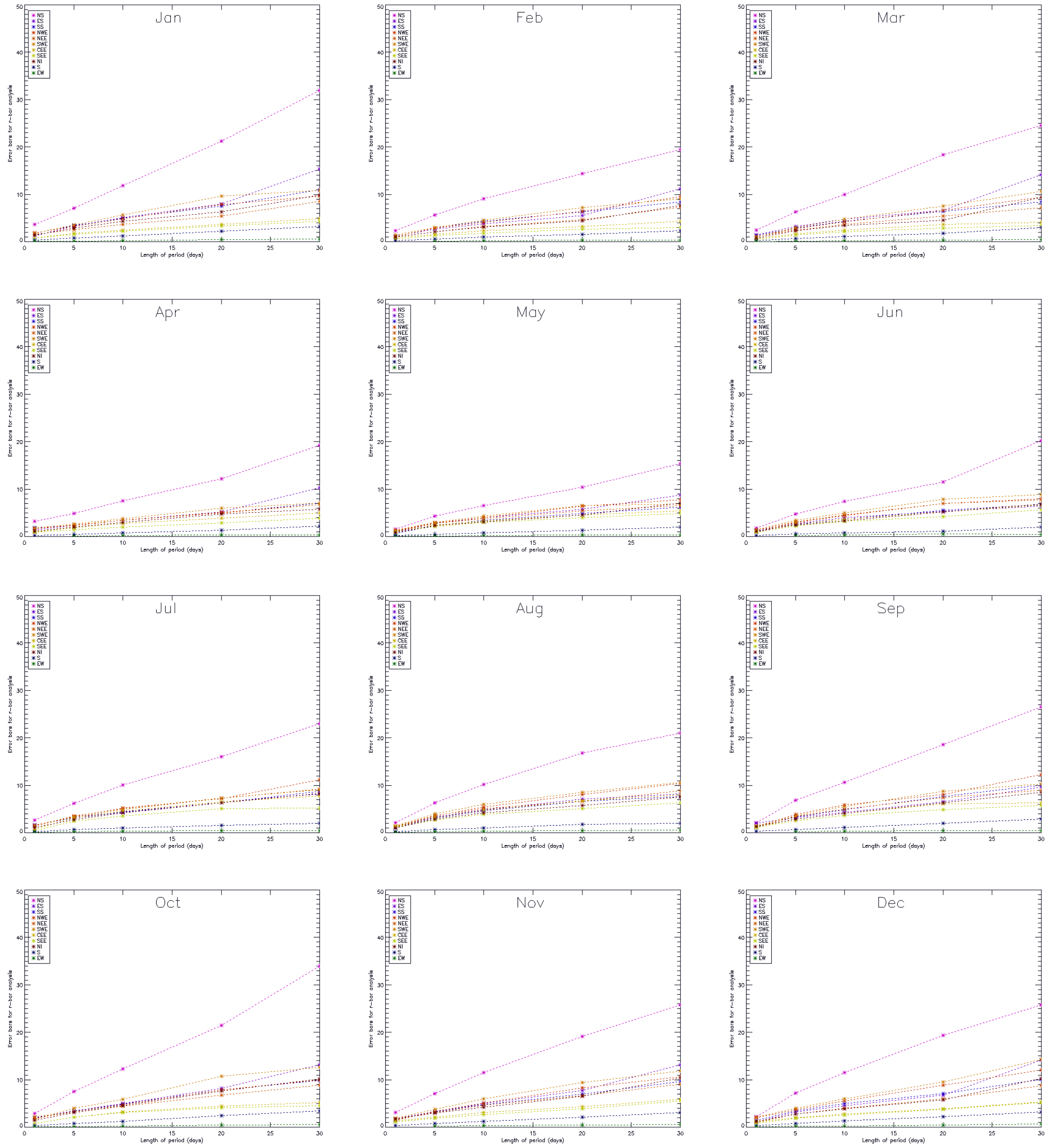


Fig 4.7. Mean inter-site correlations for each of the UK regions by month, for 1, 5, 10, 20 day and month-long periods, using AVGR.

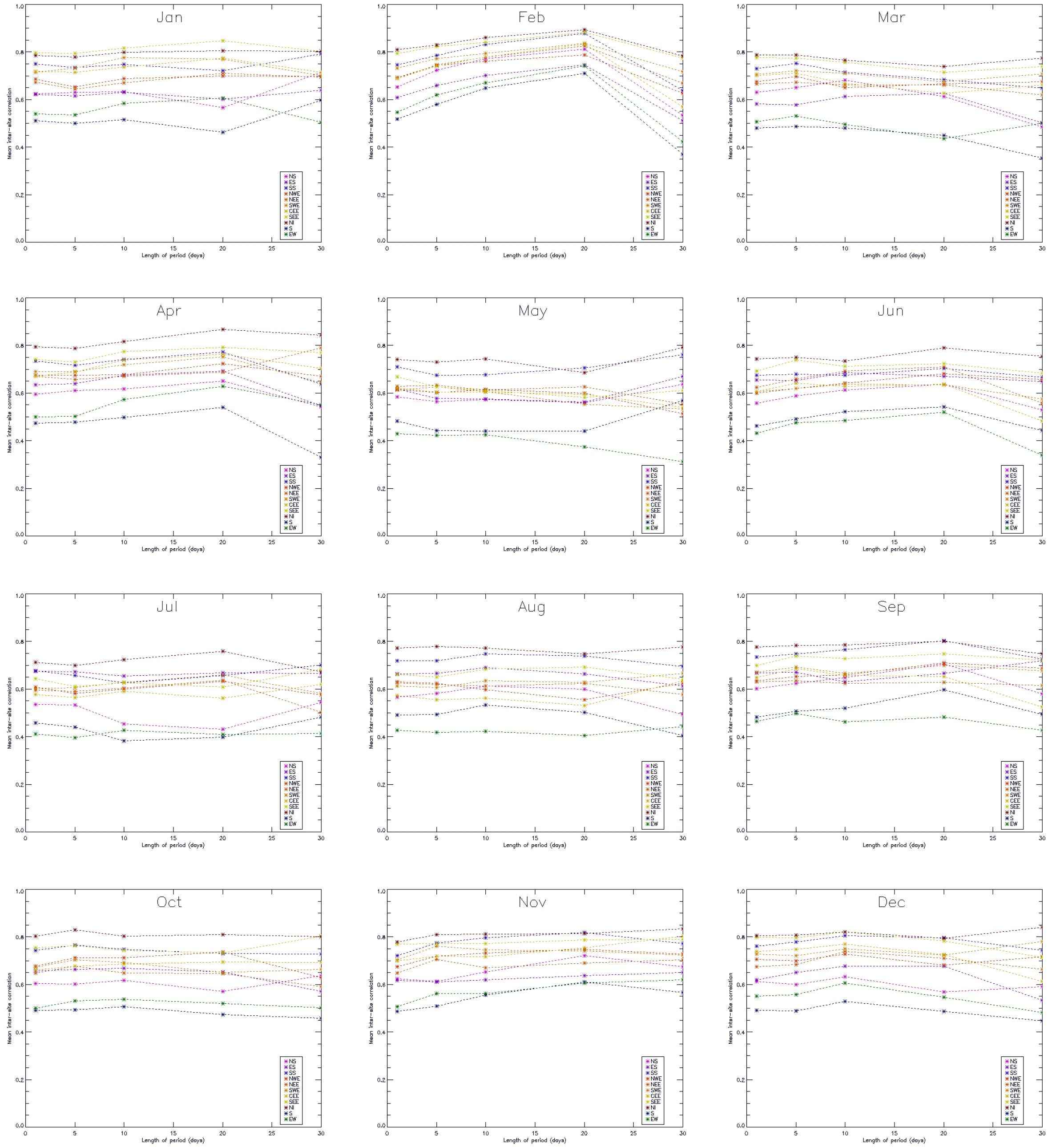


Fig 4.8. Standard errors based on mean inter-site correlations for each of the UK regions by month, for 1, 5, 10, 20 day and month-long periods, using AVG7.

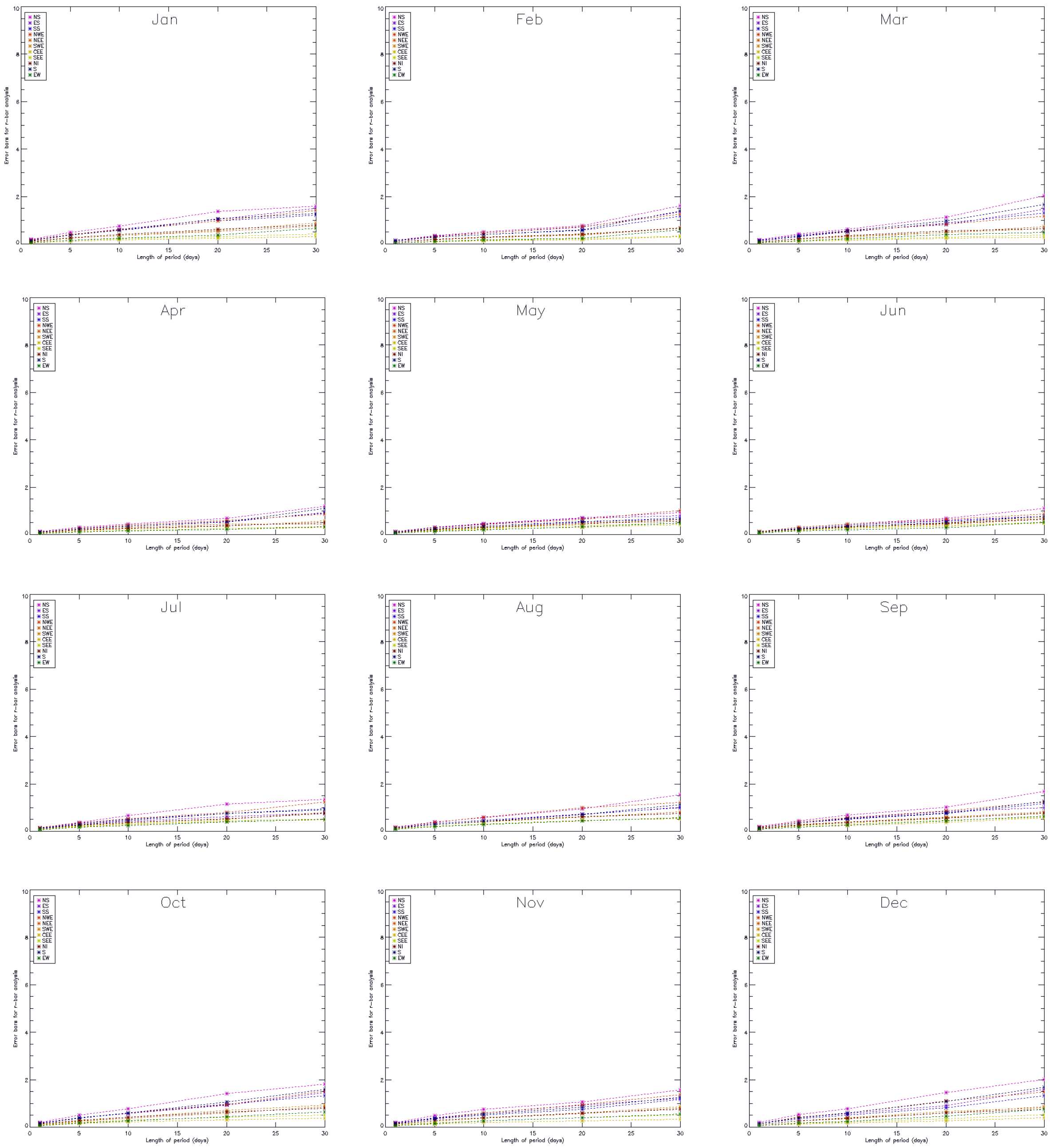
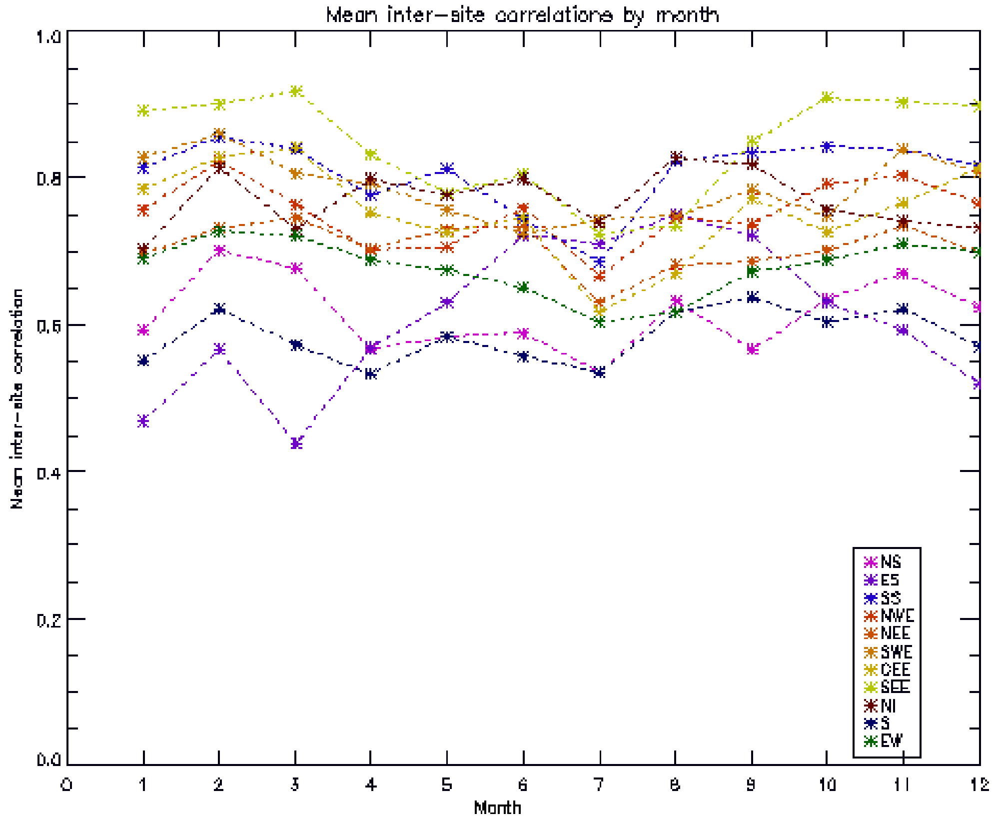


Fig 4.9. Standard errors based on mean inter-site correlations for each of the UK regions by month, for 1, 5, 10, 20 day and month-long periods, using AVGR.



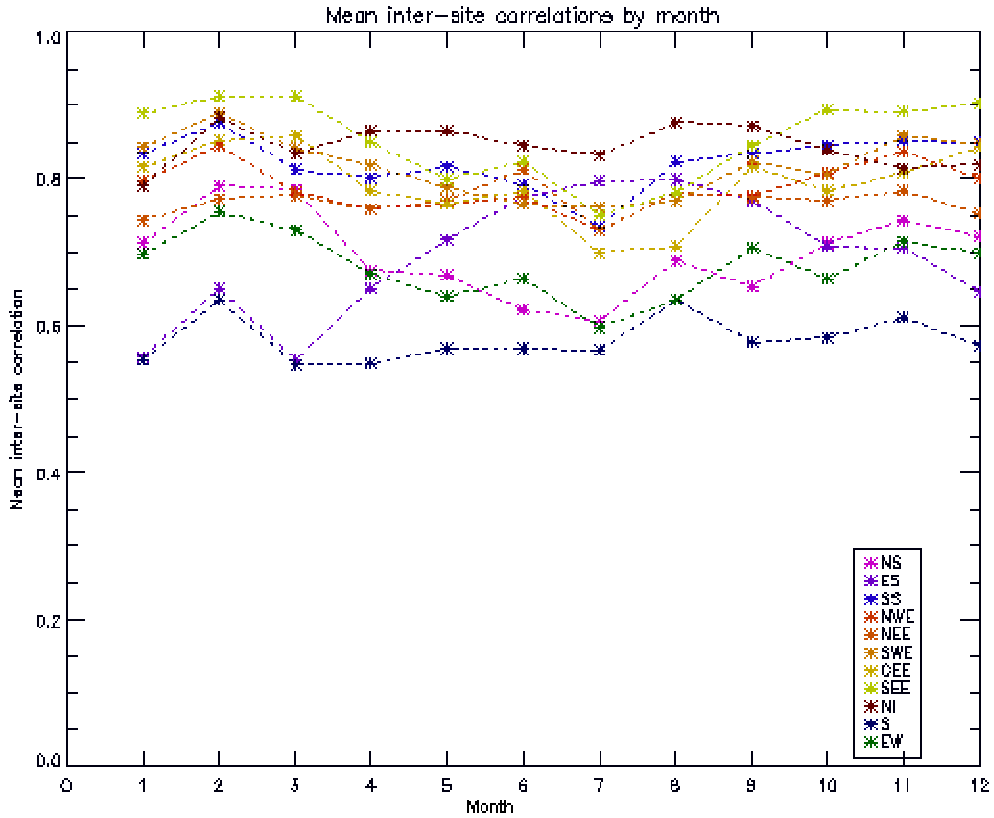


Fig 4.10. Mean inter-site correlations for monthly values for each UK region, based on r-bar using AVG7 (top) and AVGR (bottom) for each of the UK regions.

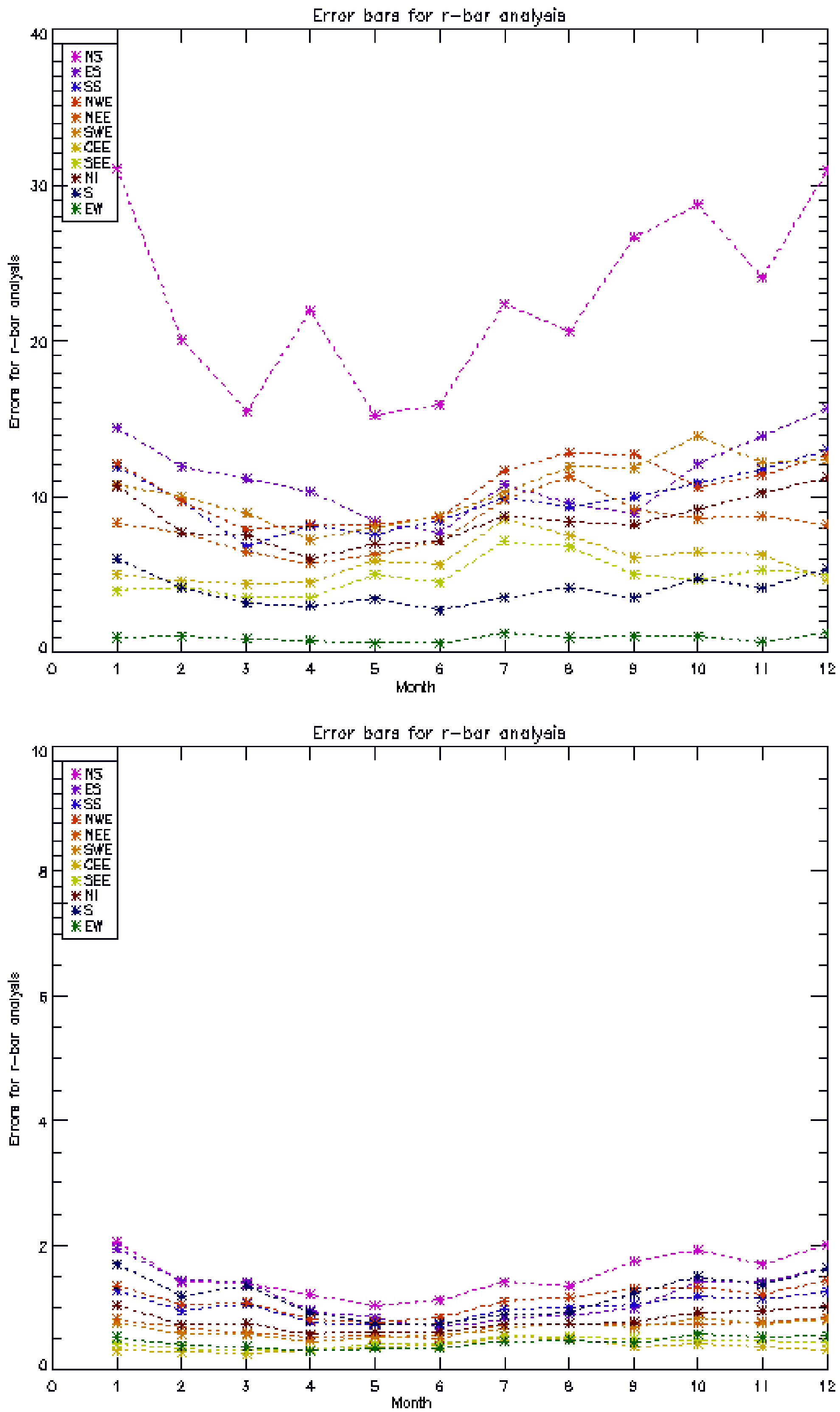


Fig 4.11. Standard errors based on mean inter-site correlations for monthly values for each UK region, based on r-bar using AVG7 (top) and AVGR (bottom) for each of the UK regions.

In addition, Wigley et al. (1984) note that the number of stations used to generate the England and Wales series fell short of the 35 (7 per region) from 1766 to 1858 inclusive, due to a shortage of continuous or near-continuous records from a sufficiently large number of reliable sites. Table 4.12 shows the number of sites used per region across England and Wales between 1766 and 1858; for more details see Wigley et al. (1984). Thus, while the AVG7 error values can be used to assess the error associated with the use of seven sites per region for the HadUKP series from 1859 onwards, the England and Wales values have larger associated error estimates prior to 1859. Fig 4.12 shows the error estimates corresponding to the time periods with different station coverage given in Wigley et al. (1984). Monthly error estimates are mostly close to 2mm during the period 1766-1788, during which there was only one site used per region. The number of sites used generally increased between 1788 and 1858, and monthly error estimates reduce accordingly, falling below 1mm for each month of the year from 1840 onwards, when at least 5 sites per region were used through to 1858.

Time period	Sites in SEE	Sites in SWE	Sites in CEE	Sites in NWE	Sites in NEE
1766-1771	1	1	1	1	1
1772-1779	1	1	1	1	1
1780-1783	1	1	1	1	1
1784-1788	1	1	1	1	1
1789-1792	2	2	2	2	2
1793-1798	2	2	2	2	1
1799	2	2	1	2	1
1800-1805	2	1	2	2	2
1806-1812	2	2	2	2	2
1813-1816	2	0	2	2	2
1817-1818	2	1	2	2	2
1819	2	1	2	2	1
1820	3	3	3	3	2
1821-1823	3	3	3	3	2
1824-1830	3	3	3	3	2
1831-1833	4	4	4	4	3
1834-1835	4	4	4	4	3
1836-1839	4	4	4	4	3
1840-1845	5	5	5	5	4
1846-1849	5	5	5	5	5
1850-1858	6	6	6	6	6

Table 4.12. Number of sites used per region during 1766-1858, from Wigley et al. (1984).

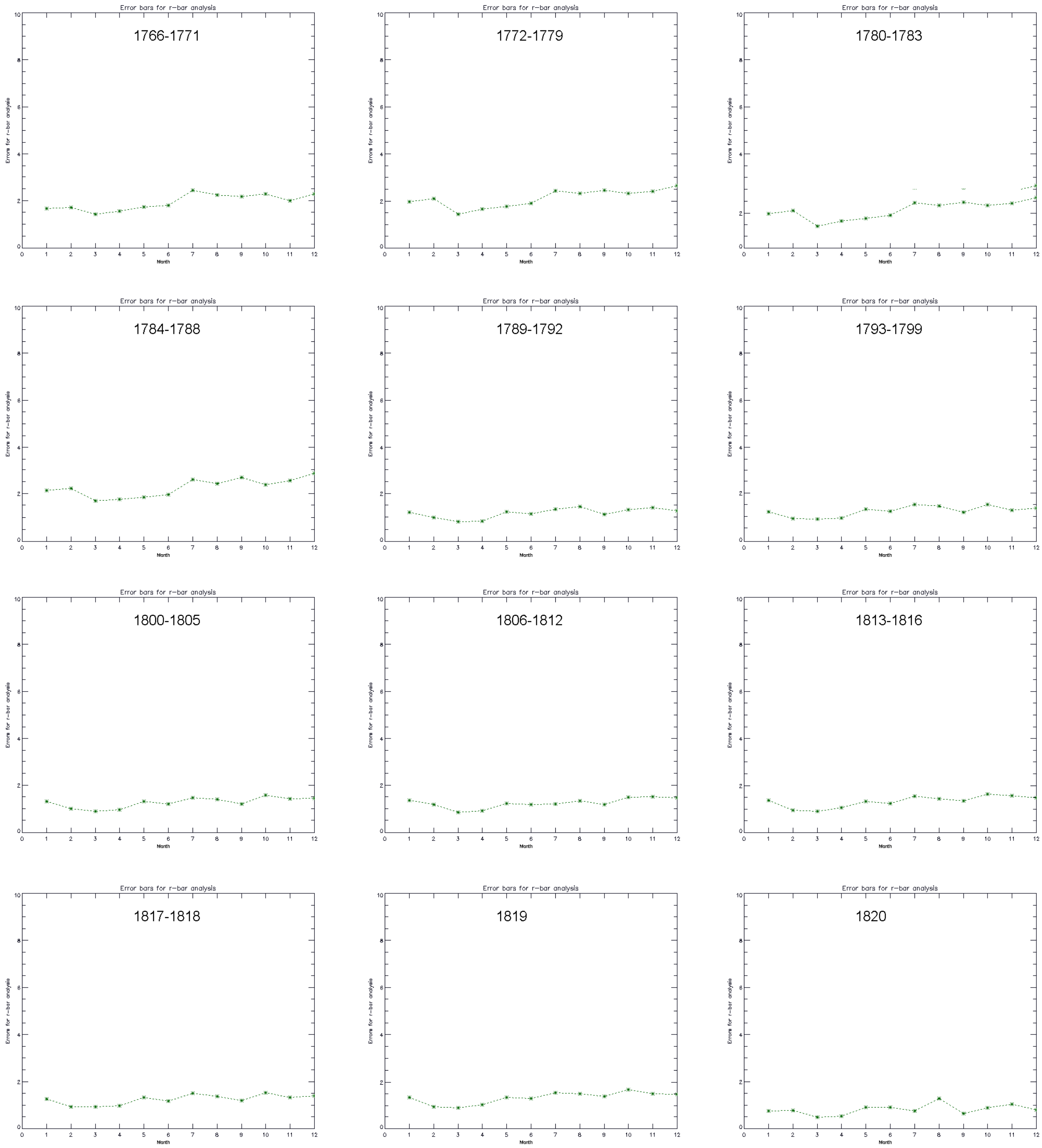


Fig 4.12. Standard errors based on mean inter-site correlations for monthly values for England and Wales, covering time periods with data available from fewer than the full 35 stations.

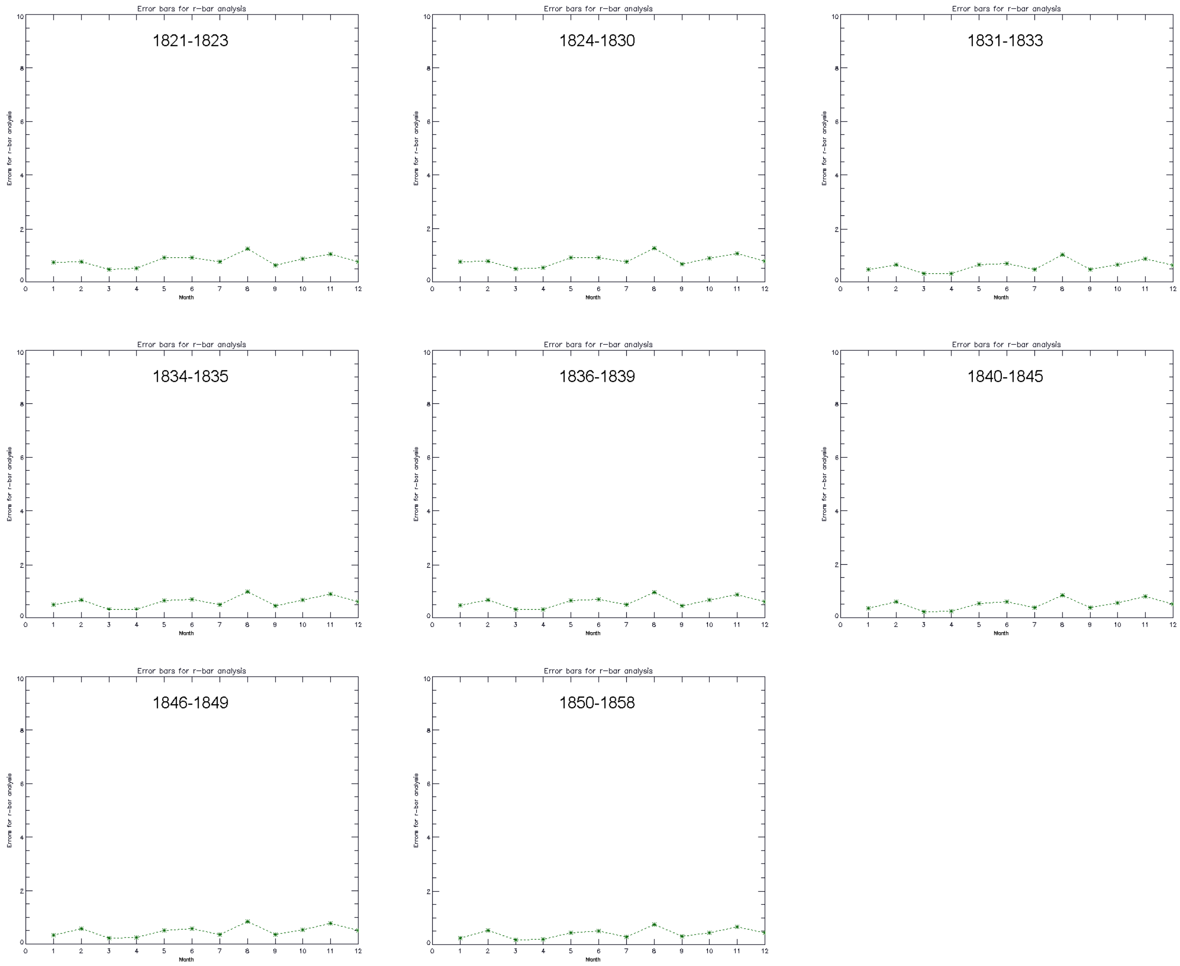


Fig 4.12. (continued).

4.4.4 Conclusions from error estimates

The error estimates derived using inter-site correlations and spatial degrees of freedom, using AVG7, are slightly higher than those stemming from the regressions between the MOHC series and the HadUKP series when AVG7 is used, with the exception of England and Wales and Scotland, where the number of sites used is greater (35 and 21 respectively). The error estimates are very similar to those obtained when performing a least squares regression between HadUKP and the MOHC series using AVGR. The results imply that the use of 7 sites per region as a representation of the 'true' mean results in similar potential for errors to the use of least squares regression between a series based on comprehensive coverage and a series based on 7 sites. As the number of sites is increased, the uncertainty stemming from spatial sampling reduces at a faster rate than the uncertainty stemming from regressions between the two series, as is evident from the results for England and Wales and for Scotland. One recurring problem with the use of a limited sample size is the tendency for bias towards the drier parts of a region (due to the fact that drier areas are generally flatter and low-lying and thus more habitable).

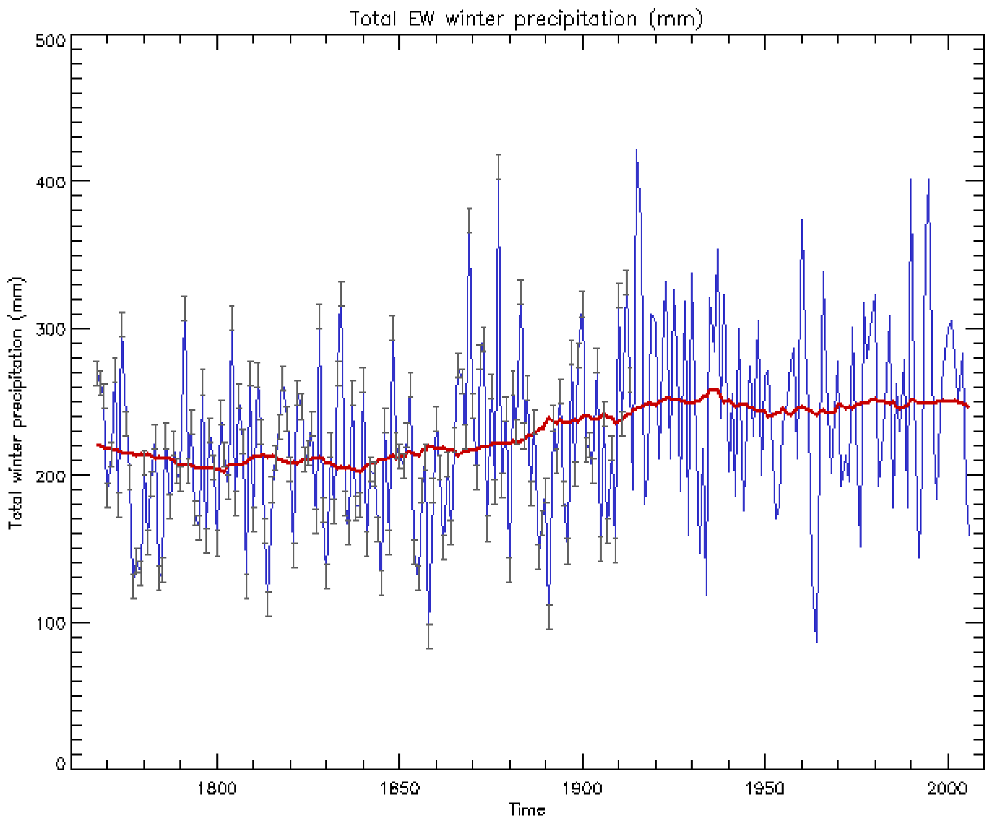
The England and Wales series has generally greater errors from incomplete spatial sampling through to 1788 than those stemming from regressions against MOHC06m and MOHC07d, because only five stations were used between 1766 and 1788 inclusive, but errors become smaller than those stemming from regression from 1789 onwards, because the number of sites used progressively increased between 1789 and 1858 inclusive, reaching the 35 sites used from 1859 onwards, and similar numbers per region were maintained in Wigley et al. (1984). The errors from spatial sampling are also considerably smaller than those arising from the regressions that Wigley et al. (1984) used to generate error estimates for their England and Wales values, given in Table IV in Wigley et al. (1984). Thus, the new monthly series for England and Wales obtained via regression against HadUKP (given in section 4.5) is probably associated with higher error estimates than the original HadUKP version for 1789-1913, but maintains homogeneity with the new series from 1914 onwards which stems directly from the MOHC06m grids- otherwise there would be a pronounced discontinuity centred on 1913/1914.

The series for the individual constituent regions of EW (SEE, CEE, SWE, NWE, NEE) are associated with similar uncertainty estimates to the original HadUKP versions for 1873-1913 as well as maintaining homogeneity with the series from 1914 onwards, and this is also true of the daily regional series extending from 1931-1957 (higher associated errors for England and Wales and for Scotland, but similar for the sub regions). It is also clear that, concerning UK rainfall, the number of sites used per region carries a much larger weight than the size of the region that is being sampled from, assuming similar coverage in each region. More work will be needed to determine whether this is a general result or only specific to UK rainfall, but it may potentially suggest that when covering larger areas (such as when determining a global mean) we can afford sparser sampling than when covering regional and local variations (this is even more true when covering global temperatures, for which inter-site correlations are higher). The results suggest that Jones et al. (1997) were right to suggest that a relatively limited, but appropriately distributed, sample over a large area can give a good representation of the "true" areal mean. 7 sites per region may have been too small a sample size in the case of UK rainfall, but finding more than 7 sites with long records and good geographic spread is very difficult in some regions, as demonstrated by the fact that Wigley et al. (1984) had to reduce the coverage further in the early years of the England and Wales record.

4.4.5 New rainfall series for the UK regions

The new rainfall series has been generated in the same format as the original HadUKP series, covering all of the UK regions. Fig 4.13 shows the seasonal winter, spring, summer and autumn precipitation totals for England and Wales, with error estimates based on the regressions prior to 1914. No error estimates are supplied for 1914-2006 as the data based on AVGR are assumed to provide a 'true' estimate of the areal mean, although it is likely that errors may arise from the interpolation methods chosen to generate the MOHC data. This consideration is outside of the scope of this thesis and may require further work, such as by obtaining all of the data and testing out different gridding algorithms. Fig 4.14 shows the seasonal winter, spring, summer and autumn precipitation totals for Scotland. No error estimates are provided for Scotland since the MOHC monthly series dates back to 1914 while the HadUKP series for Scotland only extends back to 1931.

These seasonal precipitation series, covering all of the sub-regions of the UK, are used as a basis for the statistical analysis in Chapter 5, where multiple indices of extreme rainfall are used to assess trends in rainfall across the UK, at a regional level, for each of the four meteorological seasons. Fig 4.13 points to an increase in winter precipitation over England and Wales, and a decline in summer precipitation. The Scottish values (Fig 4.14) show less of a downward trend in summer, and if anything the winter trend is downward between the 1920s and 1960s, followed by a sharp rise since the 1970s. More analysis on this is presented in Chapter 5, including assessments of the statistical significance of the results.



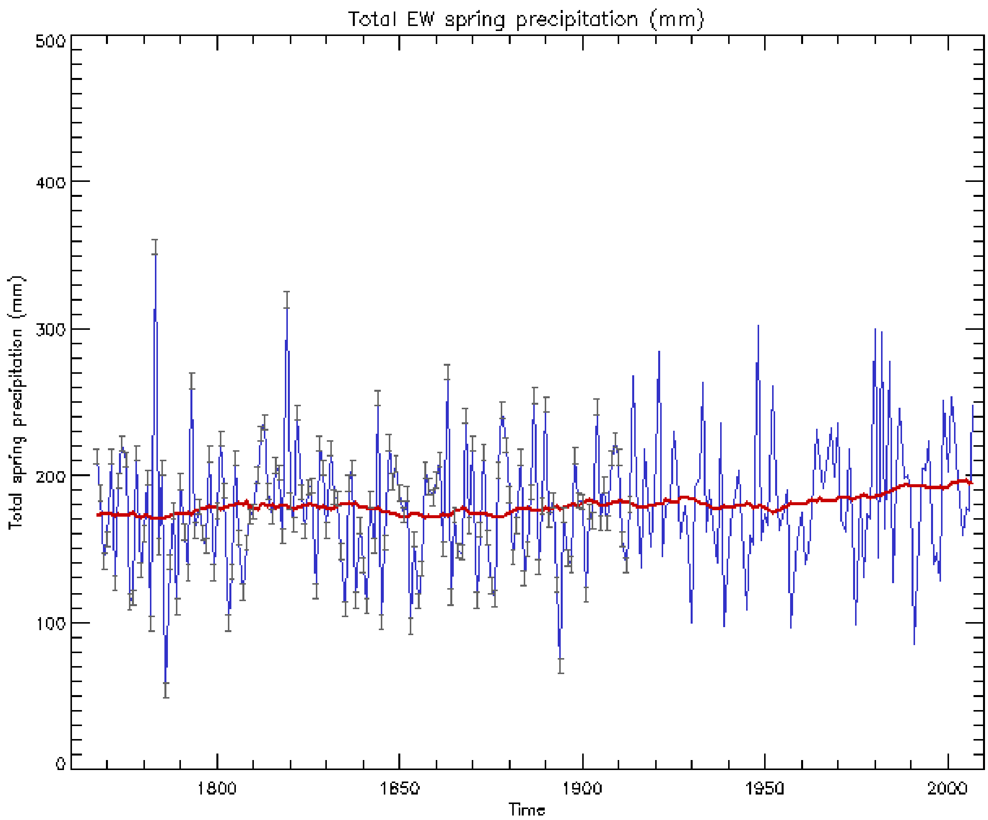
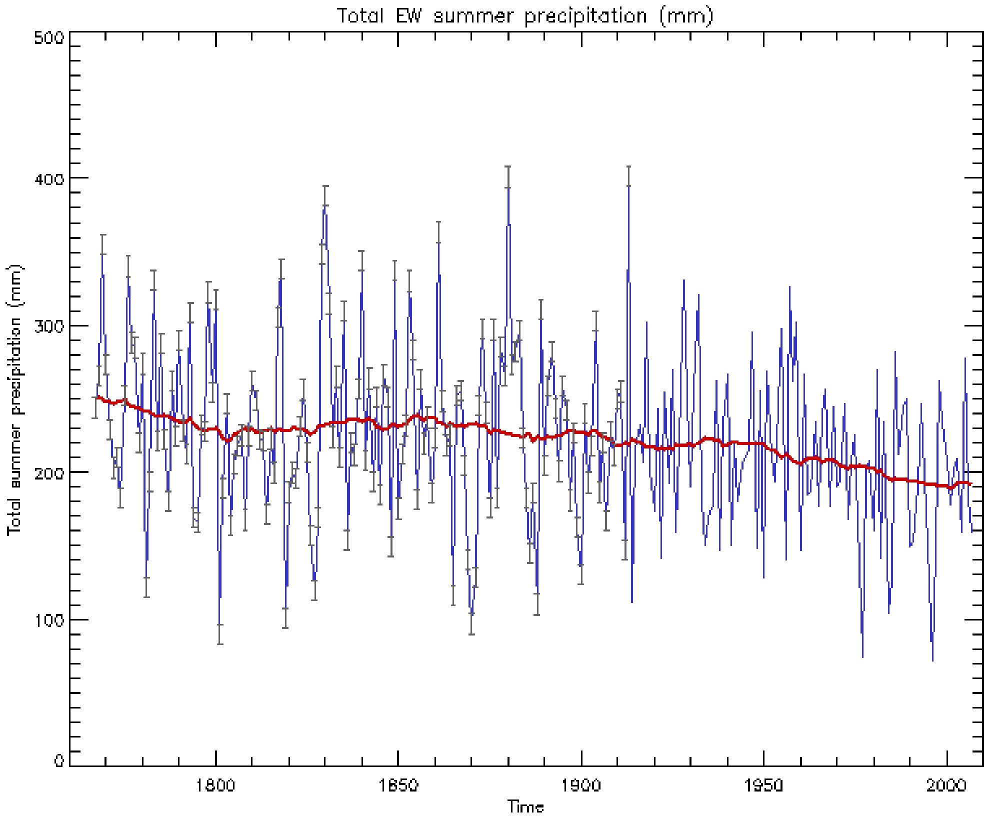


Fig 4.13. Seasonal precipitation totals for England and Wales with associated error bars. The red line is the series smoothed using a 51 point moving average.



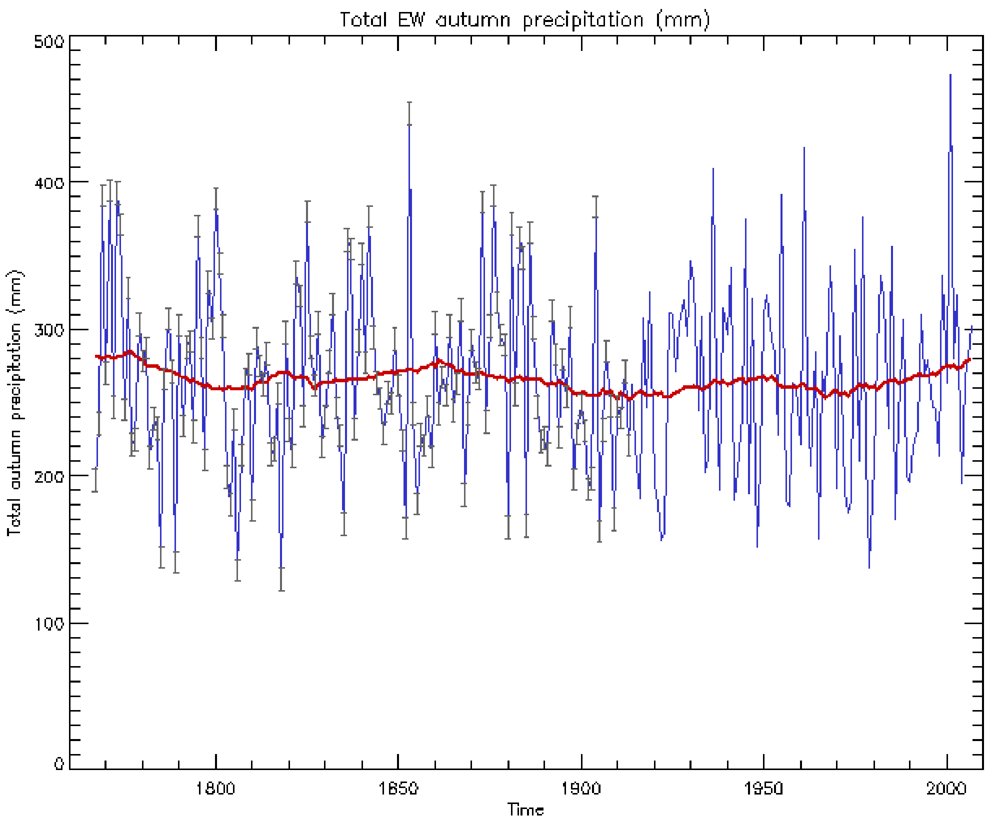
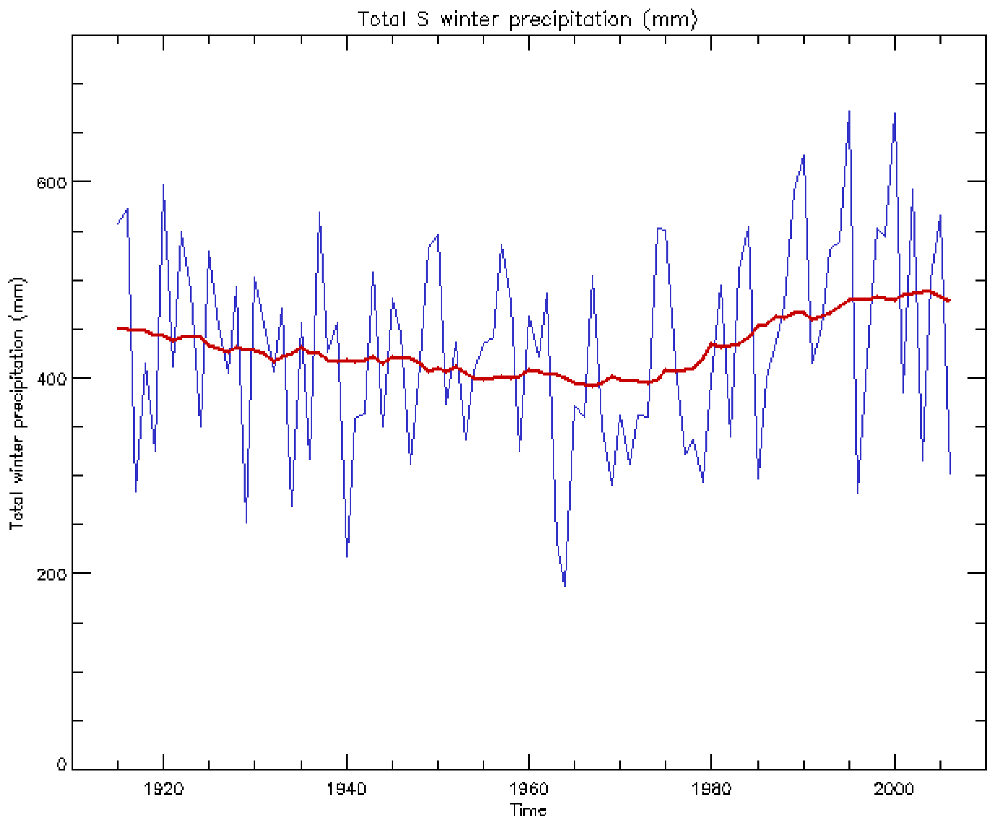


Fig 4.13. (continued)



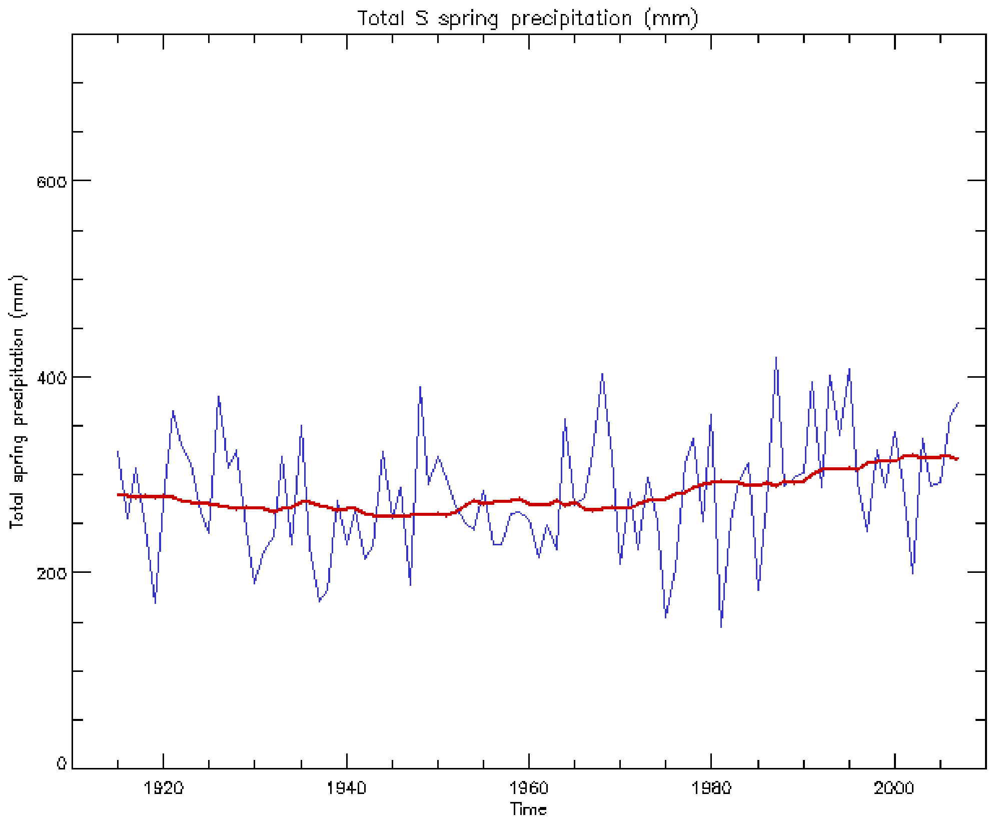
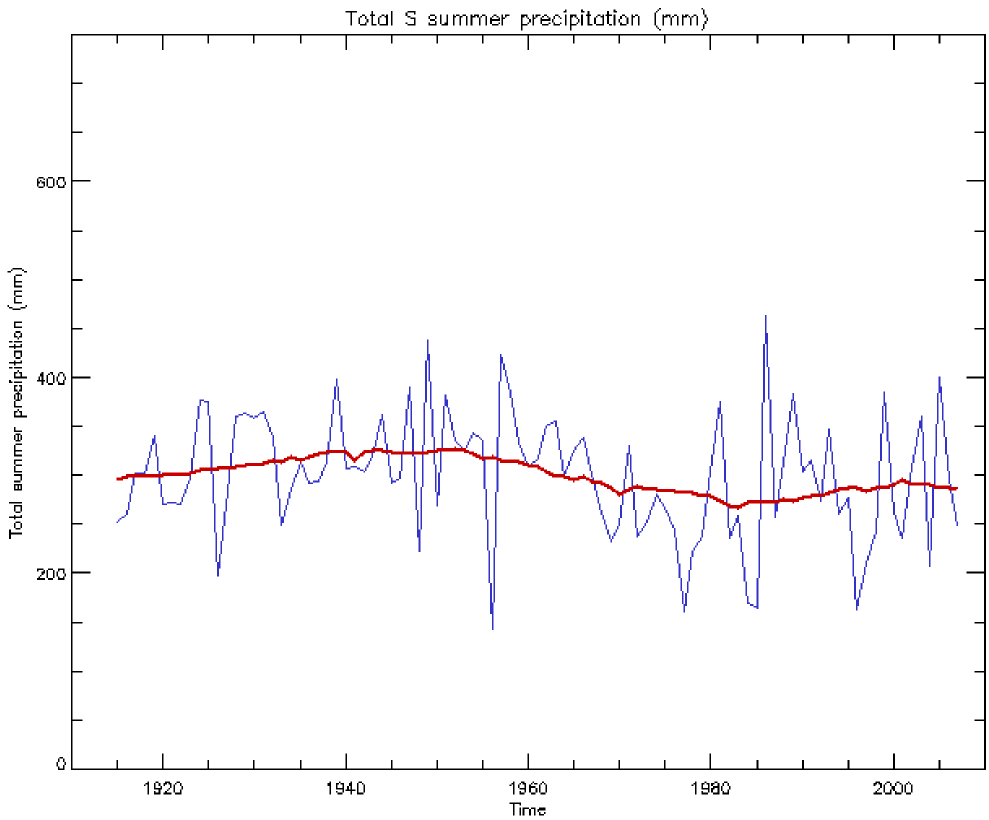


Fig 4.14. Seasonal precipitation totals for Scotland. The red line is the series smoothed using a 31 point moving average.



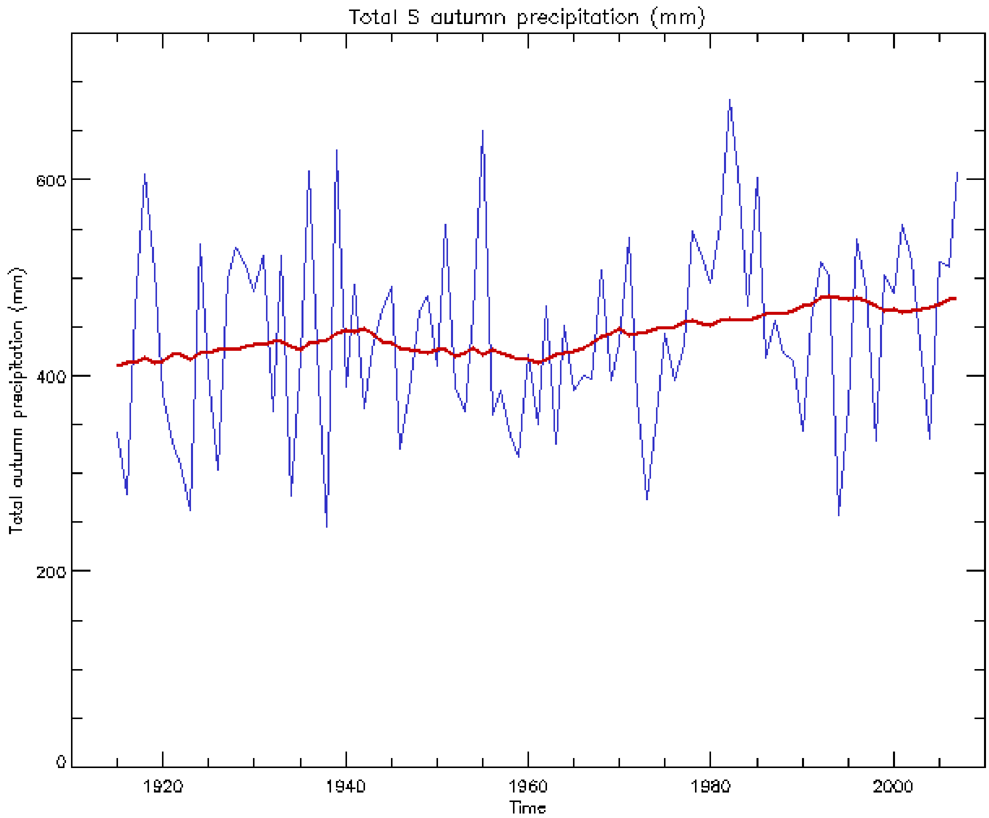


Fig 4.14. (continued)

5. Analysis of precipitation extremes using gridded data

5.1 Summary

A number of indices are used to analyse changes in precipitation extremes over the UK over the respective periods for which data are available, for each of the four meteorological seasons:

- Percentiles of daily wet-day rainfall totals (50, 90, 95 and 99), restricted to days with 1mm precipitation or more
- The maximum 5-day precipitation total
- The simple rainfall intensity index (total precipitation / number of days with 1mm precipitation or more)
- The consecutive dry day index (longest number of consecutive days with less than 1mm precipitation)

The percentiles have been calculated via re-arranging the daily precipitation totals from lowest to highest and using the following formula to determine the value corresponding to the relevant percentile:

$$n = \frac{PN}{100} + 0.5$$

where *N* is the number of values, *P* is the Pth percentile (so for example, for the 50th percentile, P = 50) and n is the value corresponding to the Pth percentile.

The analysis covers each of the UK regions individually and the national series for Scotland and England & Wales. Graphs are generated for each individual measure for each season, assessing all regions of the UK. Trend lines are derived fitting the data to the equation y = A + Bx, and statistical significance is determined by determining the number of standard deviations of the trend relative to the mean value. All analysis covers the period 1931 to 2007, for which daily precipitation data are available for all regions. Section 5.2 establishes and analyses trends in extreme seasonal precipitation, Section 5.3 establishes and analyses trends in mean seasonal precipitation and some conclusions are given in Section 5.4. In the tables, statistically significant values at the 95% level are given in bold, and statistically significant values at the 99% level are bold and underlined.

5.2 Trends in extreme UK daily precipitation

5.2.1 Extreme UK daily precipitation in winter, 1932-2007

The overall trend in winter precipitation has been positive across the UK over the period, but in many cases the trend falls short of the 95% significance level. The 50th percentile of wet-day precipitation shows a statistically significant increase in the Scottish regions, NWE and NEE, but the trend is only weak for the other regions, especially SEE. The upward trend in the 90th percentile is statistically significant only for NI, while the increase in the 95th percentile is also significant for SWE and EW as well as NI. The 99th percentile shows a statistically significant increase for ES, NEE and S, and the maximum 5-day totals are significant for S and ES. The increases in the wet-day index are more significant, with only CEE, SEE and NS producing trends that fall short of the 95% significance level. The changes in the consecutive dry-day index are weak and fall short of statistical significance.

All measures of extreme precipitation (Fig 5.1, Fig 5.2) show some evidence of an increase in the 1990s followed by a decline in the 2000s to values more representative of the average for 1931-1990. The peak in the 1990s is particularly evident in the Scottish regions, especially for the 50th percentile, the maximum 5-day totals and the wet day index. This peak is most likely associated with the strongly positive NAO and unusual storminess over the eastern Atlantic and North Sea during the period (e.g. Wang et al., 2008). This is also supported by the correlations with the winter NAO index (Osborn, 2011) given in Table 5.2. The NAO is positively correlated with all high precipitation indices for NS, S and SS, and is most strongly correlated with the 50th percentile of precipitation for NS and S. Correlations are mostly weak for the other regions but are slightly positive for NWE, SWE and EW. Thus, with the exceptions of CEE and SEE, all regions show a clear trend towards greater daily extremes of winter precipitation, with ES having the strongest signal, but it is not clear from the data whether there is a long-term upward trend or just a highly anomalous decade in the 1990s, particularly given that many of the indices do not show statistically significant upward trends. The results suggest that the increase in mean intensity of daily precipitation has been more pronounced than the increase in extreme high daily totals and extreme 5-day totals.

The trends for each region for each variable are given in Table 5.1, while the plotted data and trend lines for England and Wales and for Scotland are given in Fig 5.1 and Fig 5.2 respectively.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	**4.36**	**3.87**	**2.44**	**2.09**	**2.00**	1.14	0.21	1.74	**3.13**	1.72	1.65
90th percentile	0.85	1.24	0.98	1.67	**2.70**	0.37	1.95	1.91	1.86	**2.18**	1.81
95th percentile	1.61	1.63	0.93	1.88	1.85	1.45	1.10	**2.31**	0.86	**2.03**	**2.23**
99th percentile	0.98	**2.77**	0.35	1.79	**2.43**	0.64	0.20	1.89	**1.97**	1.80	1.69
Max 5-day total	1.75	**2.21**	1.67	1.73	0.75	0.79	1.30	1.72	**1.99**	0.85	1.39
Wet day index	**3.22**	**2.55**	1.78	**2.65**	**2.55**	0.81	0.58	**2.97**	**2.59**	**2.20**	**2.20**
Consec. dry day	-0.35	1.40	-0.19	-0.62	-0.11	0.16	-0.54	-0.53	-0.17	-0.14	0.36

Table 5.1. Trend values (mm) divided by the population standard deviation for each region, for each extreme precipitation index, for winter (DJF). Bold values reached the 95% significance level, underlined values reached the 99% significance level.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	**0.38**	**0.44**	**0.70**	**0.32**	0.10	0.11	0.04	0.16	**0.65**	0.11	0.20
90th percentile	**0.33**	0.12	**0.45**	0.23	-0.05	-0.07	0.06	0.13	**0.50**	-0.08	0.19
95th percentile	**0.34**	0.03	**0.44**	0.20	-0.03	0.02	0.13	0.28	**0.34**	-0.16	0.16
99th percentile	0.28	0.08	**0.39**	0.19	-0.01	0.23	0.08	0.30	**0.33**	-0.07	0.22
Max 5-day total	**0.32**	-0.00	**0.51**	0.15	-0.14	0.10	0.16	0.27	**0.34**	-0.02	0.26
Wet day index	**0.38**	0.24	**0.63**	0.28	0.04	0.04	0.03	0.22	**0.58**	-0.11	0.20
Consec. dry day	**-0.35**	0.01	-0.19	-0.23	0.11	-0.02	-0.05	0.00	-0.20	-0.17	0.04

Table 5.2. Correlations between observed precipitation values by each extreme precipitation index and the seasonal NAO for winter (DJF) for each region. Bold values reached the 95% significance level, underlined values reached the 99% significance level.

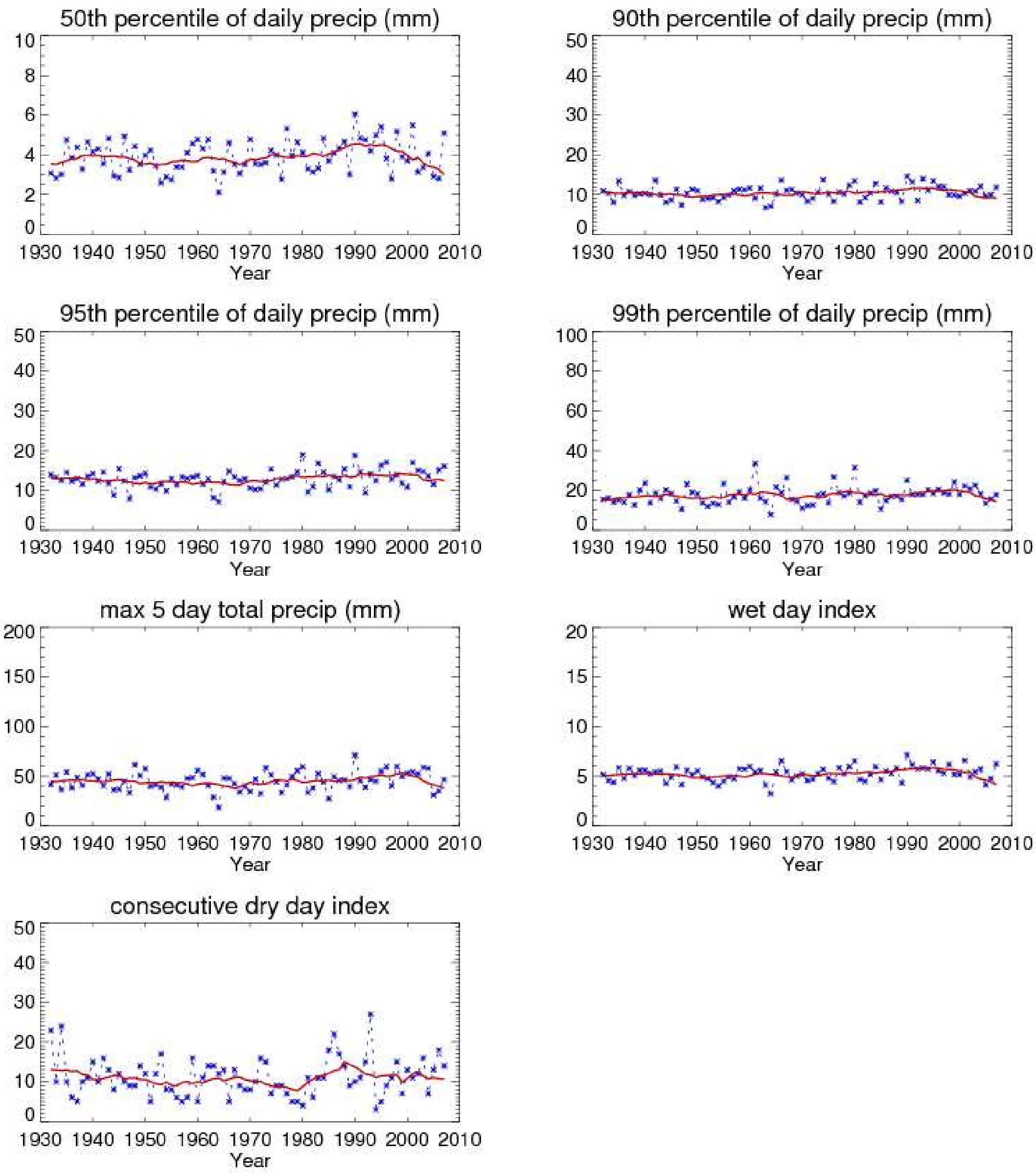


Fig 5.1. Measures of extreme daily precipitation over England and Wales, 1932-2007, for the winter quarter (DJF). Winters are dated by the January. The red line represents a decadal moving average of the series.

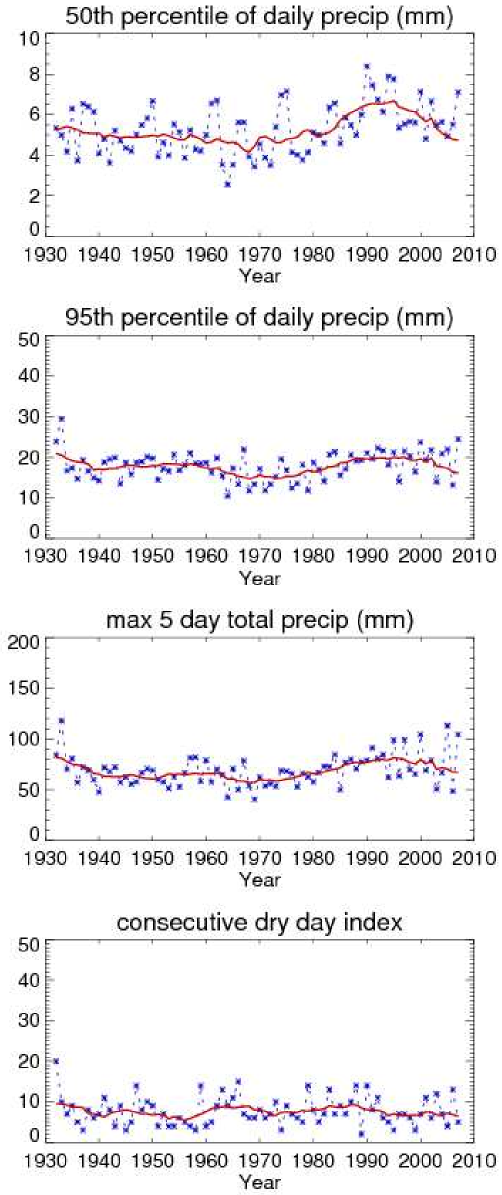


Fig 5.2 Measures of extreme daily precipitation over Scotland, 1932-2007, for the winter quarter (DJF). Winters are dated by the January. The red line represents a decadal moving average of the series.

5.2.2 Extreme UK daily precipitation in spring, 1931-2007

There is also evidence of an upward trend in spring precipitation in northern and western Britain over the period, but the trend is weaker than in winter, and few of the positive values reach the 95% significance level. The 50th percentile shows a statistically significant increase for SS, NS and S (especially NS). Increases in the 90th percentile are statistically significant only for SS, NWE and NI, in the 95th percentile only for NWE and S, and in the 99th percentile only for SS. The maximum 5-day totals show only weak upward trends with a statistically significant trend observed only across Scotland as a whole. As in the case of winter, the wet day index shows a more significant upward trend with statistically significant increases for SS, NS, NWE, S and NI. Trends in the consecutive dry day index are very weak and do not approach the 95% significance level.

In most cases the graphs show a steady increase in spring extreme precipitation across the country, but in NS, SS and S there is strong evidence of a peak around 1990 with a succession of unusually wet springs, contributing to the statistical significance of the upward trend. Precipitation has declined since then in those regions but, in the case of most of the variables, has not yet fallen back to the average frequency over the period 1931-1980. Thus, the trends in spring precipitation in northern and western Britain are the same as in winter, with a clear trend towards more intense mean daily precipitation, but much weaker evidence for an increase in the extreme high 1 day and 5-day totals. As with the observed changes in winter precipitation, these trends in NS and S are consistent with changes in the seasonal NAO (Table 5.4), but other regions show little correlation with the NAO, with small negative correlations for NEE. There is no statistically significant evidence for long-term changes in spring precipitation in central or southern England, and suggestions of a reduction in incidence of long dry spells in north-east and east England.

The trends for each region for each variable are given in Table 5.3, while the plotted data and trend lines for England and Wales and for Scotland are given in Fig 5.3 and Fig 5.4 respectively.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	**2.11**	1.37	<u>**4.02**</u>	1.54	0.57	0.58	0.29	0.71	**2.09**	1.17	1.57
90th percentile	**2.13**	1.66	1.85	**2.09**	-0.13	0.60	0.17	-0.33	1.78	<u>**2.58**</u>	0.81
95th percentile	1.67	0.19	1.37	**1.97**	-0.06	0.62	0.04	0.21	**1.96**	1.27	0.77
99th percentile	**2.00**	0.19	1.81	0.41	0.88	0.42	0.72	0.76	1.62	0.48	0.48
Max 5-day total	1.28	0.80	1.90	1.94	1.08	0.78	0.21	0.79	**1.96**	0.36	0.51
Wet day index	<u>**2.74**</u>	1.14	<u>**2.89**</u>	**2.18**	0.01	0.14	0.46	0.34	**2.48**	**2.17**	1.29
Consec. dry day	-0.31	0.62	-0.49	-0.16	-1.72	0.22	0.35	1.02	-0.15	0.68	-0.31

Table 5.3. Trend values (mm) divided by the population standard deviation for each region, for each extreme precipitation index, for spring (MAM). Bold values reached the 95% significance level, underlined values reached the 99% significance level.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	0.23	0.08	<u>**0.43**</u>	0.20	-0.22	-0.18	**-0.36**	0.09	0.39	0.17	-0.10
90th percentile	0.11	-0.05	<u>**0.43**</u>	0.08	-0.22	-0.04	0.07	0.02	0.27	-0.06	0.02
95th percentile	0.06	-0.03	0.27	-0.07	-0.13	-0.08	-0.11	-0.13	0.12	-0.06	-0.10
99th percentile	0.11	-0.08	0.21	-0.04	-0.09	-0.05	-0.08	-0.12	0.04	-0.06	-0.07
Max 5-day total	0.27	-0.09	**0.34**	0.07	0.07	-0.03	0.03	0.05	0.19	0.08	0.05
Wet day index	0.23	-0.05	<u>**0.43**</u>	0.07	-0.20	-0.14	-0.18	0.04	0.30	-0.02	-0.12
Consec. dry day	**-0.37**	-0.20	-0.29	**-0.31**	-0.11	-0.12	-0.02	-0.03	-0.24	**-0.33**	-0.12

Table 5.4. Correlations between observed precipitation values by each extreme precipitation index and the seasonal NAO for spring (MAM) for each region. Bold values reached the 95% significance level, underlined values reached the 99% significance level.

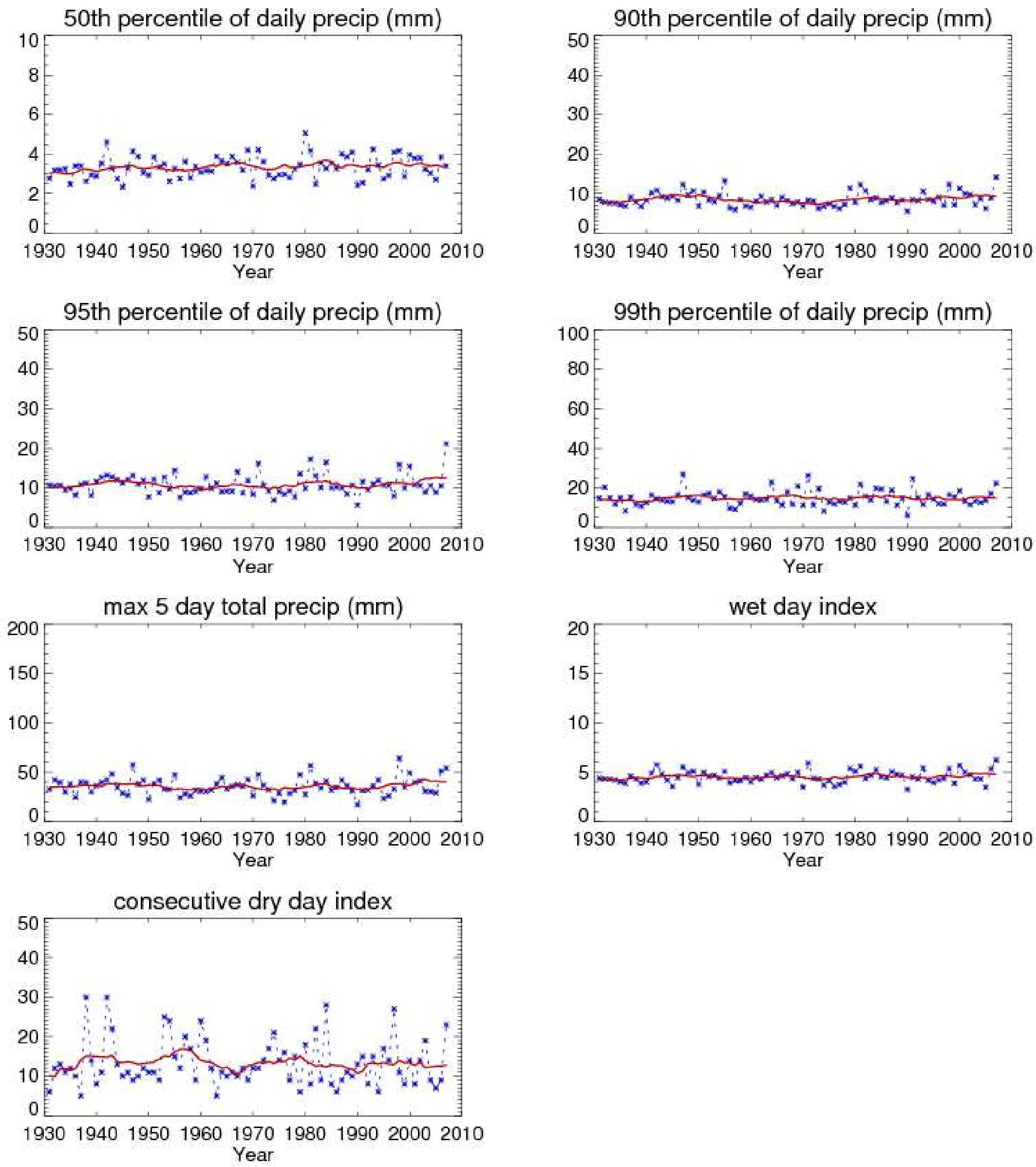


Fig 5.3 Measures of extreme daily precipitation over England and Wales, 1931-2007, for the spring quarter (MAM). The red line represents a decadal moving average of the series.

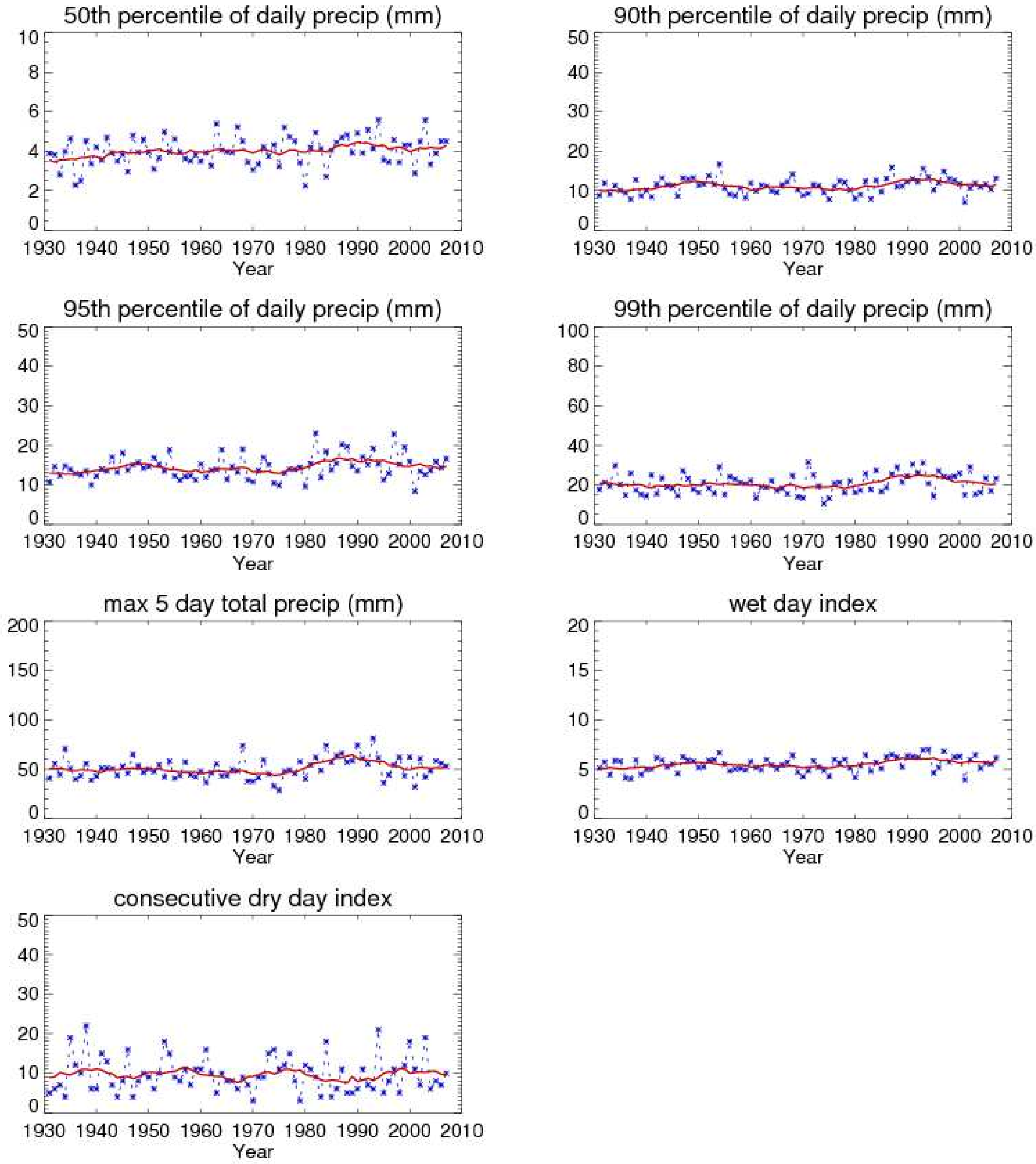


Fig 5.4 Measures of extreme daily precipitation over Scotland, 1931-2007, for the spring quarter (MAM). The red line represents a decadal moving average of the series.

5.2.3 Extreme UK daily precipitation in summer, 1931-2007

The trend values for summer precipitation over the period are mostly negative (except for CEE and SEE) but most of them do not reach the 95% significance level. There is a statistically significant reduction in the 50th percentile for NWE, and in the maximum 5-day totals for ES and NI.

The graphs of UK extreme summer precipitation show periods of low values in the late 1980s and 1990s in the Scottish regions, NWE and NEE, emphasised most especially in the 90th and 95th percentiles and the 5-day totals, followed by a recovery in the 2000s. In NEE, the 99th percentile and maximum 5-day totals have swung to the opposite extreme in the 2000s, with unusually high values, but over too short a time period to reach statistical significance. Conversely the 50th percentile did not show this behaviour. There is also evidence of a peak in extreme summer precipitation around 1960.

The evidence for long-term trends in UK extreme daily summer precipitation is thus weak and mixed, with evidence of a significant decline in mean wet-day precipitation over Northern Ireland, north-west England and north Wales, but not in the other regions, and no increase in prolonged dry spells. The trends for each region for each variable are given in Table 5.5, while the plotted data and trend lines for England and Wales and for Scotland are given in Fig 5.5 and Fig 5.6 respectively. Correlations with the NAO are weak (Table 5.6) but small negative correlations prevail in all regions with the exception of NS, perhaps reflecting the need for a different set of indices to determine the behaviour of the summertime NAO, as per the analysis of Folland et al. (2009) for example which showed a more significant negative correlation between European precipitation and the summer NAO using alternative indices.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	0.08	0.10	-0.23	**-2.20**	0.57	1.79	-0.35	0.17	-1.08	-1.90	-0.33
90th percentile	-0.26	-1.48	-1.73	-1.13	-0.13	0.79	-0.53	-0.49	-1.14	-0.77	0.35
95th percentile	-0.22	-0.46	-1.17	0.09	-0.06	1.14	0.24	-0.64	-1.49	0.49	-0.02
99th percentile	-0.91	-1.06	-1.72	-0.34	0.88	1.16	1.02	0.04	-1.51	-1.66	0.20
Max 5-day total	-0.76	**-2.11**	0.14	-0.07	1.08	1.58	0.27	-0.56	-1.81	**-2.20**	0.53
Wet day index	-0.14	-0.69	-1.14	-1.73	0.01	1.23	0.18	0.61	-1.58	-0.98	0.76
Consec. dry day	-1.62	-1.59	-0.98	-1.23	-1.72	0.06	-0.50	0.03	-1.54	0.05	-0.58

Table 5.5. Trend values (mm) divided by the population standard deviation for each region, for each extreme precipitation index, for summer (JJA). Bold values reached the 95% significance level, underlined values reached the 99% significance level.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	0.04	-0.19	0.21	0.04	-0.19	-0.20	0.11	-0.19	0.03	0.14	-0.17
90th percentile	-0.09	-0.13	0.28	-0.15	-0.20	-0.06	-0.07	0.07	0.01	-0.14	0.01
95th percentile	-0.08	-0.19	0.17	-0.08	-0.13	-0.15	-0.15	0.03	-0.11	-0.12	-0.04
99th percentile	-0.13	-0.18	0.15	-0.17	-0.17	-0.15	-0.09	-0.04	-0.15	-0.12	-0.09
Max 5-day total	-0.07	-0.09	0.06	-0.02	-0.27	-0.19	-0.19	-0.10	-0.05	-0.09	-0.14
Wet day index	-0.06	-0.23	0.22	-0.02	-0.28	-0.19	-0.03	-0.09	-0.04	-0.06	-0.15
Consec. dry day	-0.04	-0.09	-0.10	0.01	-0.02	-0.04	0.11	0.13	0.05	-0.02	0.08

Table 5.6. Correlations between observed precipitation values by each extreme precipitation index and the seasonal NAO for summer (JJA) for each region. No values reached the 95% significance level.

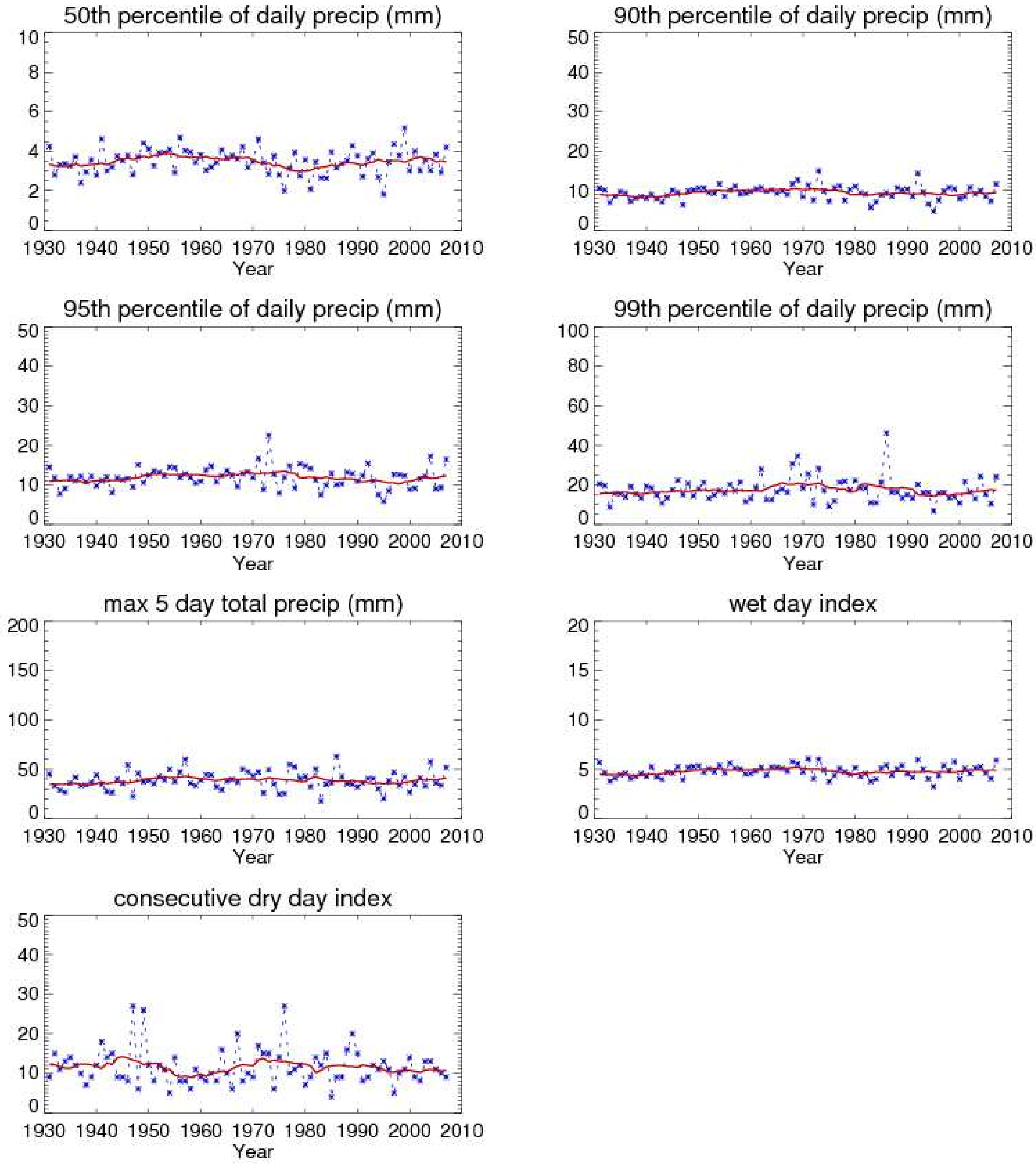


Fig 5.5 Measures of extreme daily precipitation over England and Wales, 1931-2007, for the summer quarter (JJA). The red line represents a decadal moving average of the series.

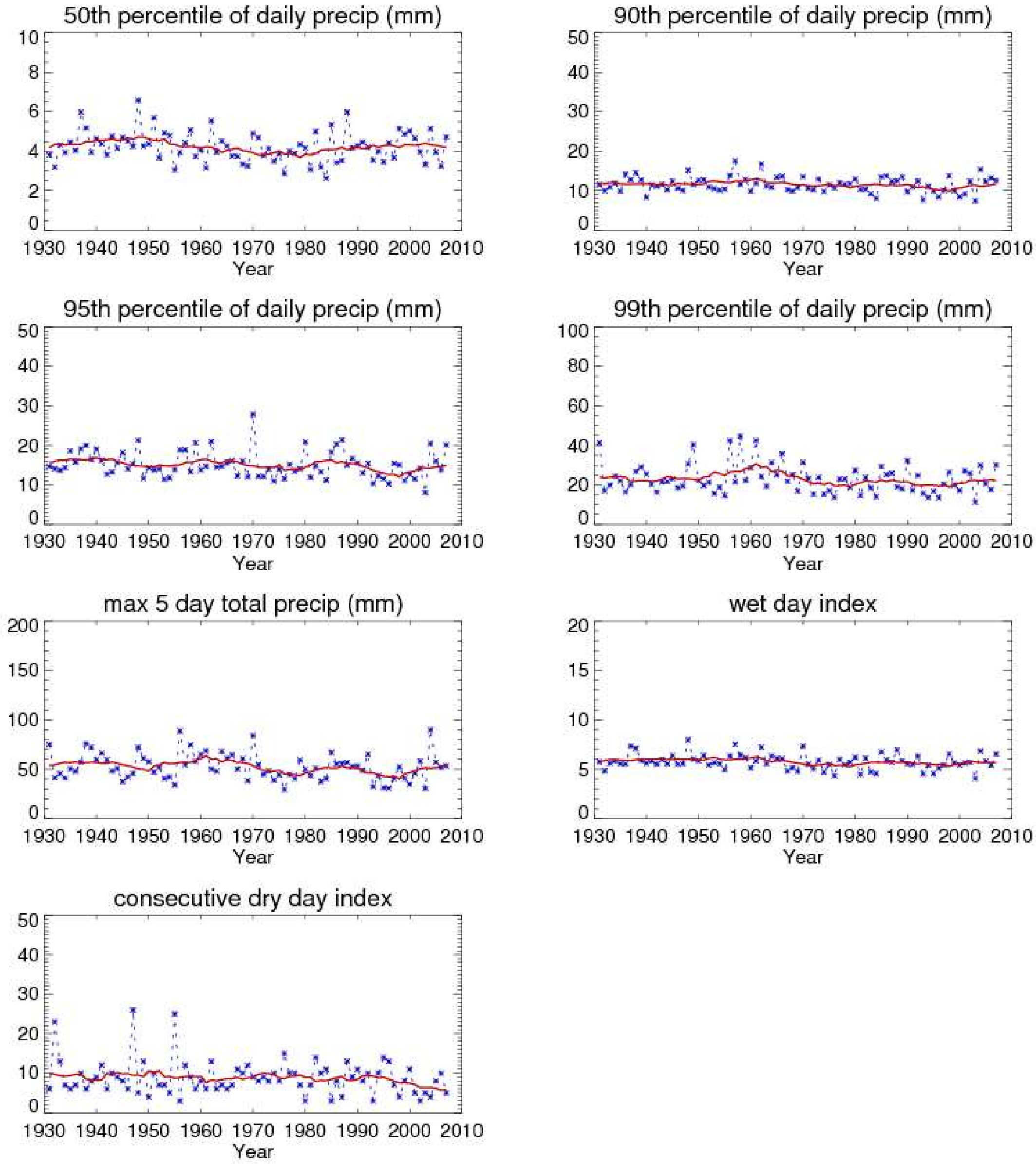


Fig 5.6 Measures of extreme daily precipitation over Scotland, 1931-2007, for the summer quarter (JJA). The red line represents a decadal moving average of the series.

5.2.4 Extreme UK daily precipitation in autumn, 1931-2007

The observed trends in autumn precipitation are weak and mixed in signal, with the only statistically significant results being a decrease in the 99th percentile for NWE and an increase in the maximum 5-day totals for SS. The trend signal in the Scottish regions is upward but, with just one exception, does not reach the 95% significance level, suggesting that as yet the increased autumn precipitation in Scotland is indistinguishable from natural short-term variability. The trends for each region for each variable are given in Table 5.4, while the plotted data and trend lines for England and Wales and for Scotland are given in Fig 5.7 and Fig 5.8 respectively. The lack of statistically significant trends is reflected by the lack of any obvious trends in the graphs, though in the case of Scotland the 50th percentile shows a peak in precipitation values around the 1980s followed by a slow decline in the 1990s and 2000s.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	0.88	1.27	0.15	1.01	0.52	0.22	1.79	0.76	0.91	0.34	1.02
90th percentile	0.23	0.85	0.83	-0.07	0.71	0.70	0.63	0.26	0.79	0.99	0.15
95th percentile	1.07	0.88	0.02	-0.25	0.14	0.66	0.44	0.65	0.95	0.33	-0.01
99th percentile	1.31	0.43	0.47	**-2.01**	-0.81	1.67	0.46	0.83	0.54	0.50	0.49
Max 5-day total	**1.98**	1.12	1.21	-0.81	-0.54	0.68	-0.29	-0.15	1.66	0.27	-0.68
Wet day index	1.05	1.22	0.35	-0.50	0.38	0.47	1.24	0.76	0.84	0.56	0.41
Consec. dry day	-0.49	0.16	-1.22	-0.55	1.01	-0.45	-0.44	-0.44	0.41	0.17	-0.30

Table 5.7. Trend values divided by the population standard deviation for each region, for each extreme precipitation index, for autumn (SON). Bold values reached the 95% significance level, underlined values reached the 99% significance level.

Measure	SS	ES	NS	NWE	NEE	CEE	SEE	SWE	S	NI	EW
50th percentile	0.33	0.06	0.29	0.18	0.08	0.10	0.11	0.12	0.26	0.13	0.01
90th percentile	0.14	0.01	0.18	0.21	-0.12	-0.02	0.07	0.14	0.10	-0.07	0.10
95th percentile	0.06	-0.08	0.05	0.18	-0.02	-0.09	0.04	0.06	0.20	-0.10	-0.00
99th percentile	0.20	0.10	0.12	0.16	0.01	-0.06	-0.09	0.12	0.21	-0.13	0.06
Max 5-day total	0.19	-0.06	0.22	0.10	-0.03	-0.08	-0.02	0.18	0.20	-0.11	0.14
Wet day index	0.25	0.00	0.29	0.27	-0.01	0.01	0.06	0.18	0.23	-0.04	0.09
Consec. dry day	-0.23	-0.19	-0.31	-0.04	-0.01	-0.13	-0.12	-0.08	-0.30	-0.13	-0.06

Table 5.8. Correlations between observed precipitation values by each extreme precipitation index and the seasonal NAO for autumn (SON) for each region. No values reached the 95% significance level.

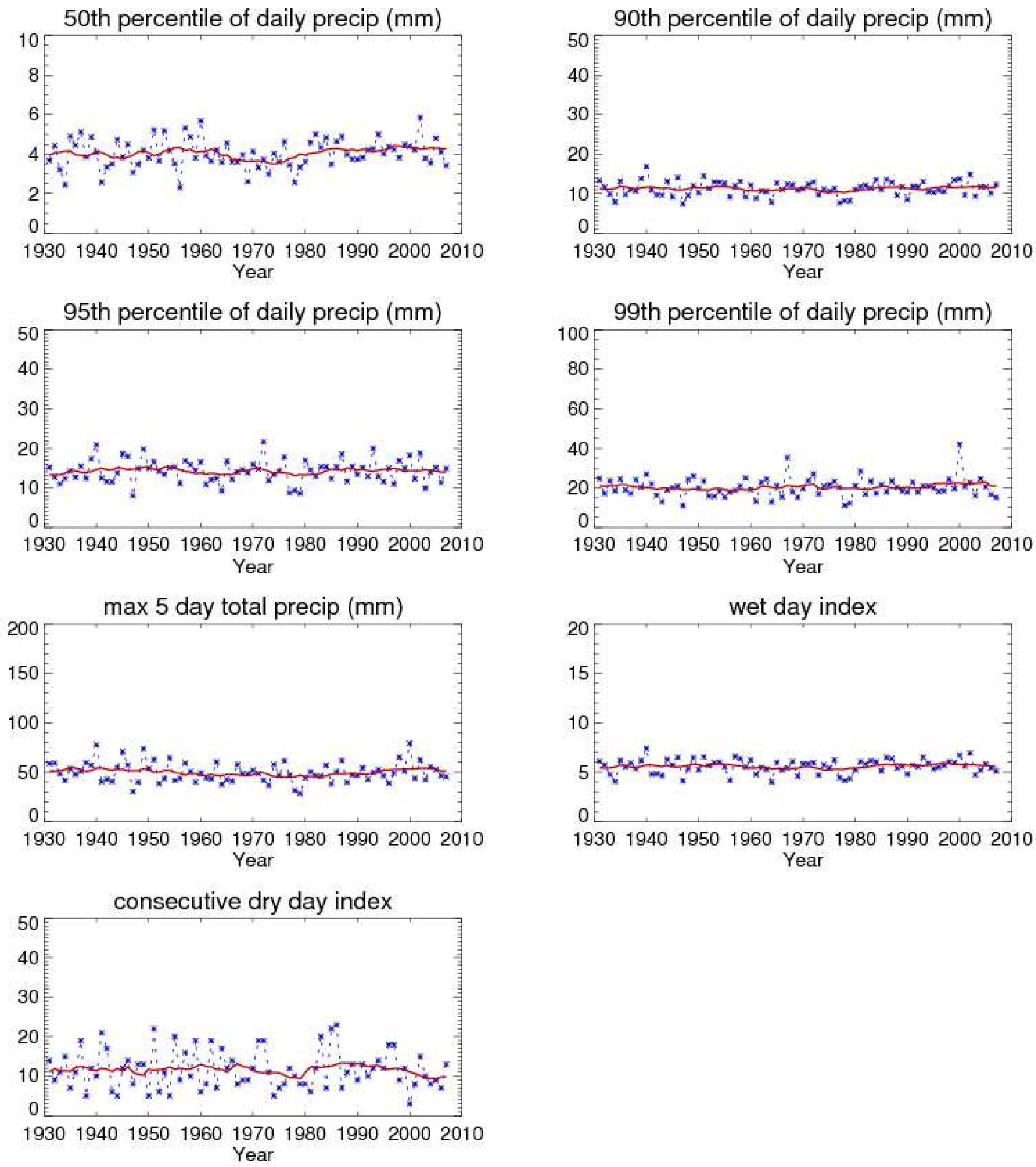


Fig 5.7 Measures of extreme daily precipitation over England and Wales, 1931-2007, for the autumn quarter (SON). The red line represents a decadal moving average of the series.

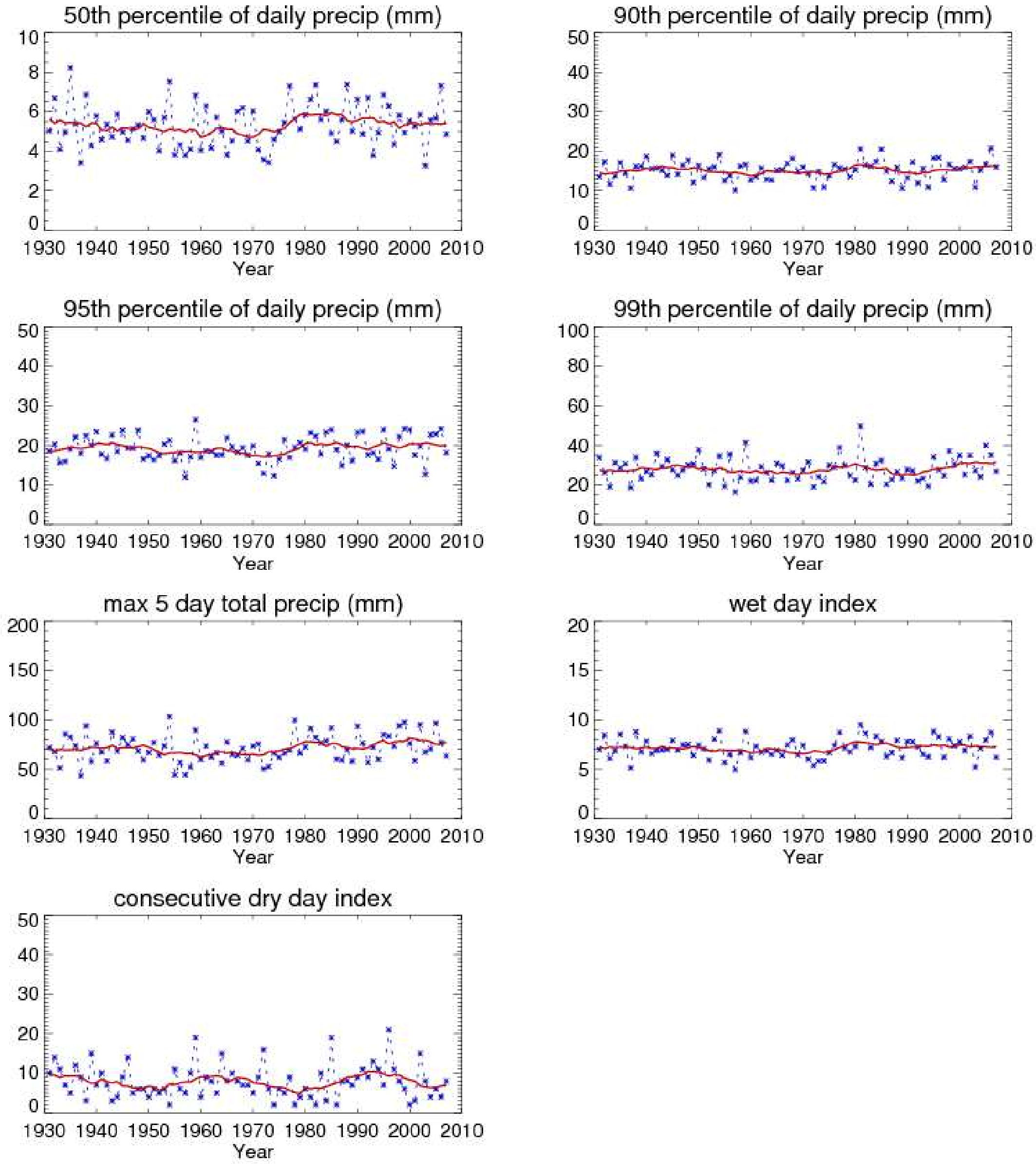


Fig 5.8 Measures of extreme daily precipitation over Scotland, 1931-2007, for the autumn quarter (SON). The red line represents a decadal moving average of the series.

5.3 Results from analysis of seasonal precipitation using monthly gridded data

The new monthly precipitation series, based on the 5km grids and extension using regression with the HadUKP series, are used to perform an analysis of long-term trends in precipitation. Monthly data spanned the period 1914-2006 for the Scottish regions and NI, 1873-2006 for the five England and Wales regions, and 1766-2006 for England and Wales. Trend lines and statistical significance are assessed in the same way as for daily extremes (see Section 5.1). Trends are also derived for the period 1931-2006 to give an approximate comparison with the results from the extremes analysis which used data for the period 1931-2007. Unfortunately the Met Office's gridded monthly data that was used in this work (which was used to generate regional monthly, seasonal and annual precipitation totals) did not yet extend to 2007.

5.3.1 Long-term trends in winter precipitation

Using the period 1931-2006, winter precipitation shows an increase in all regions, though this is statistically significant at the 95% level only in S and NS. The evidence for increased mean winter precipitation since 1931 is thus weaker than for the evidence for increased daily intensity, suggesting an emphasis on heavier and/or more prolonged daily precipitation. Extending the coverage for the Scottish regions and Northern Ireland to 1914-2006 causes the positive trends for S and NS to drop below 95% significance. Fig 5.2.2 suggests that Scottish winter precipitation remained consistent at 400-450mm until the mid 1950s, then temporarily fell towards 1970, and has increased to 450-500mm since the mid 1980s.

Extending the England and Wales regions to 1873-2006 increases the extent of the positive trends for those regions, though none of them reach 95% significance. In contrast, extending the England and Wales series to 1766-2006 results in an upward trend that is significant at the 99% level. Fig 5.9 shows an erratic upward trend in England and Wales winter precipitation over the 241-year record, with a mean of near 200mm until around 1860, increasing to nearer 250mm since the 1920s. The trend is unlikely to be due to improved rainfall/snowfall recording and more likely a consequence of higher sea surface temperatures and/or a change towards a more positive NAO.

5.3.2 Long-term trends in spring precipitation

Using the period 1931-2006, all regions have seen an increase in mean spring precipitation, with the largest increases occurring in northern and western Britain over the period. Increases have reached the 95% significance level in NWE, and the 99% significance level in SS, NS and S. Thus, unlike in winter, the increases in mean daily intensity are matched or exceeded in terms of statistical significance by increases in the mean monthly amounts. The least statistically significant increases occurred in CEE and SEE. Fig 5.3.2 suggests little or no trend in Scottish spring precipitation until approximately 1980 and then a sharp upward trend.

Extending the period of coverage to 1914-2006 over the Scottish regions and Northern Ireland reduced the extent of the upward trend, but increases in SS, NS, S and NI are still significant at the 95% level. Increasing the England and Wales period to 1873-2006 resulted in a regional shift in the distribution of positive changes, with a much weaker upward trend shown in NWE which does not approach 95% significance, while conversely a much increased positive trend for SWE comes close to reaching 95% significance. England and Wales as a whole saw an upward trend over the period 1766-2006 but it is not statistically significant. Fig 5.3.1 illustrates the lack of a strong trend in spring precipitation in England and Wales.

5.3.3 Long-term trends in summer precipitation

Over the 1931-2006 period, mean monthly summer precipitation shows a downward trend in all regions. In ES, NS, NWE, S and NI, the trend is significant at the 95% level. Given the much weaker evidence for a decline in precipitation intensity and high extreme precipitation, this suggests that the trend for drier summers in the UK has not been associated with a reduction in summer extreme precipitation.

The Scottish trends for 1914-2006 are also downward, but only reach the 95% significance level in ES, while in NI the significance of the trend increased, reaching the 99% level. The England and Wales regions show a more significant decline in precipitation when the period was extended to 1873-2006, with all regions displaying a decline that is significant at the 95% level. England and Wales as a whole have had a downward trend that reaches the 99% level of significance over 1766-2006. Fig 5.3.1 suggests that much of the decrease has occurred since the 1960s, and Fig 5.3.2 shows a similar decline since the 1960s in Scotland.

5.3.4 Long-term trends in autumn precipitation

Over the period 1931-2006, NEE is the only region to experience a downward trend in autumn precipitation, but while other regions consistently show upward trends, the upward trend is only significant at the 95% level in NS, while it came close to 95% significance in SS and S. This is similar to the existent, but not statistically significant, evidence for an increase in extreme precipitation in autumn.   Over the period 1914-2006, the trend reached close to 95% significance in SS, S and NS, but reduces close to zero in ES. The England and Wales regions over 1873-2006 show statistically insignificant downward trends in SEE and CEE, and weak upward trends in the other regions. Over 1766-2006, the trend in autumn precipitation over England and Wales is weakly negative. Fig 5.3.1 suggests no long-term trend in autumn precipitation over England and Wales, with the comparatively high decadal average of the 1990s and 2000s being skewed upwards by the record-breaking wet autumn in 2000. Fig 5.3.2 suggests an erratic upward trend in Scottish autumn precipitation since approximately 1975.

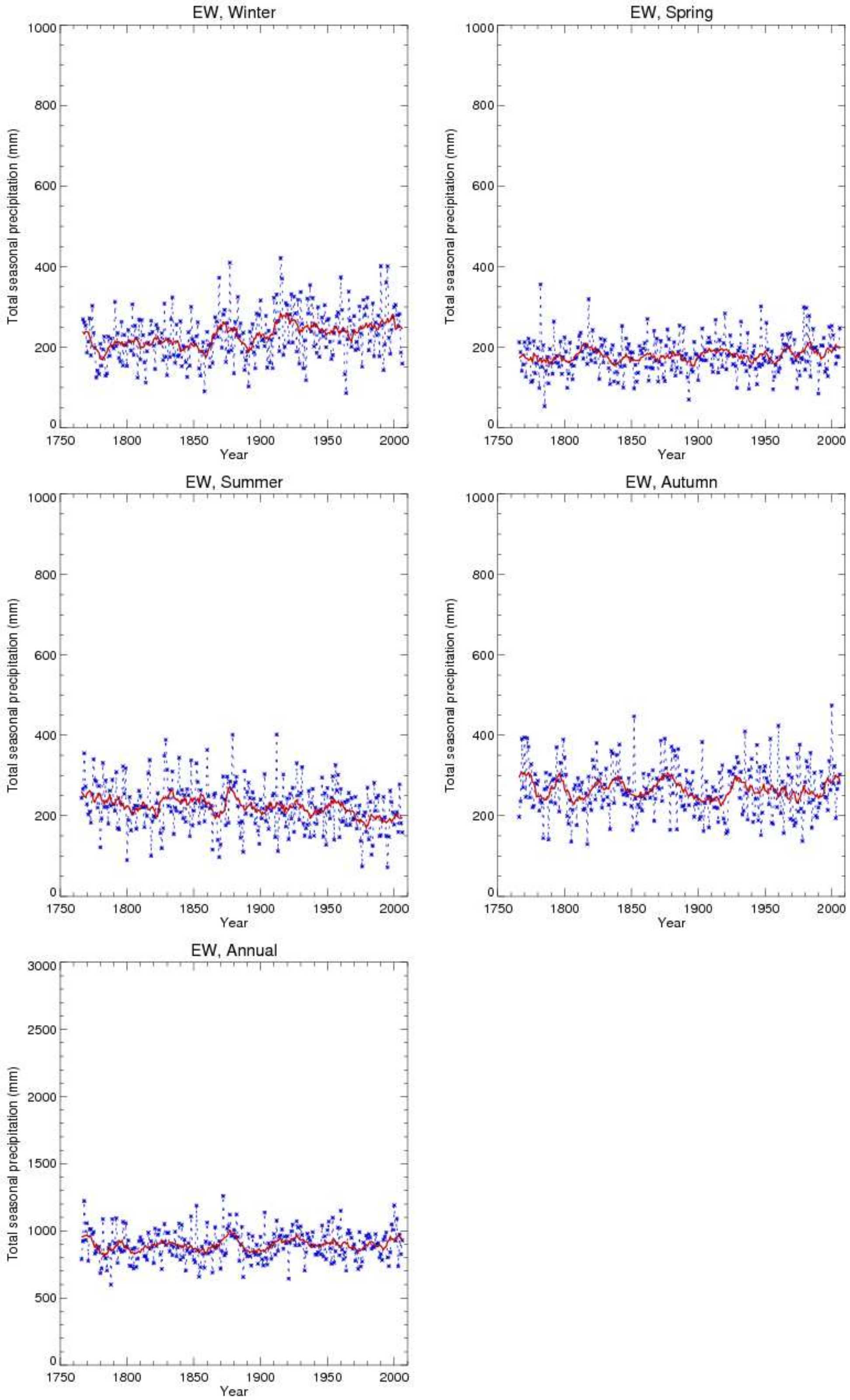


Fig 5.9 England and Wales seasonal and annual precipitation using MOHC06m, 1766-2006. There is an upward trend in winter and a downward trend in summer.

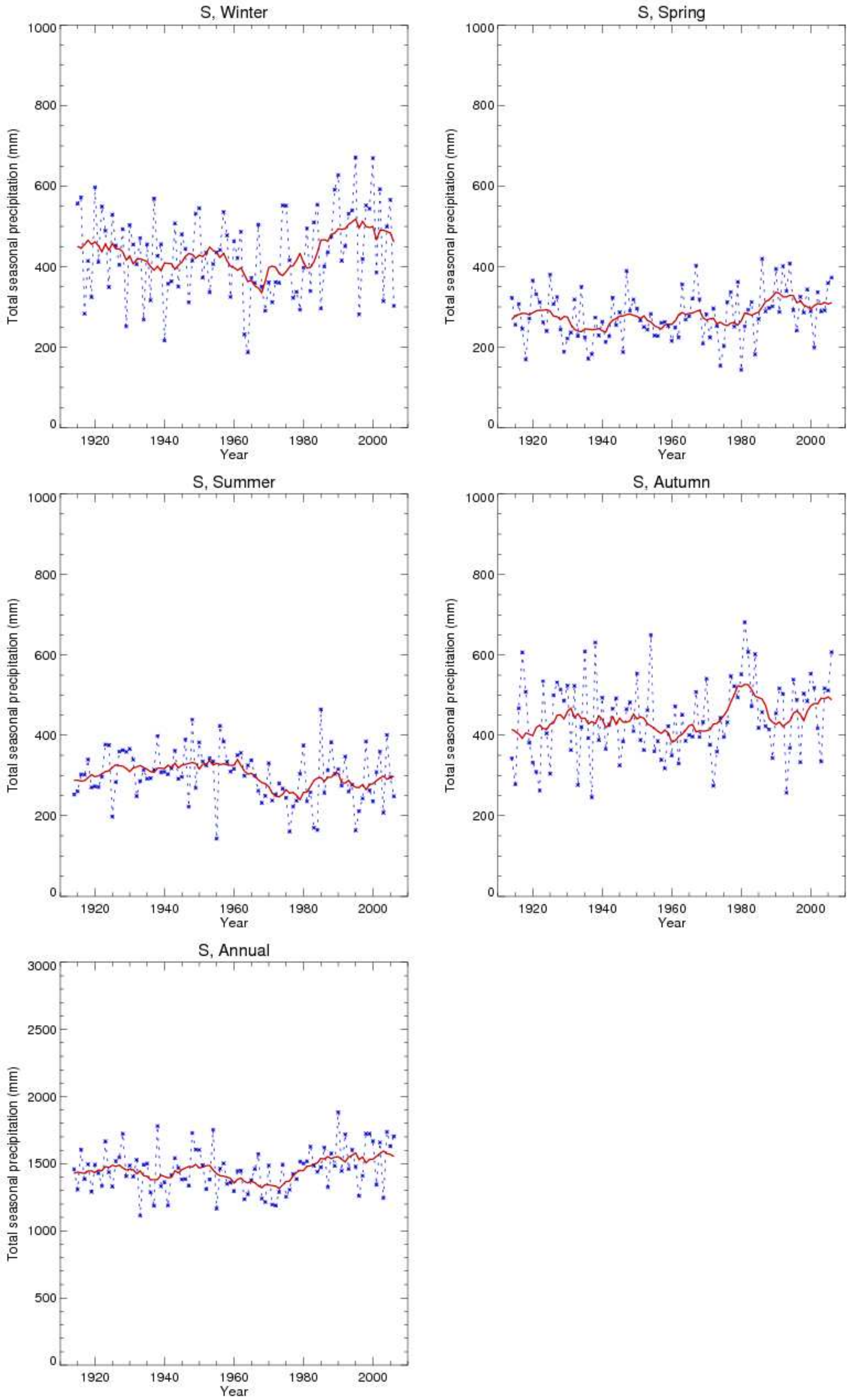


Fig 5.10 Scotland seasonal and annual precipitation using MOHC06m, 1914-2006. There is an upward trend in winter and a downward trend in summer.

5.4 Conclusions and Discussion

Chapters 4 and 5 have extended the work on UK rainfall (see Chapter 2) ranging from Wigley et al. (1984) to Alexander and Jones (2001), providing a new homogenised UK precipitation series and analysing observed trends in the data, including the use of several indices of extreme precipitation and assessments of the statistical significance of precipitation trends and in correlations between precipitation and the NAO. This statistical analysis is the first such analysis to be applied to a UK-wide rainfall dataset based on a comprehensive network of rain gauges, albeit developed with the use of interpolation particularly in the more sparsely populated regions.

UK winter precipitation amounts and intensity have shown an upward trend over the analysis period, with a larger emphasis on increased intensity rather than increased raw amounts. The increases have been most pronounced across the Scottish regions, and to a lesser extent in Northern Ireland, NWE and NEE. In contrast there is no substantial evidence for an increase in winter precipitation amounts in CEE and SEE. Some caution is needed over using the increases in northern Britain as evidence of a long-term trend, as the NAO switched to a strongly positive state during the 1990s (Gillett, 2005) and a positive NAO is correlated with higher winter precipitation in northern and western Britain as well as increased mean wet-day amounts, consistent with the findings of Osborn et al. (2000) and Osborn et al. (2008). This is also supported by the decline in precipitation amounts and intensity during the 2000s, which is correlated with a decline in the mean signal of the NAO during the same period. The fact that the 50th percentile showed more significant increases over the period in the most affected regions than the extreme precipitation indices, and that the 50th percentile is most strongly correlated with the NAO for the same regions, supports the notion that much of the increase may be due to changes in the NAO. There is some evidence that anthropogenic forcing may contribute to the northward shift of the polar jet and increasingly positive NAO (Gillett et al., 2003) but this does not explain the large shift in the Atlantic storm track and positive NAO observed in the 1990s (Gillett, 2005), suggesting that the results obtained here could be largely or entirely due to inter-decadal variability. The England and Wales series suggests a statistically significant increase in winter precipitation amounts over the period 1766-2006, indicating that winters were generally drier in the late 18th and 19th centuries than during the twentieth century.

In spring, there is a similar trend for increased extreme precipitation, especially increased wet-day amounts, though the signal for increased maximum 5-day extreme precipitation is weaker. Spring precipitation and precipitation intensity have shown stronger trends over Scotland than over England and Wales, which is consistent with the findings of Alexander and Jones (2001) and Osborn et al. (2000). In contrast to the increases noted in the other measures of extreme precipitation, there were marked decreases in the 90th percentile of wet-day precipitation in some regions.

There is evidence in Scotland for a strong increase in precipitation in the 1980s and 1990s and a decline in the 2000s, which may, as with winter precipitation, be related to changes in the NAO. The analysis for England and Wales suggested that the increase in north Wales and north-west England has been more significant in recent years, whereas the increase in south Wales and south-west England became more significant when the series was extended back into the late 19th century.

Summer precipitation has shown a downward trend in all regions, regardless of which time period is used, but the signal for decreased mean precipitation is stronger than for decreases in extreme summer precipitation. This finding differs from some recent studies such as Osborn et al. (2000) and Fowler and Kilsby (2003a, 2003b), suggesting that the summers of the 2000s may have produced more extreme precipitation events, offsetting the prior observation of a significant move towards less intense events. NWE showed a significant decline in the mean wet-day precipitation and the wet day index, and there were consistent declines in the Scottish regions, but in CEE, SEE and NEE some variables showed upward trends, notably the 99th percentile of wet-day precipitation and 5-day maxima in NEE. This appears to be associated with individual extreme events in the 2000s (August 2004, June 2007 and July 2007 were all exceptionally wet) and involves too short a timescale to be able to determine whether it is part of a long-term trend towards more extreme summer precipitation. Over much of the country there is evidence for a period of drier summers between the 1970s and 1990s, peaking in the 1990s, followed by a reversal of the trend in the 2000s. Although Osborn et al. (2000) noted a decline in the frequency of wet days in summer, there is no evidence of an increase in the length of dry spells as denoted by the consecutive dry day index. Extending the period of coverage for England and Wales to 1766-2006 suggested that there has been a slow decline in England and Wales summer precipitation over the period, with wetter summers in the late 18th and 19th centuries than in the twentieth century.

Autumn precipitation has shown weak upward trends, both for absolute amounts and extremes, over the UK. In Scotland there was a period of anomalously high precipitation centred around 1980, followed by a decline to values close to the long-term average. Thus there is only limited evidence to suggest that the record-breaking wet autumn of 2000 was part of a long-term trend towards more extreme precipitation in autumn; the wet autumn of 2000 could also be explained largely by anomalous atmospheric circulation patterns, in particular the persistence and intensity of low pressure systems and southerly displacement of the jetstream (Blackburn and Hoskins, 2001), although Pall et al. (2011) argue that anthropogenic global warming probably increases the likelihood of such extreme wet autumns occurring. The findings for annual precipitation are consistent with those found in earlier studies, with no long-term trend over England and Wales, but an increasing trend in Scotland due to the wetter winters and springs.

Overall, these results support the general consensus from earlier studies that winters and springs have been becoming wetter, with more extreme precipitation, over northern and western Britain. Caution must be exercised when deriving conclusions from statistical significance of precipitation trends, as separating signals of long-term anthropogenic forcing from multi-decadal variability is a non-trivial task (Osborn et al., 2008). For example much of the observed increase in winter precipitation and intensity may be due to changes in the NAO, which have been far stronger than can be explained by anthropogenic forcings alone. More data will be needed to determine with near-certainty whether the recent increases in winter and spring precipitation are part of a long-term trend that we can expect to continue due to anthropogenic forcings over the coming century, though the evidence from both data and climate models continues to suggest that this is the most probable scenario. However, the evidence for drier summers is less convincing, and there is evidence of a strong recovery in summer precipitation during the 2000s following frequent dry summers between the 1970s and 1990s.

6. Regional climate model simulations of precipitation: comparisons with observed values using ERA-40 forced runs

6.1 Summary

This chapter assesses the accuracy of nine regional climate models at simulating precipitation patterns across the UK, focusing on mean rainfall, extreme rainfall and the pattern of convective vs large-scale rainfall, using model integrations from the ENSEMBLES project. The analysis uses ERA-40 forced runs since this is the best an RCM-based analysis can do (the ERA-40 reanalysis approximates past conditions more closely than GCM runs, and it also ensures a like-for-like comparison, whereas, for example, using different GCMs to drive the RCMs would make the results prone to bias due to the different strengths and weaknesses of individual GCMs. Section 6.2 gives some background information on ERA-40 and the ENSEMBLES project, then Section 6.3 covers the results of the RCM analysis. Section 6.4 derives conclusions from the analysis in Section 6.3 and determines which of the RCMs are the best performing at simulating precipitation and some of its variability across the UK.

6.2 The ERA-40 reanalysis

The ERA-40 reanalysis, produced by the European Centre for Medium-Range Weather Forecasting (ECMWF), is based upon observed data from a wide variety of sources, including both satellite and conventional observations (ECMWF, 2007), and is based on Cycle 23r4 of the ECMWF's Integrated Forecast System (ECMWF, 2004), providing 6-hour forecasts. The quality of the ERA-40 reanalysis has been assessed positively through the accordance with mean observed sea-level pressure and geopotential 500hPa temperatures being very high in the Northern Hemisphere, but there is considerable "noise" in the Southern Hemisphere outputs, particularly prior to 1979 (ECMWF, 2004). Although there are problems with the handling of precipitation in the tropical oceans, precipitation is well-handled across the Northern Hemisphere continents (ECMWF, 2002, Bosilovich, 2008). Klepp et al. (2005) suggest that the ERA-40 reanalysis is good at handling frontal precipitation from depressions in the North Atlantic, but that significant convective precipitation events from post-frontal depressions in polar outbreaks in winter are mainly absent.

This implies that the ERA-40 reanalysis may underestimate the extent of troughs and polar lows, and associated convective activity, during wintertime outbreaks of polar air across the UK. These issues will be taken into account during the remainder of this chapter.

6.2.1 The ENSEMBLES project

The ENSEMBLES project has been a five-year research project, involving 67 institutions across Europe, led by the Met Office and funded by the European Commission (Met Office, 2010). Its aims were to generate probabilistic projections of temperature and precipitation changes over the 21st century, assess the likely impacts of climate change, gain a clearer picture of the feedback processes within the climate system and provide high-resolution climate observation datasets for Europe which can be used to validate climate model performance. Model runs are available for 13 RCMs driven by the ERA-40 reanalysis, for comparison with observed data, and future projections are available from the same RCM integrations driven by associated global climate models.

6.3 Verification of the accuracy of precipitation simulations of ERA-40 driven models

Using the RCM integrations from the ENSEMBLES project, gridded UK daily precipitation at 25km resolution was extracted from nine different RCMs, covering the period 1958-2002 (see Table 6.2). All of the models were driven by the ERA-40 reanalysis from ECMWF. These outputs are compared with the observed daily precipitation derived from the Met Office gridded 5km data, for which John Caesar (UK Met Office) generated a 25km version in order to make direct comparisons possible with the RCM outputs. The comparisons discussed in this chapter have been generated via plots using 25km grid boxes superimposed on a map of the UK, highlighting the geographical distribution of precipitation-related variables and anomalies relative to the observed data. Only eight of the models have been used due to the fact that the other models used different grids, making direct comparisons with observed data less straightforward.

There have been many previous studies relating to the earlier PRUDENCE ensemble (e.g. Beniston et al, 2007, Fowler et al., 2010, Fowler and Ekstrom, 2009, and Frei et al., 2006) which focused on the estimated changes in climate variables, including precipitation extremes, across the UK and Europe between the present and the period 2071-2100 in association with IPCC climate change scenarios, using model runs driven by associated GCMs, but none of these studies committed to strong conclusions regarding the relative performances of the individual models. Frei et al. (2003) performed an analysis of daily precipitation simulation in five RCMs driven by ERA-15, the previous version of the ECMWF reanalysis (ECMWF, 2004), centred on the European Alps, and noted that the use of ERA-15, rather than global climate model integrations, as the driving mechanism significantly reduced the extent of the circulation anomalies that affected the results for GCM-driven RCMs.

Here, the reliability of simulations of UK precipitation from eight individual RCMs from the PRUDENCE ensemble is assessed, covering mean precipitation totals and correlations with observed values as well as extremes, and this includes an analysis of how realistically the models handle convective precipitation as opposed to large-scale precipitation. The use of ERA-40 as the driving model in all cases enables direct comparisons to be made between the outputs of the different models. This enables an assessment of the best that RCMs can do with the current generation of RCMs.

The following variables are used to test the accuracy of the models:

1) Seasonal precipitation totals.
2) Percentage of the total precipitation that is of convective origin (as opposed to large-scale).
3) 1, 2, 5 and 10-day seasonal maxima (taking a mean over the 40 year period, and computing absolute maximum values over the entire period)
4) The correlation between observed and simulated daily precipitation values

It has not proved possible to determine the breakdown of observed convective vs large-scale precipitation, so this variable is used mainly to test whether the models give a realistic representation of the regional distribution of convective precipitation. The other variables are all compared directly with observed values from the 25km version of the NCIC gridded dataset.

6.3.1 Simulations of seasonal precipitation totals

Simulations of seasonal precipitation totals show a bias for most model outputs towards overestimates in central, eastern and southern England and underestimates in western districts during winter (see Fig 6.1). This distribution is most prominent in winter but is also evident during spring (Fig 6.2) and autumn (Fig 6.4). This is consistent with the findings of Fowler and Kilsby (2007b) when analysing the ensemble of RCMs when driven by GCMs, and implies a tendency for RCMs to underestimate orographic enhancement in the west and the rain shadow effect in the east. Summer precipitation (Fig 6.3) is generally underestimated by HadRM3, RACMO2, HIRHAM5, HIRHAM and CLM, but REMO, RCA and RCA3 show different patterns.

HadRM3 produces the smallest positive anomalies in south-east England in winter and spring, with overestimates of 20-40% over a small area around the Wash in winter, but it also underestimates over most of upland Britain, particularly the Scottish Highlands where underestimates approach 50% in autumn and winter, and there is a consistent tendency to overestimate precipitation along the west coast of Scotland in all four seasons, with overestimates of 40% or more locally. Spring precipitation is overestimated by HadRM3 across most southern and eastern parts of England with overestimates in the 40-60% range. Summer underestimates from HadRM3 are of the order of 10-20% over most of the country.

RACMO2 produces the smallest anomalies out of the models considered, but produces overestimates over a wider area of eastern England than HadRM3 during autumn and winter, with overestimates of apprixmately 40% in parts of eastern England in winter. Precipitation is underestimated in many western and upland areas but not by more than 20%, while in summer small underestimates occur over most of the country. Overall both HadRM3 and RACMO2 accurately pinpoint the general distribution of precipitation over the UK but underestimate the extent of the difference between the wettest and driest parts of the country.

The HIRHAM5 outputs suggest that the model has problems resolving precipitation around some coastal fringes, with overestimates of 60% or more for some grid boxes around the coasts, most notably Teeside, the Wash and south-east Scotland. Precipitation is overestimated significantly in central and eastern England in winter with excesses of 40-60% at some grid boxes, and it is underestimated in most upland and western areas, particularly in summer when underestimates approach or exceed 50% at some grid boxes, but in spring and autumn, with the exception of the aforementioned large anomalies around the coasts, the HIRHAM5 outputs show similar accordance with observed values to those of HadRM3 and RACMO2.

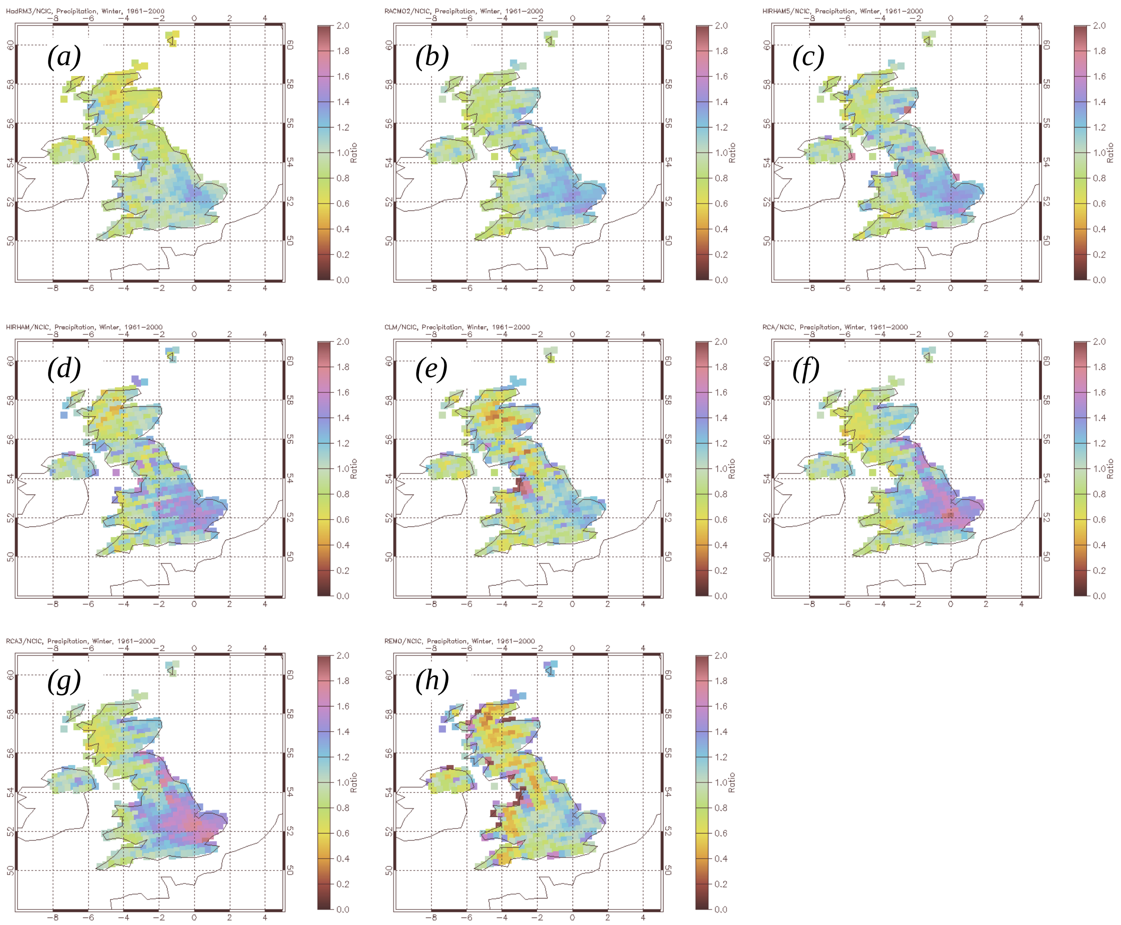


Fig 6.1. Ratio of mean simulated seasonal precipitation for the period 1961-2000 to NCIC observed precipitation, for boreal winter (DJF). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

HIRHAM, an earlier revision of HIRHAM5, performs less well than HIRHAM5, with sharp contrasts between anomalies at adjacent grid boxes highlighting the fact that the model does not handle the distribution of precipitation across the UK as accurately as HadRM3, RACMO2 or HIRHAM5. Precipitation is overestimated by 40-60% over large areas of eastern England during winter, while there is a tendency for underestimates in upland and western areas. Summer precipitation shows the greatest accordance with observed values but even in summer there are considerable differences in anomalies between adjacent grid boxes.

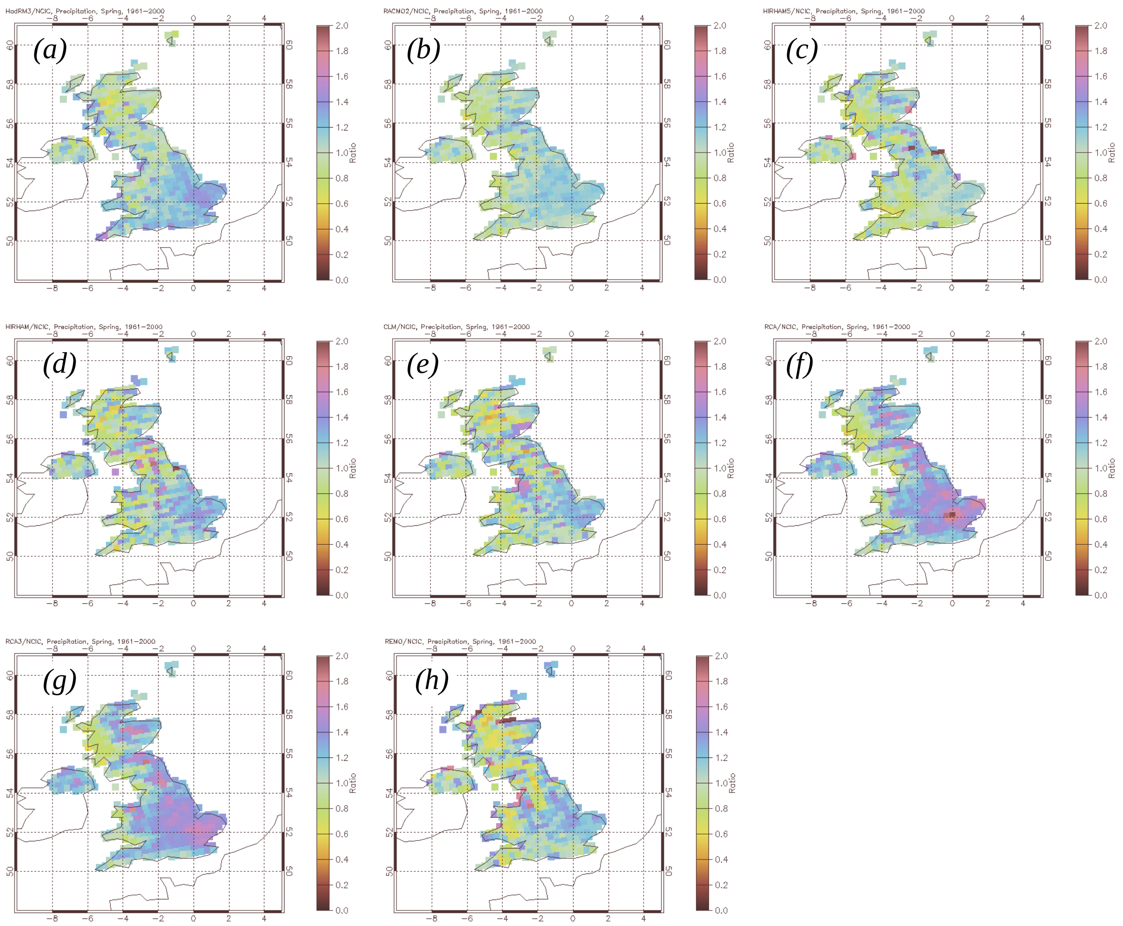


Fig 6.2. Ratio of mean simulated seasonal precipitation for the period 1961-2000 to NCIC observed precipitation, for boreal spring (MAM). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

CLM produces a clearly-defined pattern of underestimates in upland areas and overestimates along the west Lancashire coast in autumn and winter, which is most pronounced in winter, giving west Lancashire almost twice the observed amount of rainfall, and parts of the Scottish Highlands less than half the observed amount. This suggests that the model underestimates orographic enhancement. In spring and summer the anomaly patterns are less well-defined and in summer overall accordance with observed values is only slightly poorer than that displayed by RACMO2.

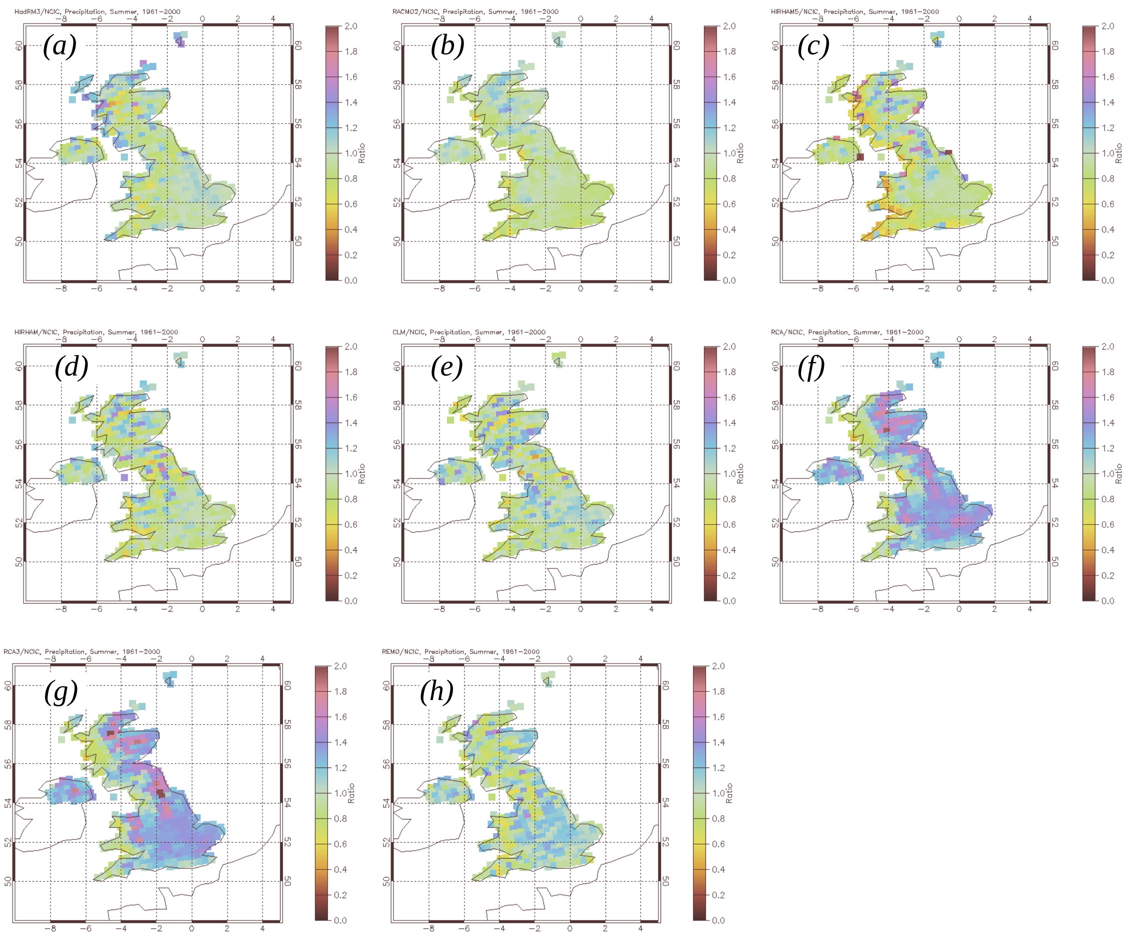


Fig 6.3. Ratio of mean simulated seasonal precipitation for the period 1961-2000 to NCIC observed precipitation, for boreal summer (JJA). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

RCA, RCA3 and REMO all have more fundamental problems handling the distribution of mean UK precipitation. Both RCA and RCA3 seriously overestimate precipitation in eastern areas (overestimates of 40 to 80% occur widely) and slightly underestimate in most western coastal districts. The overestimates occur mostly over eastern England in winter and spring, but extend to the eastern two-thirds of Scotland in summer and autumn and also to central parts of England. The RCA outputs produce far more extreme versions of the anomalies seen in the CLM outputs, with well-defined areas of large underestimates in upland regions of the UK and overestimates approaching 100% in some west-coast areas, particularly the Lancashire coast, suggesting a severe underestimation of the effects of orographic forcing.

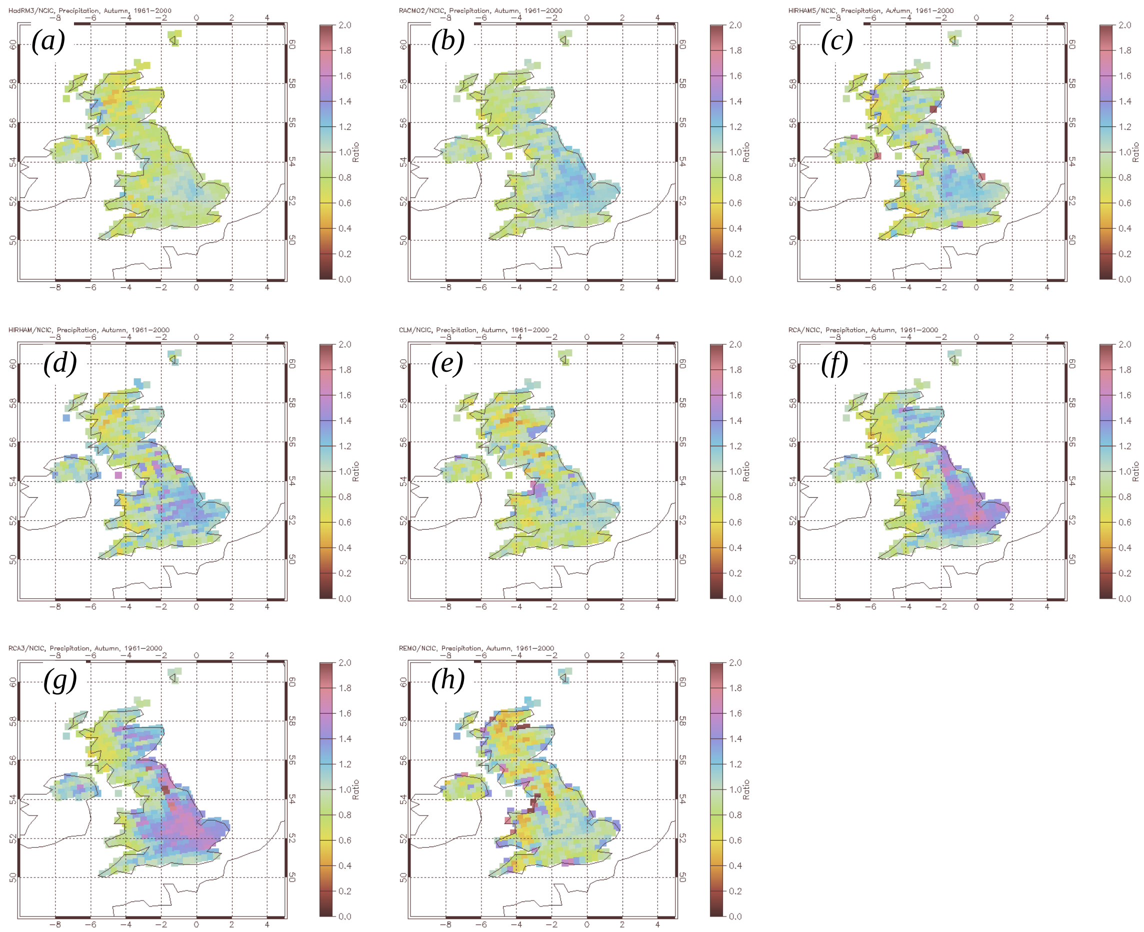


Fig 6.4. Ratio of mean simulated seasonal precipitation for the period 1961-2000 to NCIC observed precipitation, for boreal autumn (SON). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

Overall, by this measure RACMO2 performs best out of the models considered, though it underestimates summer precipitation and overestimates in most central and eastern parts in winter, spring and autumn. HadRM3 is a close second and gives similar anomaly patterns but underestimates precipitation all year round in parts of the Scottish Highlands and overestimates along the west coast of Scotland. HIRHAM5 slightly outperforms HIRHAM and CLM but is well behind RACMO2 and HadRM3, while RCA, RCA3 and REMO have very significant problems in reproducing UK seasonal precipitation totals.

6.3.2 Simulations of mean and median 1, 2, 5 and 10-day maxima

Extreme precipitation anomaly distributions are similar to those for seasonal precipitation totals but the models have a stronger tendency to underestimate extreme precipitation over larger areas of the country than for seasonal precipitation, consistent with earlier studies which have found that climate models generally produce too much light precipitation and drizzle at the expense of extreme high precipitation (e.g. Dai et al., 2006). There is a consistent tendency for extreme precipitation to be underestimated to the largest extent in upland and western regions of the country, while winter, spring and autumn (especially winter) see slight overestimates in parts of eastern England for most outputs.   Fig 6.1.5, 6.1.6, 6.1.7 and 6.1.8 show the respective ratios of simulated mean 5-day maxima for winter, spring, summer and autumn relative to observed values for all of the models considered.

When assessing extreme precipitation, HadRM3 shows a similar anomaly distribution as for mean precipitation but with a tendency to underestimate over a larger proportion of the country.   The mean and median 1, 2, 5 and 10-day extreme precipitation are overestimated in western Scotland in all four seasons, by more than 40% at a few individual grid boxes. The 5 and 10-day maxima are generally overestimated in spring across England and Wales, by 10-20% at most grid boxes, but the 1 and 2-day maxima are less so, while in winter overestimates occur in a small area centred around Cambridge. Otherwise, extreme precipitation is underestimated by 20% and locally by as high as 40% across most of the country, and the underestimates are most pronounced for 10-day maxima.

As with mean precipitation, underestimates are most consistent and most pronounced in upland parts of Britain. This is broadly consistent with the findings of Rivington et al. (2008), who noted a tendency for HadRM3 to “drizzle” too much, giving too high a number of small rainfall events and with rare exceptions, the most extreme events were underestimated across the UK.

RACMO2 shows a consistent pattern of underestimates of extreme precipitation over most of the country, for the mean and median 1, 2, 5 and 10-day maxima.   In spring, extreme 1 and 2-day precipitation is underestimated by 20-40% in most regions with the exception of eastern England where some grid boxes have overestimates of up to 20%, but underestimates are less dominant for extreme 5-day precipitation and less dominant still for extreme 10-day precipitation, with only western Scotland, west Wales and the south of south-west England having general overestimates of 20%. Extreme winter precipitation is overestimated by up to 20% in parts of eastern England and southeast Scotland and underestimated by 20-40% in most other regions, while extreme autumn precipitation shows a similar anomaly distribution but with the area of overestimates being less widespread, centred around Cambridgeshire. Extreme summer precipitation is underestimated by 20-40% in most regions including eastern England.

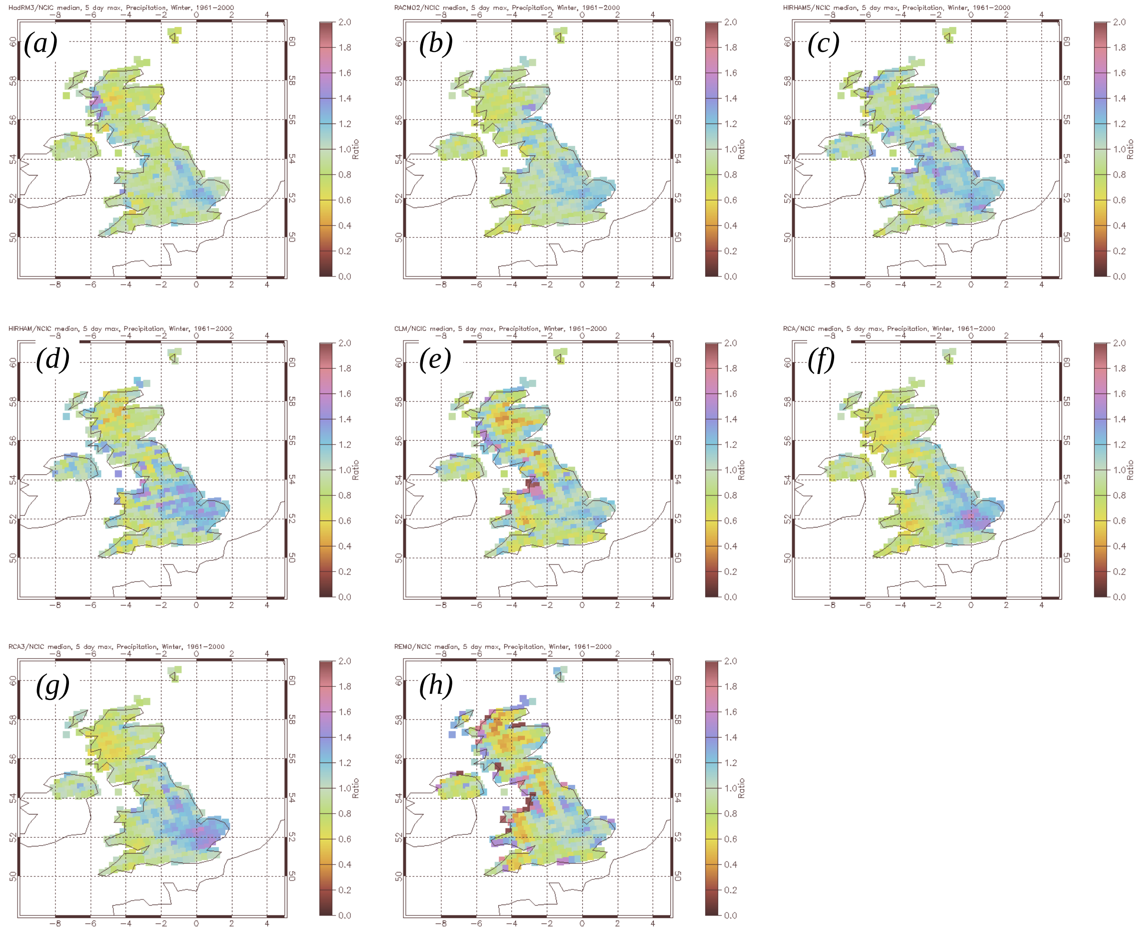


Fig 6.5. Ratio of median 5-day maximum rainfall,1961-2000 to NCIC observed precipitation, for boreal winter (DJF). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

HIRHAM5 shows a less spatially coherent pattern of anomalies for projections of mean and median 1, 2, 5 and 10-day maximum precipitation, with significant differences between adjacent grid boxes, suggesting that the model has problems handling the distribution of extreme precipitation in the UK, more so than for seasonal precipitation totals. Although the percentage anomalies are lower at the individual grid boxes that saw large overestimates of seasonal precipitation, the absolute errors are still very large due to the fact that larger absolute values are being compared, especially in the case of 5 and 10-day extremes. Extreme winter precipitation is generally overestimated by 20-40% in a band extending across from west Lancashire to East Anglia, and spring has a mixed pattern but with most grid boxes within 20% of observed values, but overestimates approach 100% at one grid box in east Cumbria. Summer and autumn have underestimates across most parts of the country, particularly for 5 and 10-day maxima and particularly around many coastal areas.

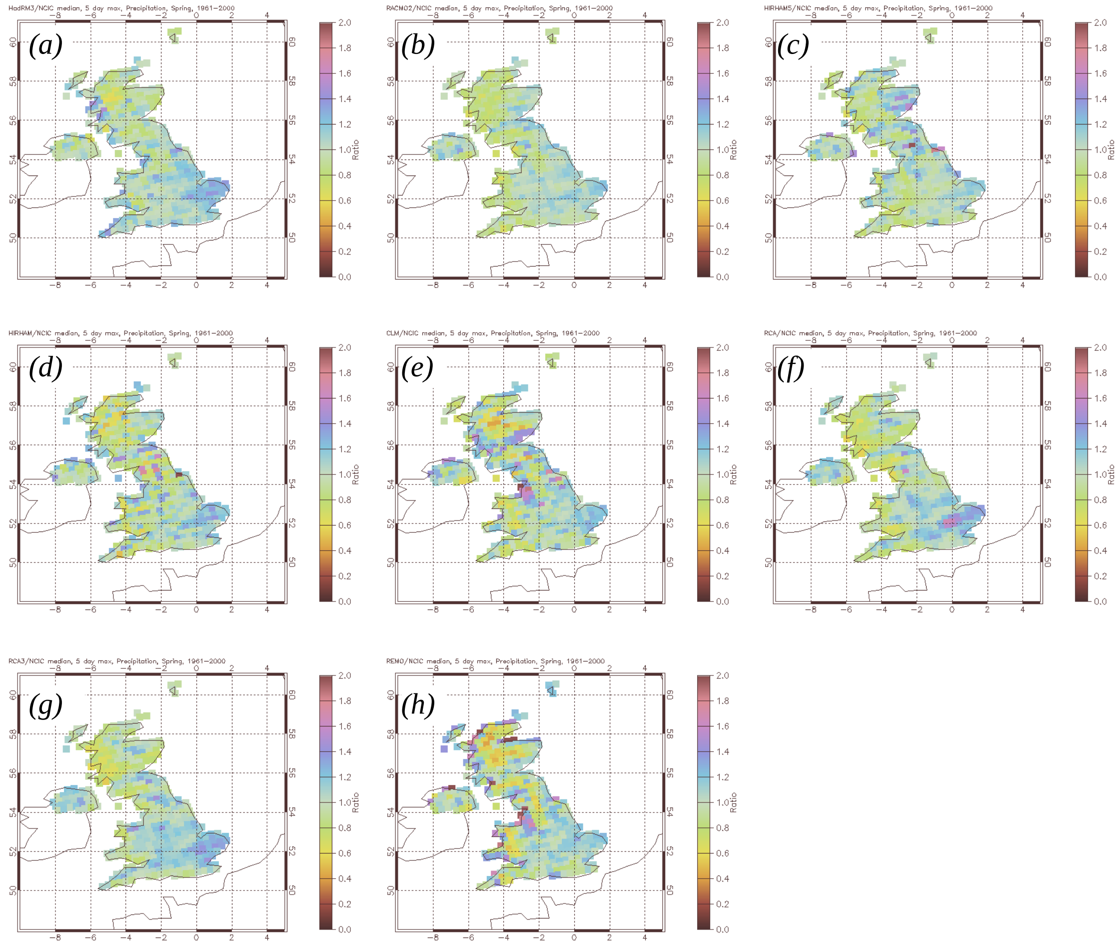


Fig 6.6. Ratio of median 5-day maximum rainfall,1961-2000 to NCIC observed precipitation, for boreal spring (MAM). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

As with the results for mean precipitation, extreme precipitation is handled more poorly by the other models. HIRHAM has a larger problem with spatial incoherency of anomalies than HIRHAM5, with a general tendency to significantly overestimate extreme precipitation in winter (by 20-40%) in eastern and central England, and underestimates of 20-40% in most areas in summer, and similar underestimates in central and western Scotland and west Wales in spring, autumn and winter also. As with the HIRHAM5 outputs, extreme 5 and 10-day spring precipitation is overestimated by almost 100% at some grid boxes in the north Pennines.

CLM shows a similar pattern of anomalies to the pattern for mean precipitation, with underestimates of extreme precipitation in upland areas in winter, spring and autumn, particularly the Scottish Highlands, and overestimates along the Lancashire coast, most strongly so in winter. In summer extreme precipitation is generally overestimated by 20-40% in East Anglia but underestimated by 20-40% at most grid boxes in other regions of the UK. 5 and 10-day extreme precipitation is mostly overestimated in spring.

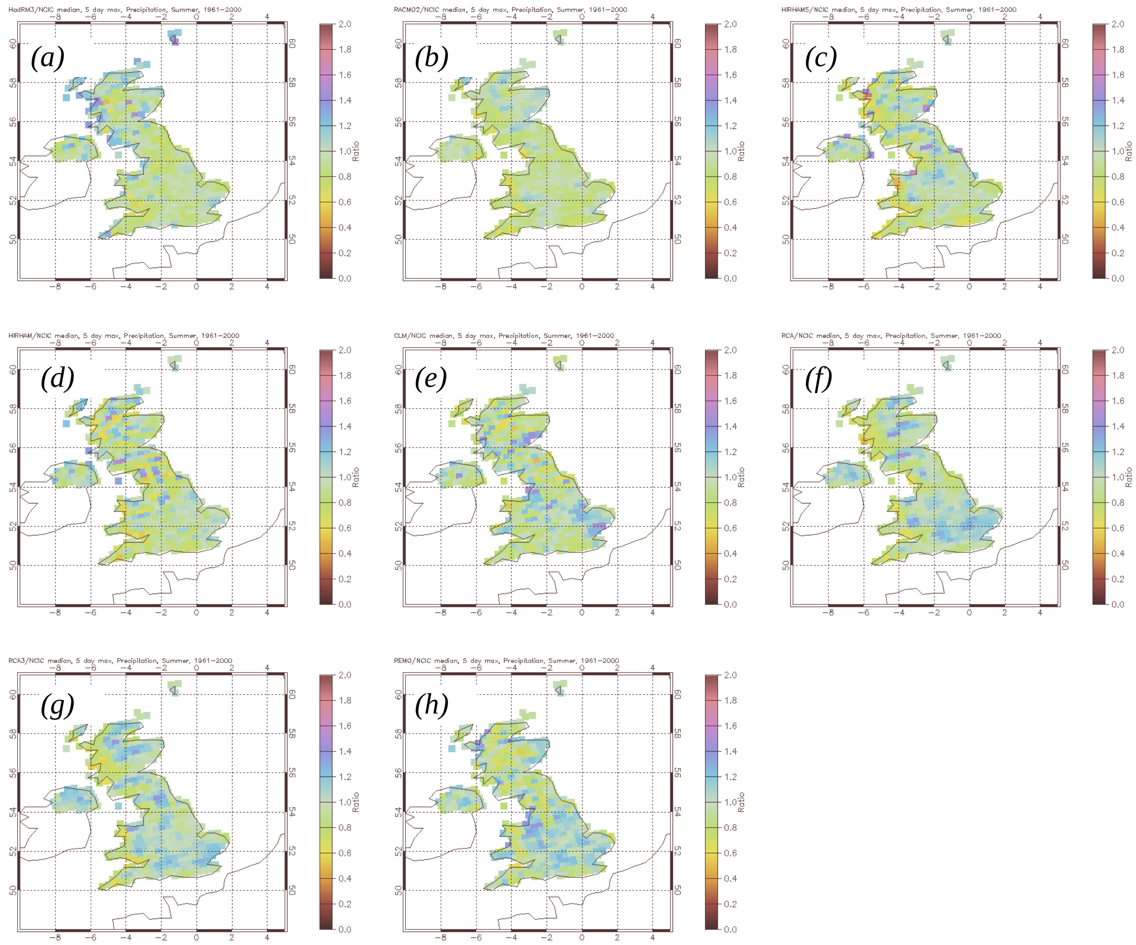


Fig 6.7. Ratio of median 5-day maximum rainfall,1961-2000 to NCIC observed precipitation, for boreal summer (JJA). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

As with the results for mean precipitation, RCA, RCA3 and REMO display significant problems at handling extreme precipitation across the UK. RCA underestimates 1-day maxima by 20-40% almost everywhere in all four seasons, but is quite accurate over parts of south-east England and East Anglia in winter, spring and autumn and overestimates by 20-40% locally in summer. As the time period is increased, there is a trend towards more widespread overestimates in eastern England in winter, and 5 and 10-day maxima are overestimated in many parts of England and Wales. Summer 5 and 10-day maxima are overestimated in most upland areas of the country, and autumn 10-day maxima are overestimated in eastern England, while otherwise overestimates of 20-40% occur generally.

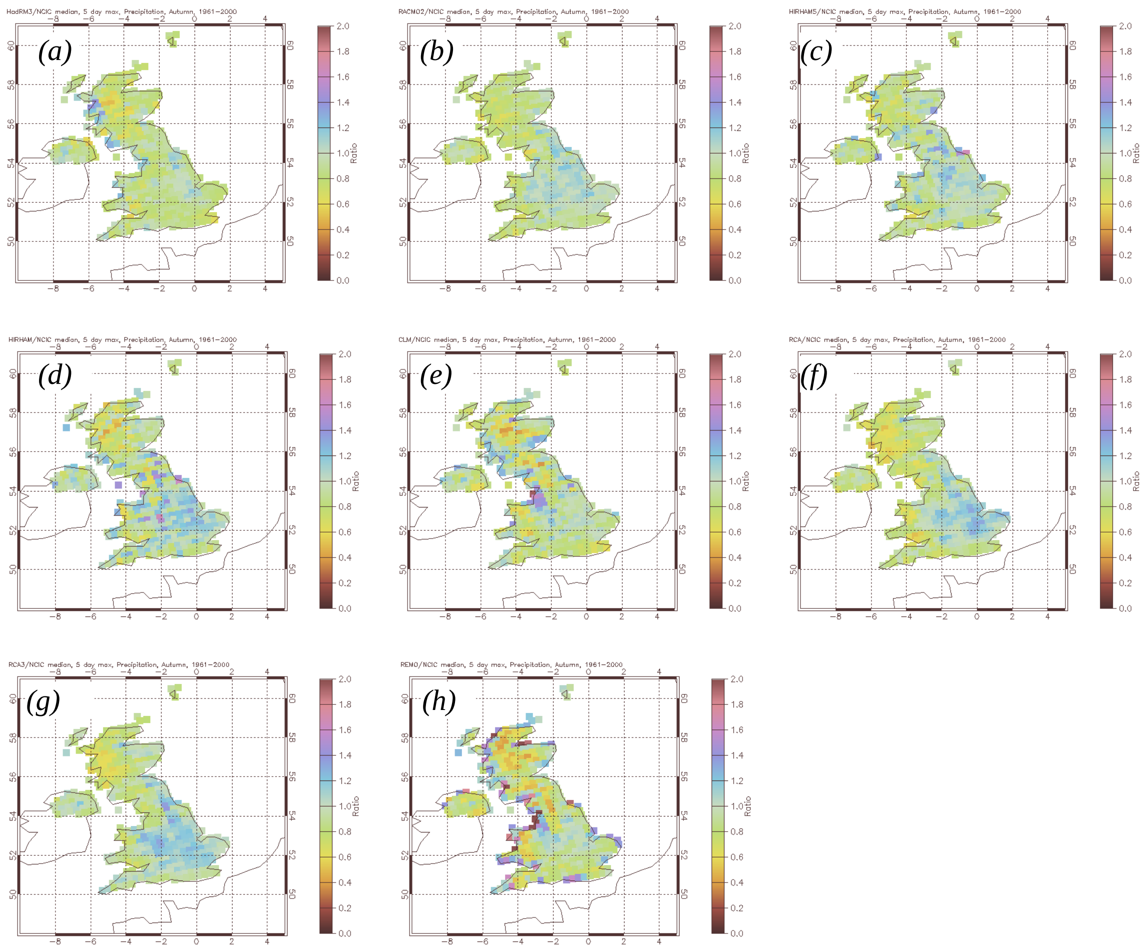


Fig 6.8. Ratio of median 5-day maximum rainfall,1961-2000 to NCIC observed precipitation, for boreal autumn (SON). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

RCA3 has similar anomaly patterns to RCA but with a bias towards projecting higher extreme precipitation, such that the aforementioned cases of overestimation are more extreme while underestimation occurs less widely, e.g. 2, 5 and 10-day maxima are overestimated by 40-60% in parts of eastern England. REMO displays the same pattern as for mean precipitation with extreme underestimates in upland areas in winter, spring and autumn and extreme overestimates around the coasts, but stronger accordance with observed values in summer with extreme precipitation values mostly within 40% of the actual NCIC values.

6.3.3. Simulation of the distribution of convective precipitation

The RCMs from the ENSEMBLES ensemble split simulated precipitation into convective and large-scale components. The model runs are available broken down into convective precipitation totals and large-scale precipitation totals as well as the combination of the two, which enables the generation of outputs that give an insight into how the models handle the occurrence of convective precipitation across the UK. However, there are no data available breaking down the UK observational data into convective vs. large-scale precipitation days, so this section analyses the model outputs regarding the distribution of convective and large-scale precipitation and the percentage of precipitation that is shown as being convective origin. This enables an analysis of the projected changes in convective vs. large-scale precipitation in the future in Section 7.3, which has not been attempted in previous studies.

Fig 6.9, Fig 6.11, Fig 6.13 and Fig 6.15 respectively show mean daily winter, spring, summer and autumn convective precipitation while Fig 6.10, Fig 6.12, Fig 6.14 and Fig 6.16 show seasonal convective precipitation as a percentage of seasonal precipitation totals for each model. The HadRM3 output of large-scale precipitation is concentrated in upland and western parts in all four seasons, least prominently in summer and most prominently in autumn and winter. Absolute convective totals are highest in western coastal areas, particularly in winter when central and eastern parts of Britain have very small amounts, while in summer convective precipitation totals show no significant regional variation.

In winter convective precipitation accounts for 20-30% of the total in many western and southern coastal areas but 10% or less in most central and eastern regions. Autumn shows a similar distribution but with convective precipitation producing 20-30% of the total in most regions with the exception of south-west England (up to 40% around the coasts) and the Scottish Highlands (around 10%). Spring and summer show a different distribution with the highest percentages occurring over England with the exception of the Pennines, Cumbria and close to the Scottish border, accounting for 50-60% of the total precipitation at most grid boxes.

The RACMO2 outputs show the same geographical distributions of large-scale and convective precipitation as HadRM3 but precipitation is much more "smoothed", i.e. less sharp differences between adjacent grid boxes, and it indicates less convective precipitation in western areas than HadRM3 in all four seasons. Convective precipitation accounts for approximately 20% of the total in most southern and western areas, similar to HadRM3 but with evidence of more in the way of convective precipitation penetrating further inland, and reaches 30-40% at some grid boxes on the west coast of Scotland. Unlike HadRM3, RACMO2 also simulates convective precipitation as producing 20% of the total on some north-facing North Sea coasts, suggesting that RACMO2 may pick up winter convection generated over the sea more readily in northerly and easterly airflows than HadRM3.

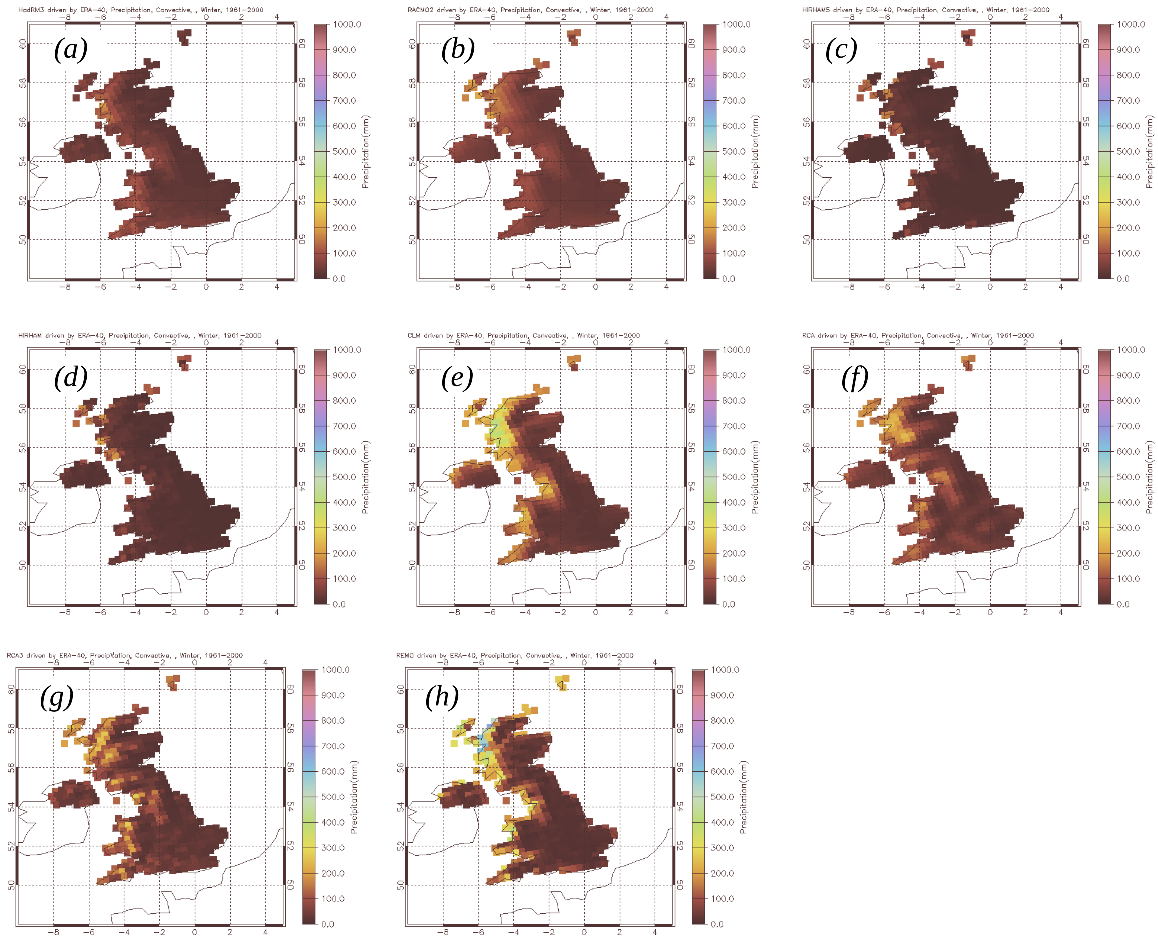


Fig 6.9. Total precipitation that is given as convective on the model outputs, for boreal winter (DJF). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

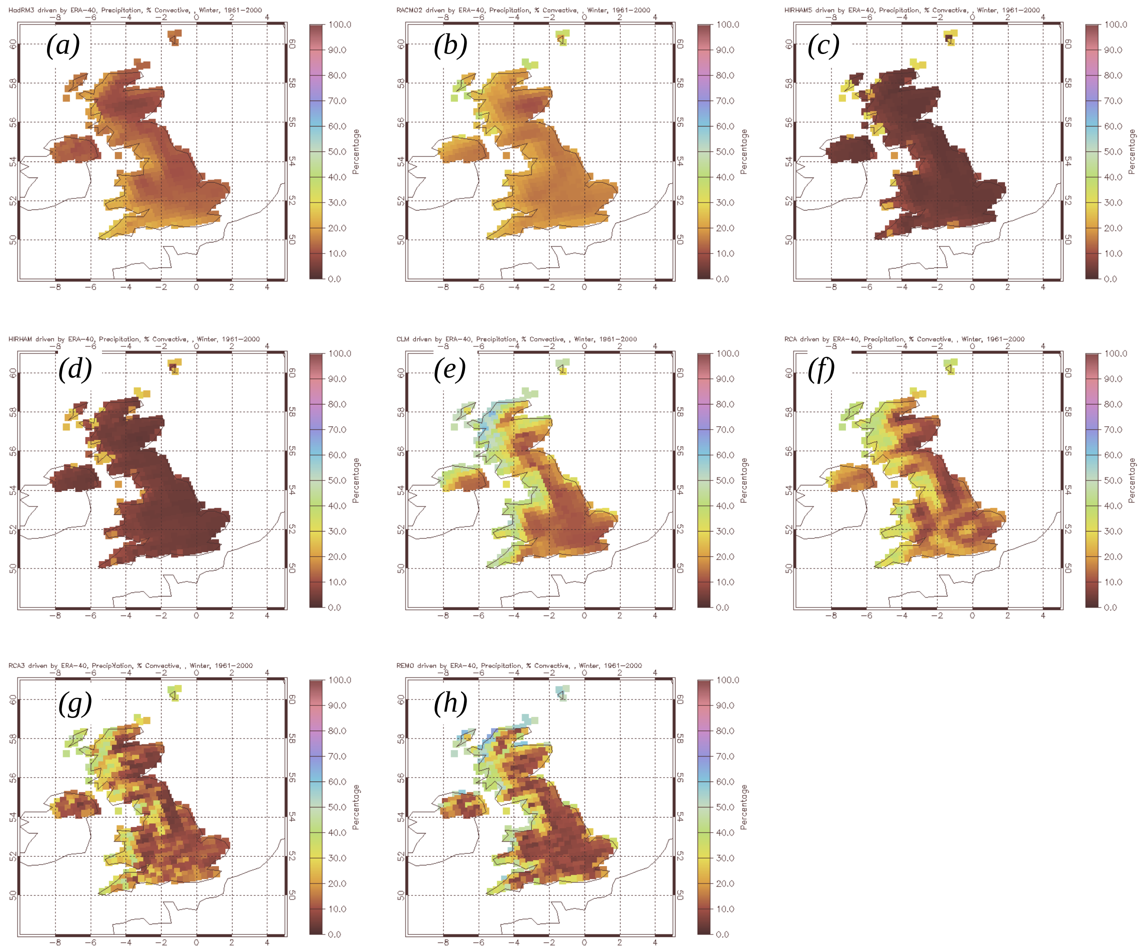


Fig 6.10. Percentage of the total precipitation that is given as convective on the model outputs, for boreal winter (DJF). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

Convective precipitation is also shown as accounting for similar percentages of the total to HadRM3 in autumn, but spring shows a more uniform distribution across the country with approximately 20% of the total precipitation being convective, except for higher values at some grid boxes in western Scotland and lower values in central and eastern Scotland. Summer has less convective precipitation than the HadRM3 outputs and there is a clear northwest-southeast split, with convective precipitation accounting for 30-40% of the total in East Anglia and parts of southeast England but approximately 10% in the Scottish Highlands.

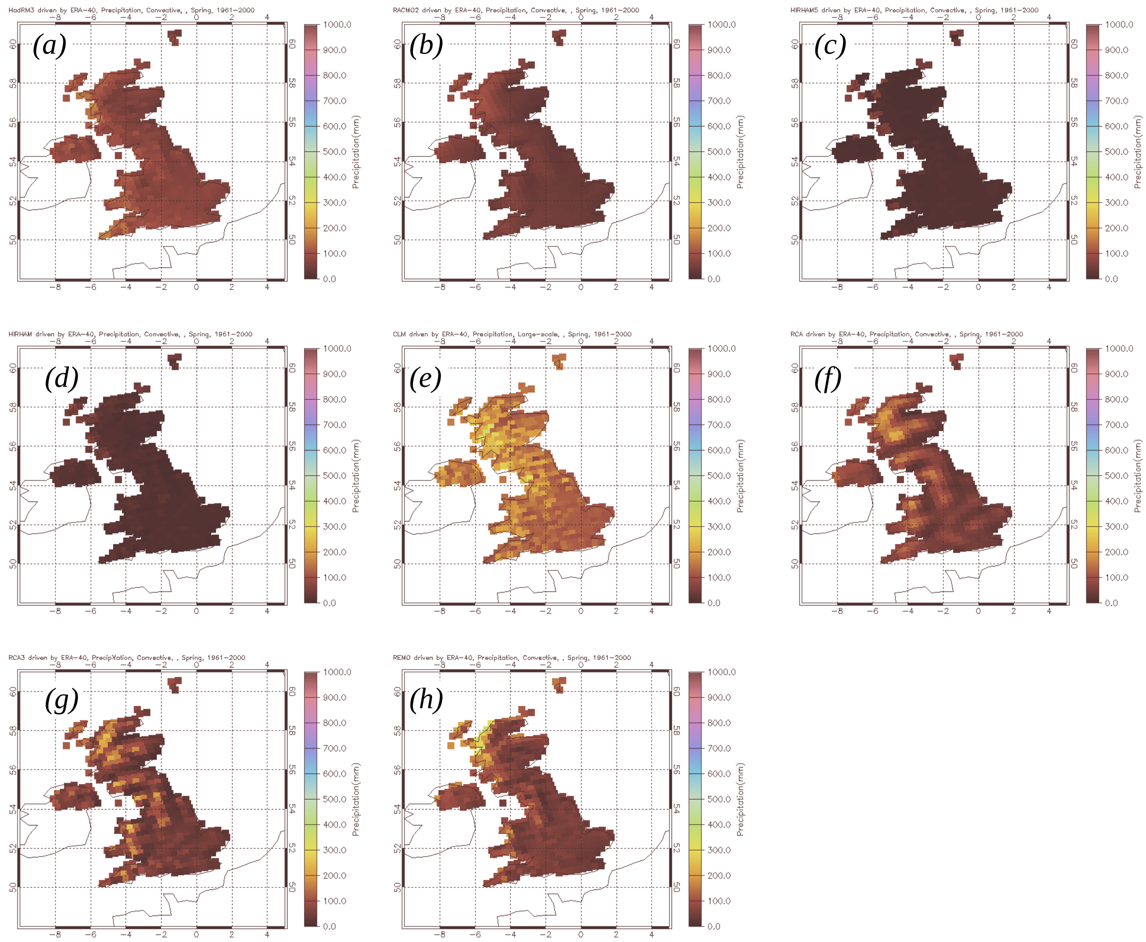


Fig 6.11. Total precipitation that is given as convective on the model outputs, for boreal spring (MAM). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

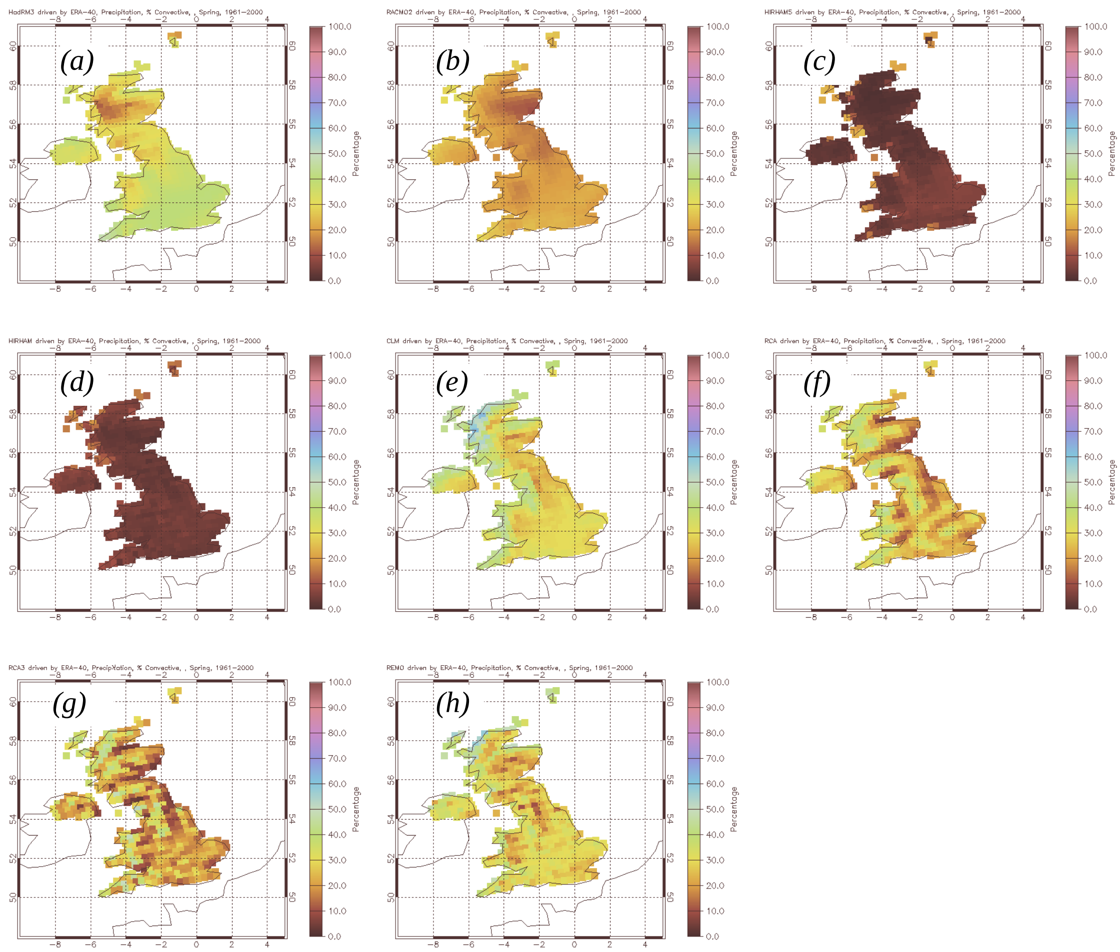


Fig 6.12. Percentage of the total precipitation that is given as convective on the model outputs, for boreal spring (MAM). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

HadRM3 and RACMO2 appear to simulate convective precipitation realistically, in line with general findings that summer convective precipitation accounts for a higher proportion of the total in eastern England than in northern and western regions, while convective events in winter tend to be focused in western coastal areas (e.g. Maraun et al., 2009), while the other models struggle. HIRHAM5 simulates convective precipitation as being almost exclusively confined to some (mainly western coastal) fringes in winter, spring and autumn, and very limited across the country in summer, while large-scale precipitation is simulated with the correct geographical distribution (as per HadRM3 and RACMO2) but with sharper differences between individual grid boxes, and the anomalous coastal grid boxes noted in Section 6.1.3 wrongly shown as having significantly greater large-scale precipitation than adjacent grid boxes.

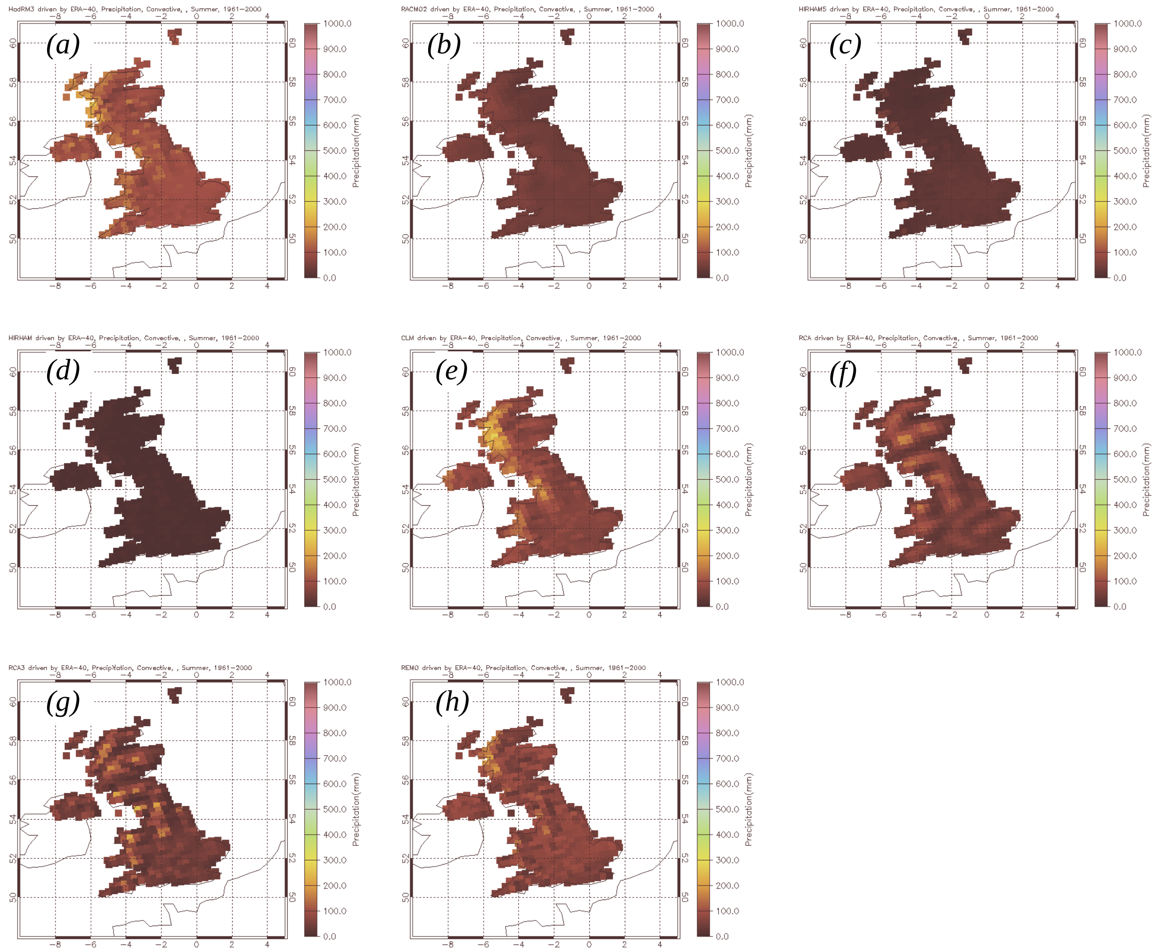


Fig 6.13. Total precipitation that is given as convective on the model outputs, for boreal summer (JJA). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

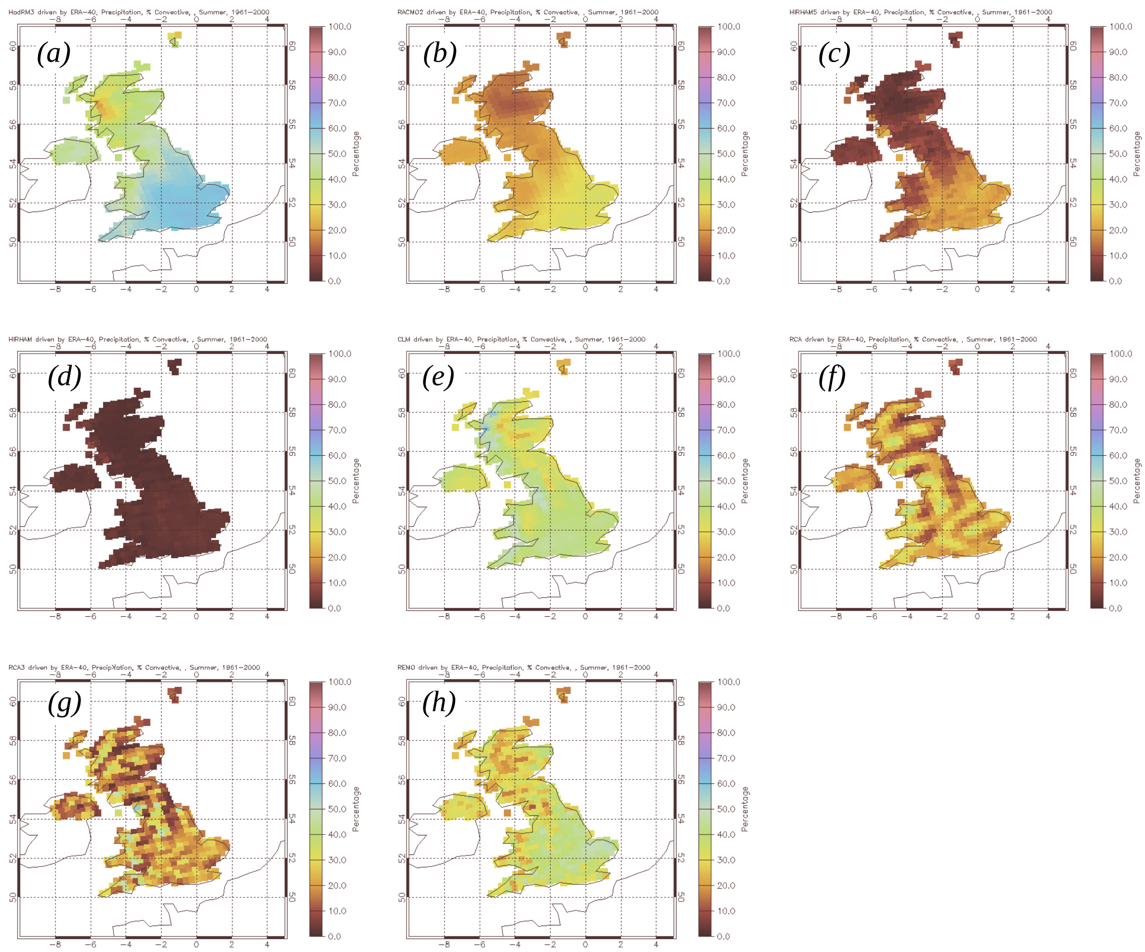


Fig 6.14. Percentage of the total precipitation that is given as convective on the model outputs, for boreal summer (JJA). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

Convective precipitation accounts for up to 30% of the total at some grid boxes around south and west-facing coasts in winter, spring and autumn, and less than 10% elsewhere. Summer sees convective precipitation account for 20-30% of the total across most of England, but 10% over most of northern England and less than 10% in Scotland except for coastal parts of the south-west. HIRHAM5 is an improvement on HIRHAM which simulates convective precipitation as being almost exclusively confined to some grid boxes along south and west-facing coasts in autumn and winter, and almost non-existent everywhere in spring and summer. Large-scale precipitation contains even sharper contrasts between individual grid boxes than on the HIRHAM5 outputs.

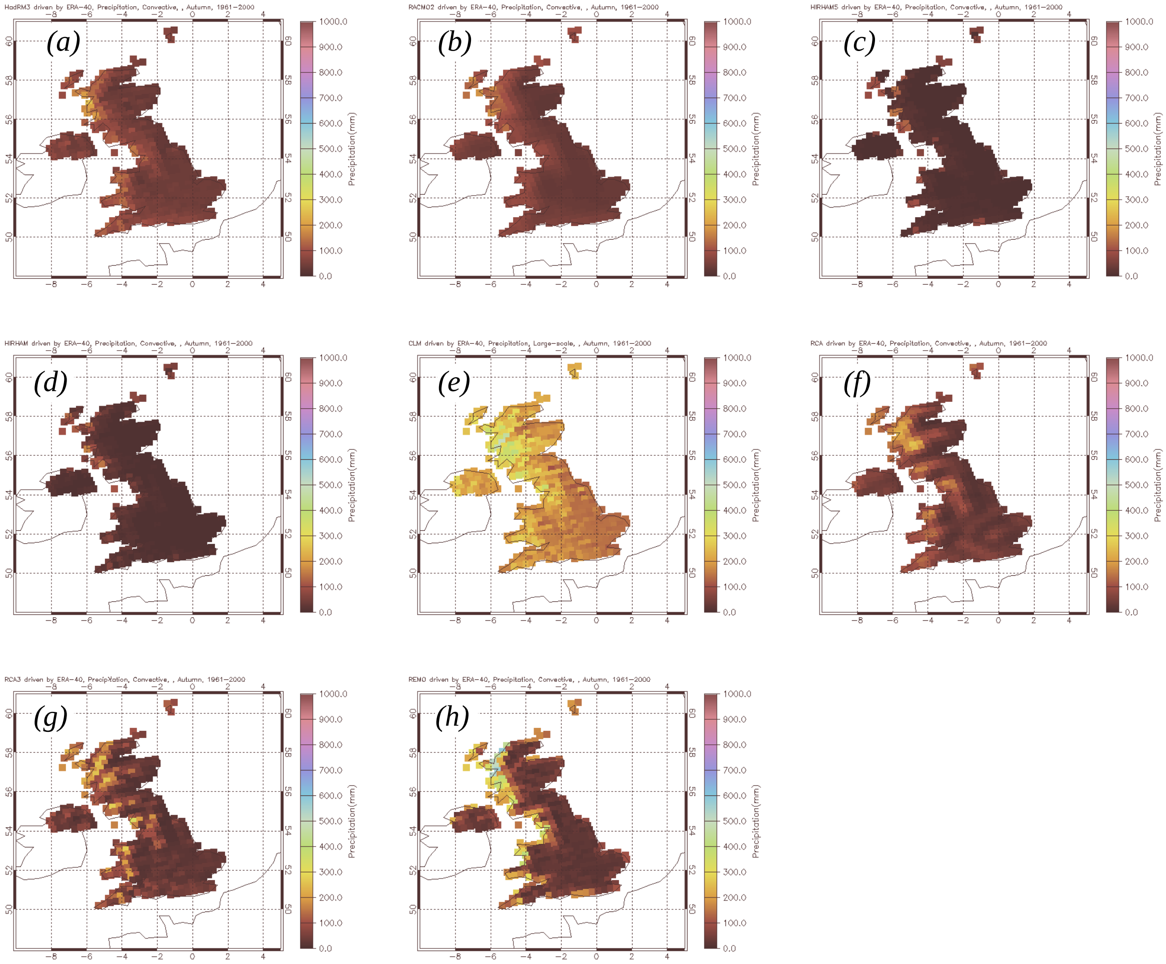


Fig 6.15. Total precipitation that is given as convective on the model outputs, for boreal autumn (SON). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

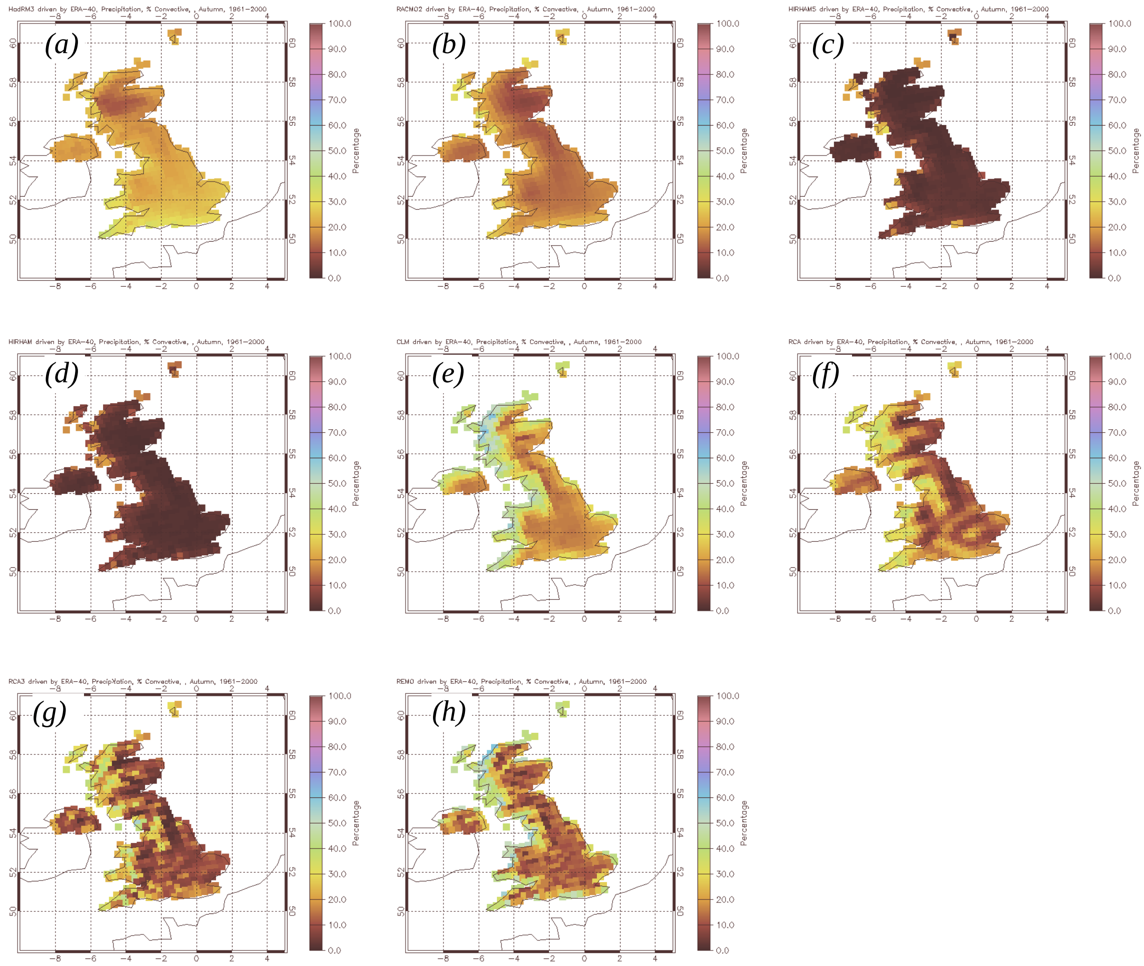


Fig 6.16. Percentage of the total precipitation that is given as convective on the model outputs, for boreal autumn (SON). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40.

CLM simulates large-scale precipitation as being most prominent in western Scotland and north-west England but there are stark differences between adjacent grid boxes and there is far less of a bias towards high ground, consistent with the tendency observed in section 6.1.3 for CLM to underestimate the effects of topography. Large amounts of convective precipitation occur near western coasts in autumn and winter, and also to a lesser extent in spring and summer. Convective precipitation produces over 60% of the total at some grid boxes in western Scotland and 30-50% in most other western areas in autumn and winter. In summer approximately 40-50% of the total precipitation is convective over most of the country, with lower values on high ground and higher values near the west coast of Scotland, while spring falls in between the autumn/winter and summer distributions.

RCA simulates large-scale precipitation as being almost uniform across the country, except for higher values around the Scottish Highlands and a "smoothed" distribution (thus failing to account for topography and other regional variation), while convective precipitation is simulated to occur mainly over the western flank of high ground and also some bands of relatively high frequency are indicated in parts of south-eastern Britain. The percentage of precipitation that is of convective origin shows a highly unrealistic distribution over the UK. RCA3 shows a similar distribution of large-scale precipitation to RCA but convective precipitation occurs mostly at a scattering of grid boxes in western Britain leading again to a highly unrealistic distribution of convective precipitation occurrence and proportion of the total across the UK. REMO simulates western coastal areas having the most large-scale precipitation, failing to account for orographic enhancement in the west, and convective precipitation in autumn and winter occurs almost exclusively around western coasts and to a lesser extent North Sea coasts. In summer the distribution across the UK is close to uniform, and as a result convective precipitation accounts for 40-50% of the total at most grid boxes in central and eastern England but less than that in most northern and western regions.

6.3.4 Correlations with observed values

For this analysis, all of the daily precipitation values for each season were correlated with observed values (excluding dry days). Correlations with observed values show much less variability between individual models than the other measures considered so far, with all models predicting the distribution of precipitation events most accurately in autumn and winter than in spring and summer, the lowest correlations with observed values occur in summer, and correlations are higher in western and upland areas than in eastern areas. Fig 6.17, Fig 6.18, Fig 6.19 and Fig 6.20 show the geographical distribution of correlations from each model for winter, spring, summer and autumn respectively.

HadRM3 is one of the worst-performing models by this measure. Correlations with observed values are highest overall in autumn, reaching 0.4-0.6 in most upland parts of western Britain, and 0.2-0.4 generally in central and eastern regions. In winter correlations are lower in eastern areas, particularly in north-east England and north-east Scotland where they fall close to zero for some grid boxes, while spring sees correlations of 0.6 or greater in western Scotland, 0.4 or above in most upland western areas but near 0.2 in eastern areas. In summer correlations are near 0.2 over most of the country. This implies that HadRM3 is good at handling organised frontal and orographic precipitation events in western areas, particularly high ground, but struggles with the less organised precipitation that often affects eastern areas.

RACMO2 shows a similar seasonal distribution of correlations to UKMO, with higher correlations in upland and western areas than in eastern areas, and the highest correlations occurring in autumn, followed by winter and spring and then summer. Correlations are significantly higher in eastern regions than on the UKMO outputs, only dropping significantly below 0.4 in south-east England in summer, while correlations in upland and western areas in autumn widely exceed 0.6 and the same is true of western Scotland in spring. This implies that RACMO2 handles the distribution of frontal and orographic precipitation events in upland and western areas slightly better than HadRM3, and handles the distribution of less organised and convective events significantly better.

HIRHAM5 produces very similar results to RACMO2, surprisingly given the model's poorer performance by the other measures considered, and in spring and autumn correlations in western Scotland approach 0.8, suggesting that HIRHAM5 is very good at handling orographic/frontal precipitation in western areas. The anomalously high precipitation totals that HIRHAM5 produces at some individual grid boxes do not appear to be related to distribution but rather raw amounts, as there are no anomalous grid boxes in the HIRHAM5 correlation outputs. HIRHAM5 is clearly an improvement over HIRHAM by this measure, for the HIRHAM outputs show lower correlations with observed values, particularly in the eastern half of Britain when they fall below 0.4 over large areas in all four seasons, although spring and autumn correlations still reach approximately 0.6 in upland parts of western Britain.

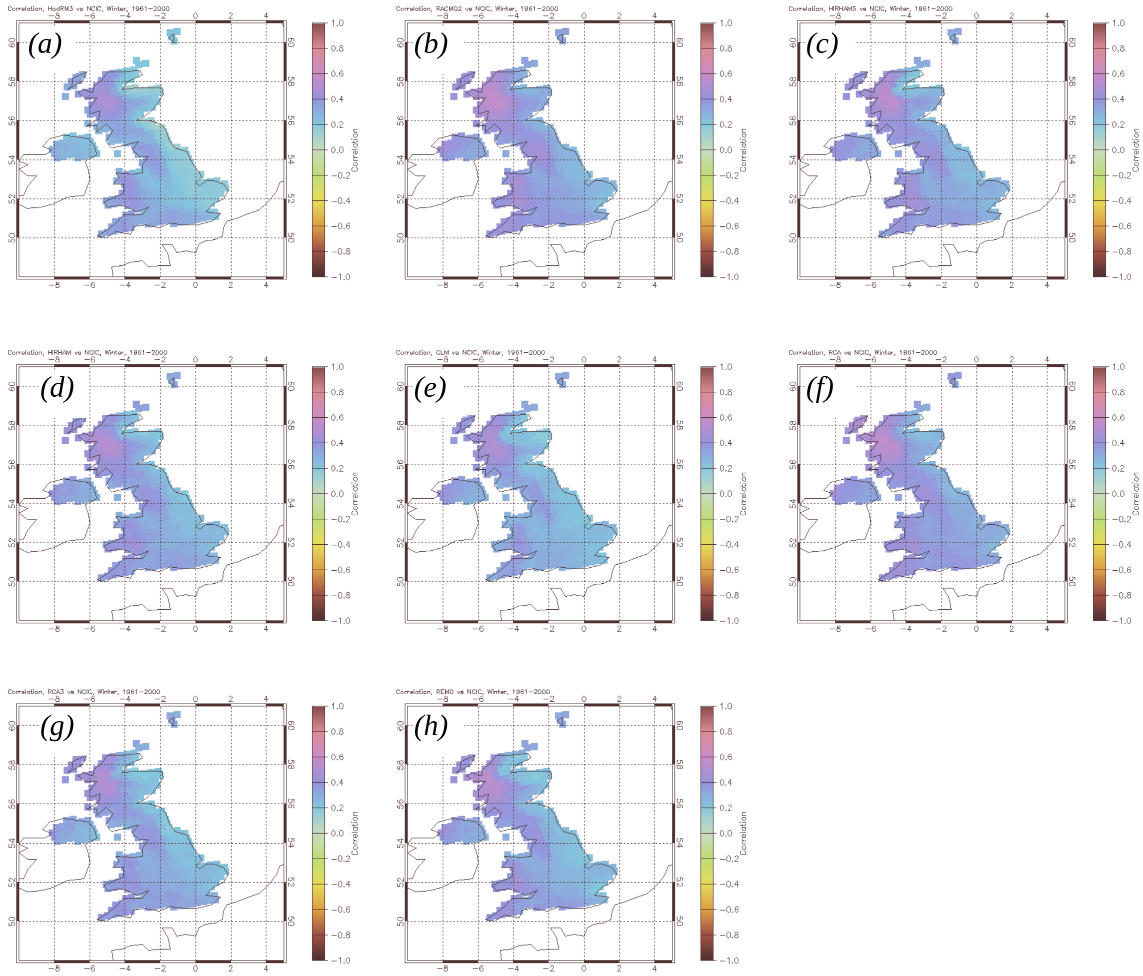


Fig 6.17. Correlations between estimated daily precipitation and observed values, for boreal winter (DJF). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40. Due to the large sample size any correlation greater than r = 0.04 is statistically significant at the 99% level.

As with the other outputs considered so far, the correlations with observed values on the CLM outputs are highest in upland and western areas and highest in autumn and spring. Correlations in upland and western areas are not as high as those of RACMO2, HIRHAM5 or HIRHAM, approaching 0.6 in autumn and spring, but near 0.4 in most parts. In the eastern half of Britain correlations are mostly between 0.2 and 0.4. RCA performs comparably to RACMO2 and HIRHAM5, suggesting that RCA is good at handling the distribution of precipitation events across the UK even though its simulation of the geographical distribution of mean, extreme and convective precipitation is strongly suspect. RCA3 is less good, producing correlations of 0.2-0.4 in eastern regions, similar to HIRHAM, while REMO is poor at handling the distribution of precipitation events in eastern areas in winter, giving correlations near 0.2, but otherwise gives correlations near 0.4 in eastern areas and 0.6 in upland western areas in autumn and spring.

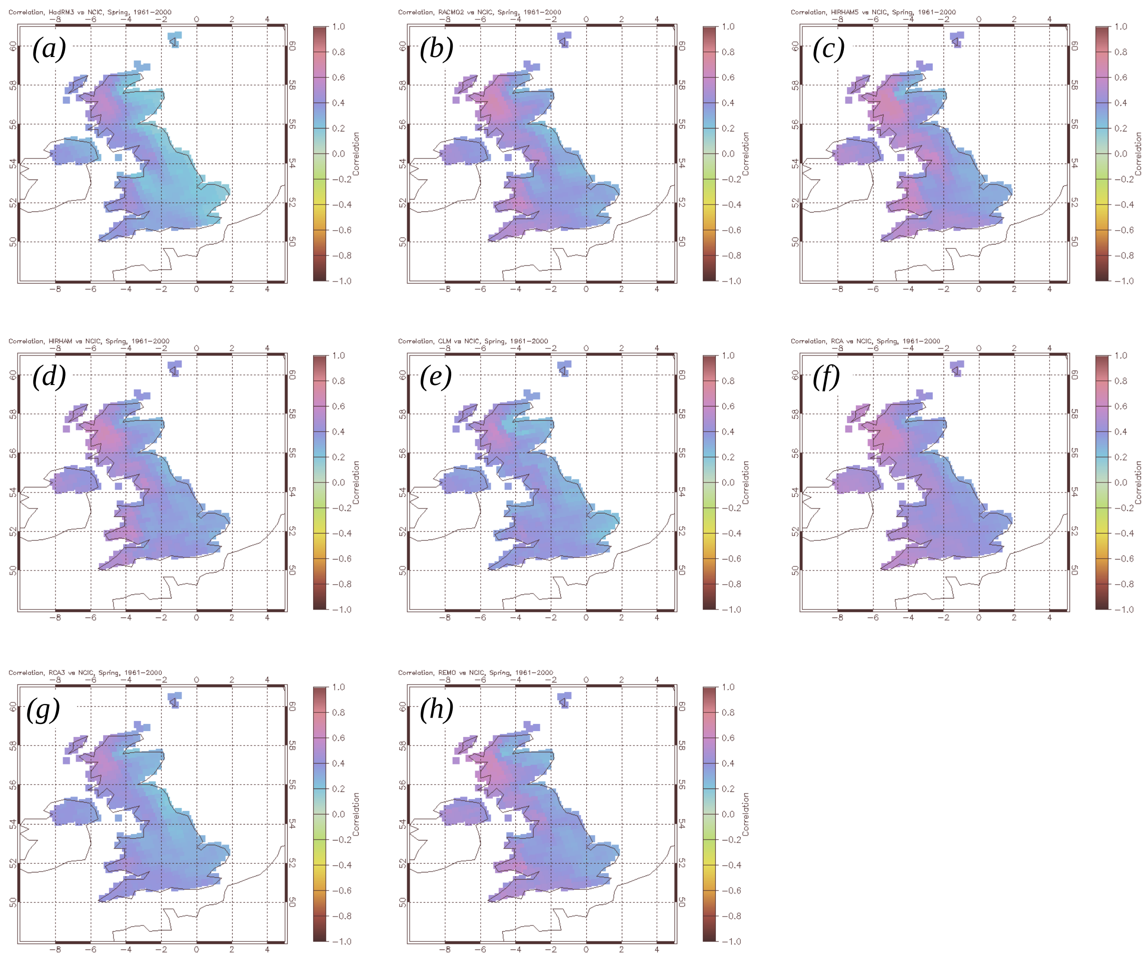


Fig 6.18. Correlations between estimated daily precipitation and observed values, for boreal spring (MAM). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40. Due to the large sample size any correlation greater than r = 0.04 is statistically significant at the 99% level.

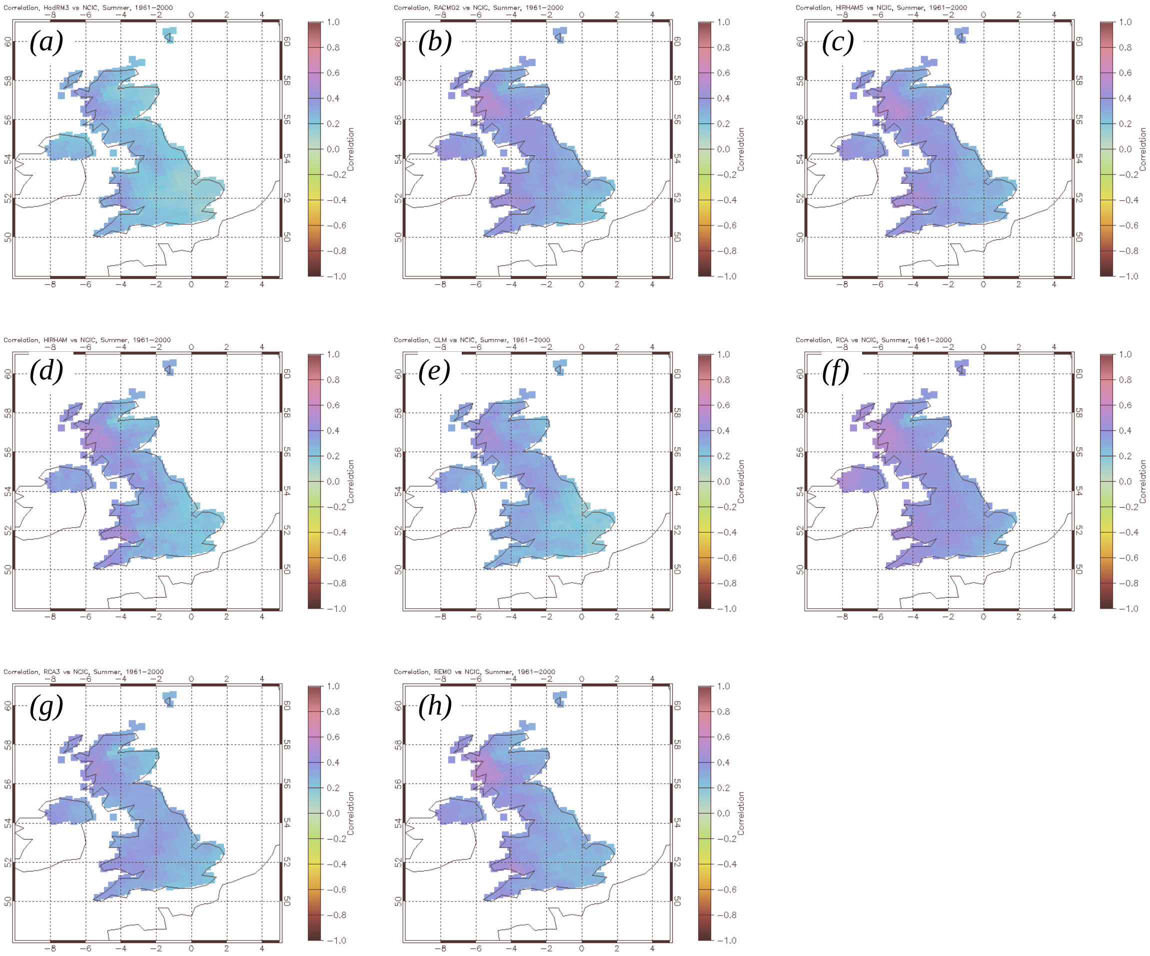


Fig 6.19. Correlations between estimated daily precipitation and observed values, for boreal summer (JJA). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40. Due to the large sample size any correlation greater than r = 0.04 is statistically significant at the 99% level.

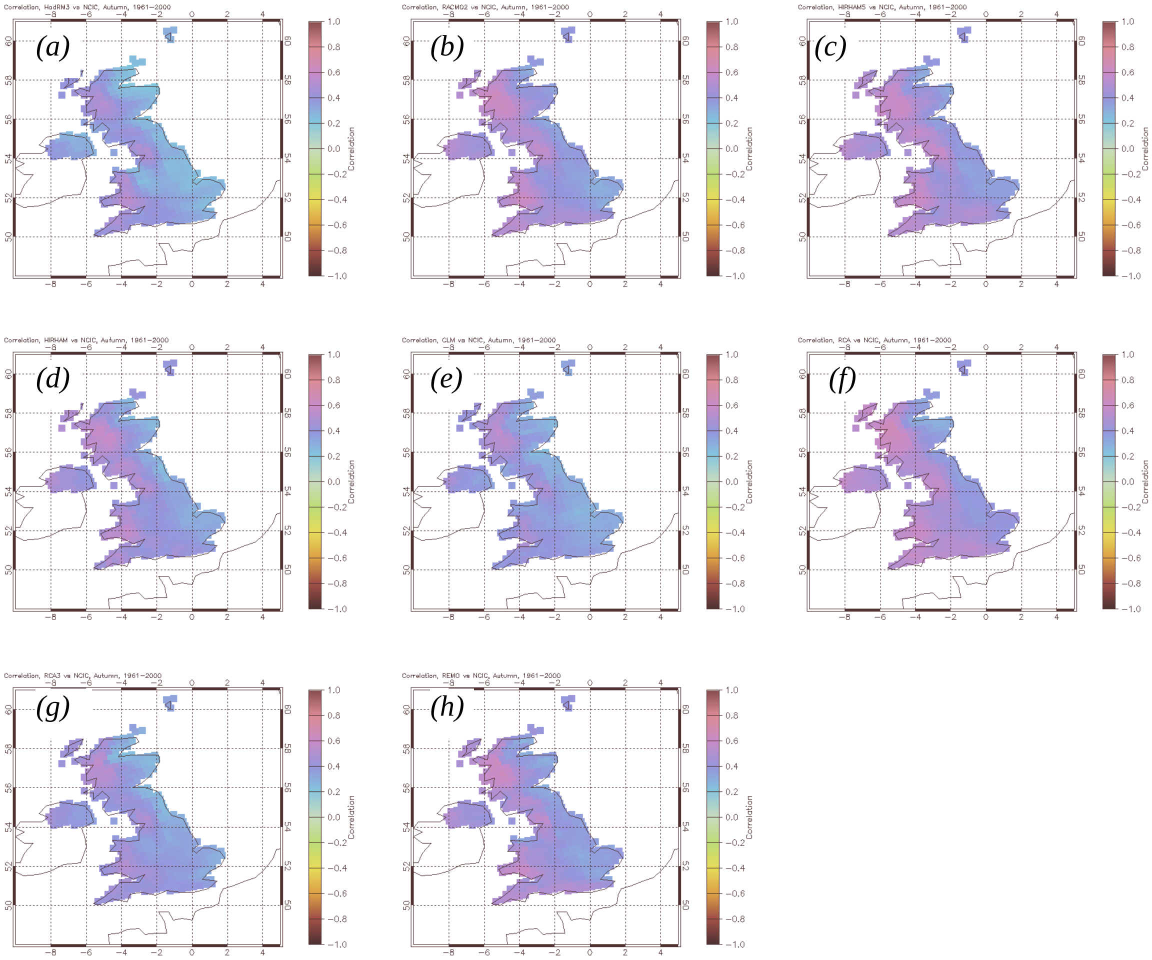


Fig 6.20. Correlations between estimated daily precipitation and observed values, for boreal autumn (SON). The outputs are derived from (a) HadRM3, (b) RACMO2, (c) HIRHAM5, (d) HIRHAM, (e) CLM, (f) RCA, (g) RCA3 and (h) REMO, all driven by ERA-40. Due to the large sample size any correlation greater than r = 0.04 is statistically significant at the 99% level.

6.4 Conclusions

By the four measures considered above, RACMO2 performed best out of the models considered, ranking among the best models by all four measures. This is consistent with the findings of van der Linden and Mitchell (2009) who, when assigning weightings to the individual models according to proficiency, had RACMO2 as clearly the best of the models. HadRM3 performed second best overall, and was the only other model to handle the amount and distribution of convective precipitation in a realistic way, but the results from the correlations analysis suggest that HadRM3 appears to have more problems handling the distribution of UK precipitation events other than frontal/orographic events in upland and western areas than most of the other models. HadRM3 also overestimates mean precipitation and extreme precipitation along the west coast of Scotland. HIRHAM5 performed third best overall but severely overestimates mean and extreme precipitation at some individual grid boxes around coastal fringes and simulates convective precipitation unrealistically with close to no convective precipitation away from some coastal fringes in winter, spring or autumn.

HIRHAM5 is an improvement over HIRHAM, which shows greater inconsistency between adjacent grid boxes as well as being even less realistic with convective precipitation simulation and producing lower correlations with observed values across eastern Britain. CLM was not far behind HIRHAM5 but has problems handling topography, underestimating mean and extreme precipitation across upland areas in winter, spring and autumn, and its simulation of convective precipitation is suspect. The other three models- RCA, RCA3 and REMO- all have serious fundamental problems handling the distribution of mean and extreme precipitation, RCA and RCA3 overestimate precipitation strongly in eastern areas, underestimating the effects of topography and the rain shadow effect, while REMO underestimates precipitation in upland areas to more of an extreme than CLM.

All models consistently overestimate mean precipitation in eastern England, particularly around Cambridgeshire, and underestimate in upland parts of western Britain. While the spatial anomaly pattern for extreme precipitation is similar, there is a consistent bias towards underestimates of extreme precipitation, relative to mean precipitation, which is consistent with earlier studies which noted a tendency for RCMs to “drizzle” too much resulting in overestimates of the frequency of light precipitation, and underestimates of extreme precipitation, though these results suggest that the underestimates do not occur uniformly across the country, with certain areas of the country showing overestimates (particularly eastern England in winter, spring and autumn). The use of the mean vs median extreme values made no significant differences to the results.

Correlations with observed values are lowest in eastern Britain and highest in upland and western areas, particularly the western Scottish Highlands, suggesting that RCMs are consistently good at simulating orographic and frontal events in western Britain in westerly types but have greater problems simulating the distribution of smaller precipitation events in eastern Britain and of convective events in summer (which could again be related to the “drizzle effect” problem). Section 7.2 explores this in more detail by covering the results from the three best-performing models in this analysis under different Lamb circulation types. The simulation of convective precipitation is unrealistic on most of the models, except for RACMO2, HadRM3 and to a lesser extent CLM and REMO. Due to the inability to differentiate actual precipitation events over the 1961-2000 period into convective vs large-scale totals it is not possible to determine whether the more modest convective fractions of total precipitation suggested by RACMO2 are more accurate than the larger ones suggested by HadRM3, though it may be relevant that HadRM3 performs less well at handling the distribution of precipitation events in central and eastern Britain.

7. Regional climate model simulations of precipitation: analysis of performance under different Lamb types and projections into the future

7.1 Summary

This chapter assesses the performance of three climate models under different circulation types, and the results are covered and analysed in Section 7.2. The models selected are the three models that were identified as the three best performing models in Chapter 6 (RACMO2, HadRM3 and HIRHAM5). Similar methodology is used to the methods used in Chapter 6, comparing ERA-40 driven integrations from the above three RCMs with observed data, restricting the coverage to dates that featured a given Lamb type across the British Isles, using the classification of Jones et al. (1993) and Jenkinson and Collison (1977). The classification of daily Lamb types is derived from observed data rather than calculated from the RCM integrations. The SW, W, NW, N, NE, E, SE and S types (combining anticyclonic, cyclonic and pure instances) are covered individually, followed by anticyclonic and cyclonic types, analysing how accurate the models are at simulating UK precipitation under different synoptic situations.

7.2 Model performance under different Lamb types

For this analysis, mean precipitation (total, convective and large-scale), the percentage of precipitation that is convective, the mean and absolute 1-day maxima, and the correlations with observed values are used. All results are generated from the results in Chapter 6 but are restricted to days featuring a given Lamb type (e.g. mean 1-day maxima for the south-westerly type are obtained via averaging the seasonal maximum precipitation values over 1961-2000, restricted to days with the south-westerly type). 2, 5 and 10-day maxima are not computed due to the small sample sizes that result due to the small number of occasions when a particular Lamb type persists for consecutive days, particularly for the less common wind directions, and the results from the previous chapter strongly suggest that the models' strengths and weaknesses at handling extreme precipitation are similar for 1, 2, 5 and 10-day maxima.

The total number of days with the respective Lamb types are given in Table 7.1. Northerly, north-easterly, easterly and south-easterly types occur somewhat less frequently than the other types, meaning that it is less appropriate to draw strong conclusions from the results for those types due to the comparatively small sample sizes. Figures illustrating the results include the ratio of simulated to observed mean 1-day maxima and convective fraction of precipitation for winter and summer, and the correlations with observed values for winter.

Lamb type	**Number of days in sample**
South-westerly	2070 (14% of total)
Westerly	2334 (16% of total)
North-westerly	1398 (10% of total)
Northerly	865 (6% of total)
North-easterly	474 (3% of total)
Easterly	481 (3% of total)
South-easterly	689 (5% of total)
Southerly	1286 (9% of total)
Cyclonic	1947 (13% of total)
Anticyclonic	2932 (20% of total)

Table 7.1. Number of days in the sample with occurrences of individual Lamb types during the period 1961-2000.

7.2.1 The south-westerly type

For the south-westerly type (Fig 7.1), all models show a similar geographical distribution of precipitation, but RACMO2 shows the smoothest distribution, with HadRM3 and HIRHAM5 showing a more “spotty” distribution with higher precipitation totals in some upland western areas, and the anomalously high precipitation totals at some eastern coastal grid boxes of HIRHAM5’s outputs are evident.

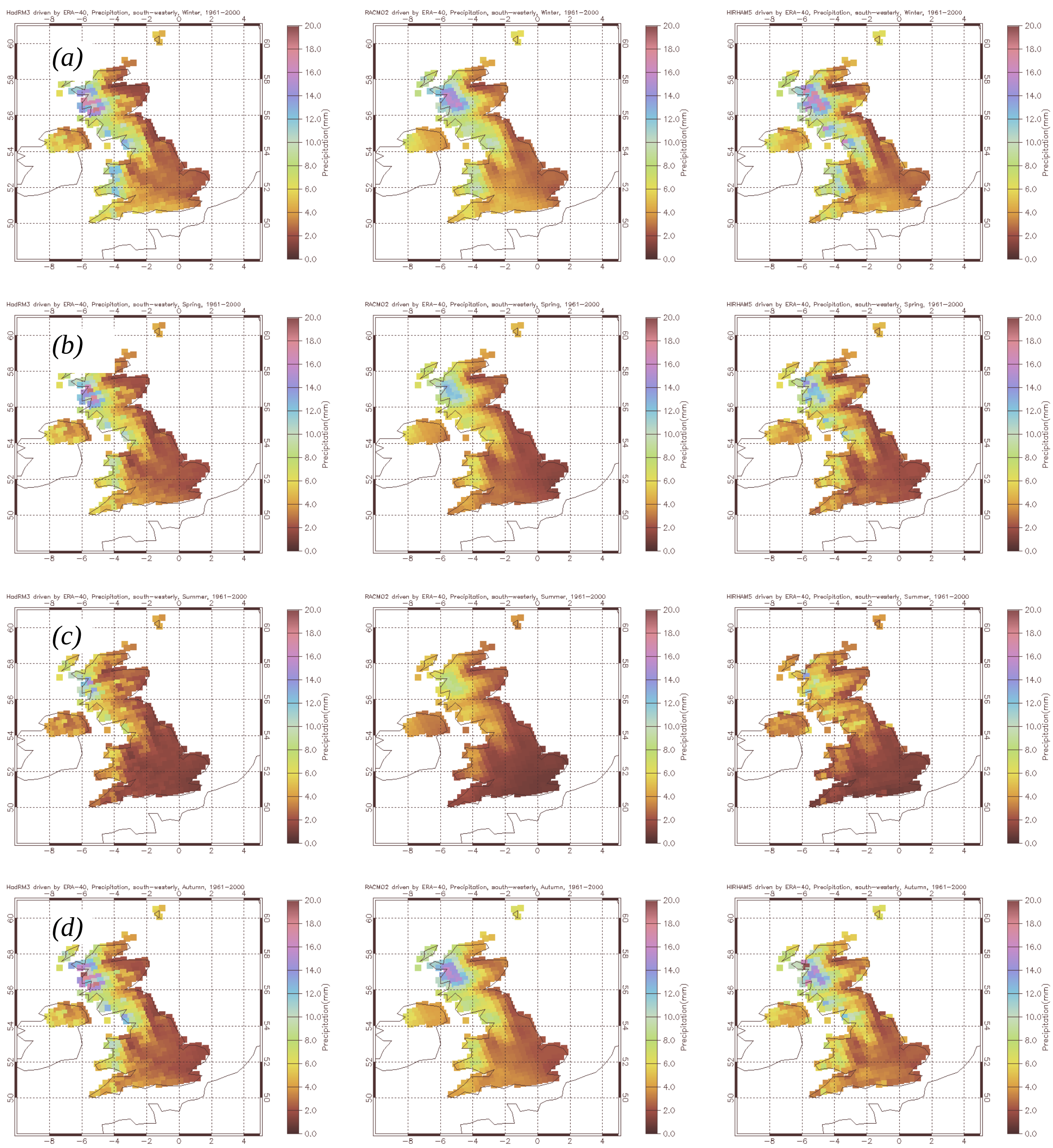


Fig 7.1. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals for south-westerly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values (Fig 7.2), HadRM3 overestimates spring precipitation across most of the country, with overestimates of around 60% in Cambridgeshire. In winter precipitation is overestimated over England and Wales, especially south-east England, but to a lesser extent, and the same is true for autumn precipitation. Summer precipitation is underestimated by 10-20% over most of the country. RACMO2 shows a similar tendency with overestimations over eastern Britain in winter, spring and autumn, the strongest overestimates occurring in eastern and south-eastern England in winter (up to 60%) and in north-eastern Britain in spring, while as with HadRM3, underestimates of 10-20% occur widely in summer except in the Scottish Highlands where overestimates of 40% or more occur, and near the south coast of England and west Wales where underestimates of up to 50% occur. HadRM3 shows a consistent tendency in all four seasons for underestimates over the Scottish Highlands and overestimates along the west coast of Scotland, which does not occur for the RACMO2 outputs. The same general patterns occur for the HIRHAM5 outputs (overestimates in eastern areas in winter, spring and autumn, underestimates in southern and south-western coastal areas in summer) but with far greater spatial inconsistency, and the large overestimates at individual grid boxes highlighted in section 6.1 are also apparent, particularly those in eastern England. All three of the models appear to correctly pinpoint the general distribution of precipitation across the UK.

The mean 1-day maxima show similar anomaly patterns, but a bias towards underestimates over larger areas of the country (the same result as found in section 6.1), the exception being in summer when underestimates of up to 40% occur across the country for HadRM3, while RACMO2 has similar underestimates near the south coast and west Wales, similar to those for mean precipitation totals.

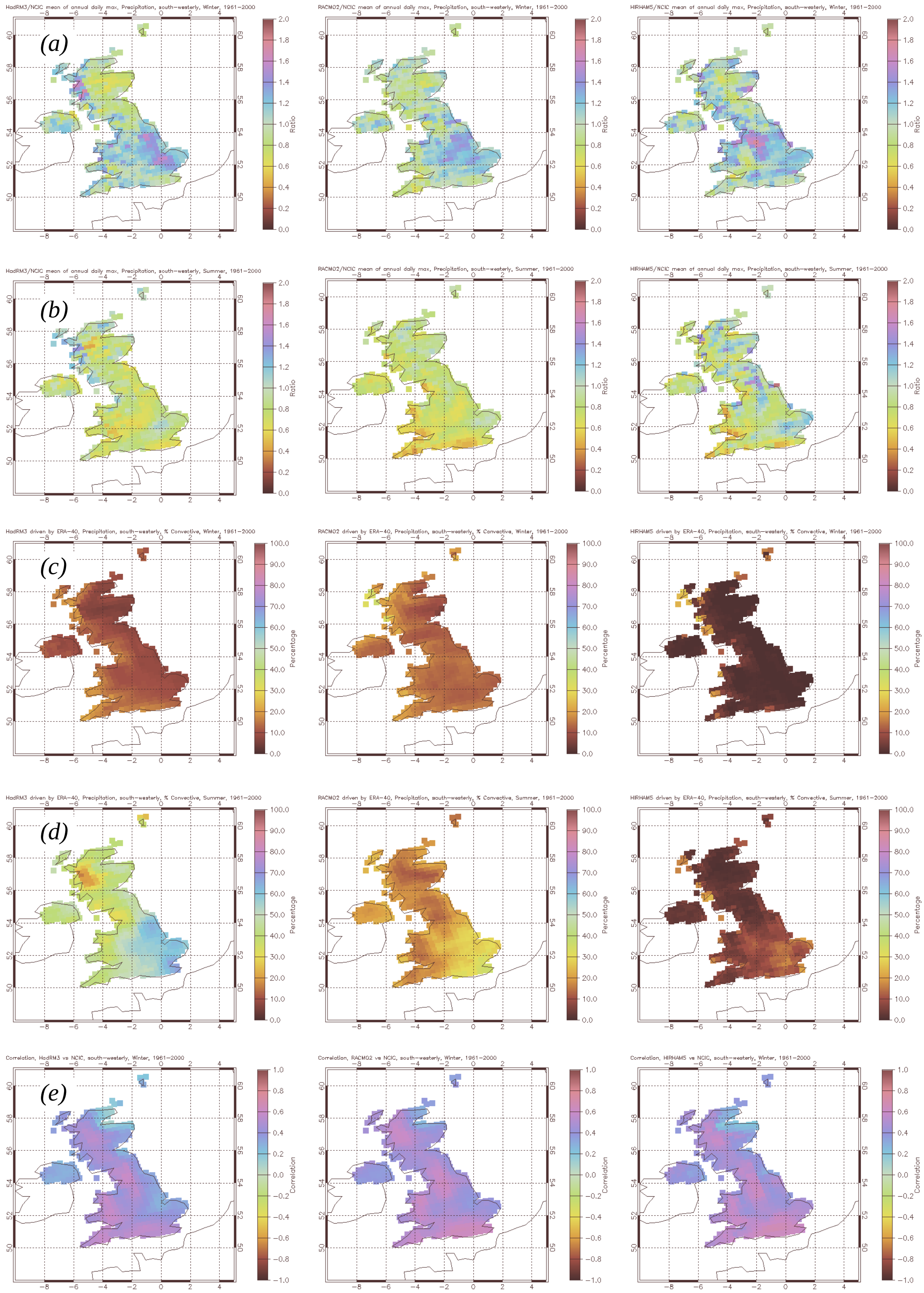


Fig 7.2. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the south-westerly type. The limit for correlation significance at the 95% level is approximately r = 0.08 (due to large sample size).

Large-scale precipitation shows a large bias towards upland and western areas for all three models. Convective precipitation shows some differences, with a bias towards western areas in autumn and winter, but HadRM3 shows a bias towards southern as well as western coasts while RACMO2 shows a greater bias towards north-western areas, especially along the west coast of Scotland. The fraction of precipitation that is convective reaches 20-30% in the most affected areas for both models. HIRHAM5, as mentioned in Section 6.1, handles convective precipitation unrealistically and in the case of the south-westerly type shows convective precipitation reserved almost exclusively for western Scotland. Spring shows a near-uniform convective fraction for HadRM3 and RACMO2, while in summer there is a bias towards south-east England with convective precipitation accounting for near 70% of the total near the Thames Estuary for HadRM3 and a peak of 40% in the southeast corner for RACMO2. HIRHAM5 also shows an increase in convective fraction in south-eastern areas in summer, but only representing 10 to 20% of the total.

Correlations with observed values are in the 0.4-0.6 range nationwide for RACMO2 and HIRHAM5, with RACMO2 marginally outperforming HIRHAM5, and the highest correlations are found in upland areas. HadRM3's correlations are similar in western and southern areas, but drop below 0.4 in parts of northern and eastern Scotland and north-east England. Spring sees similar correlations except in the northeast where they fall well below 0.4 for all three models. Summer sees the lowest correlations with observed values, with correlations of 0.2 to 0.4 in most regions for the HIRHAM5 and RACMO2 outputs, highest in the south-west, and correlations of 0.2 or below for the HadRM3 outputs. The lowest correlations are found in areas in the lee of high ground, supporting the prior suspicions that the models (especially HadRM3) have greater problems handling the smaller and less organised precipitation events that occur to the lee of high ground, as opposed to the frontal and orographic events that occur frequently in upland areas and areas facing the wind.

7.2.2 The westerly type

For the westerly type (Fig 7.3), the models' simulation of mean precipitation gives a similar geographical distribution to the distribution associated with south-westerly types, but with less precipitation affecting southern Britain. Again the RACMO2 outputs are significantly smoother than those of HadRM3 and HIRHAM5, with the anomalous grid boxes of HIRHAM5 again apparent.

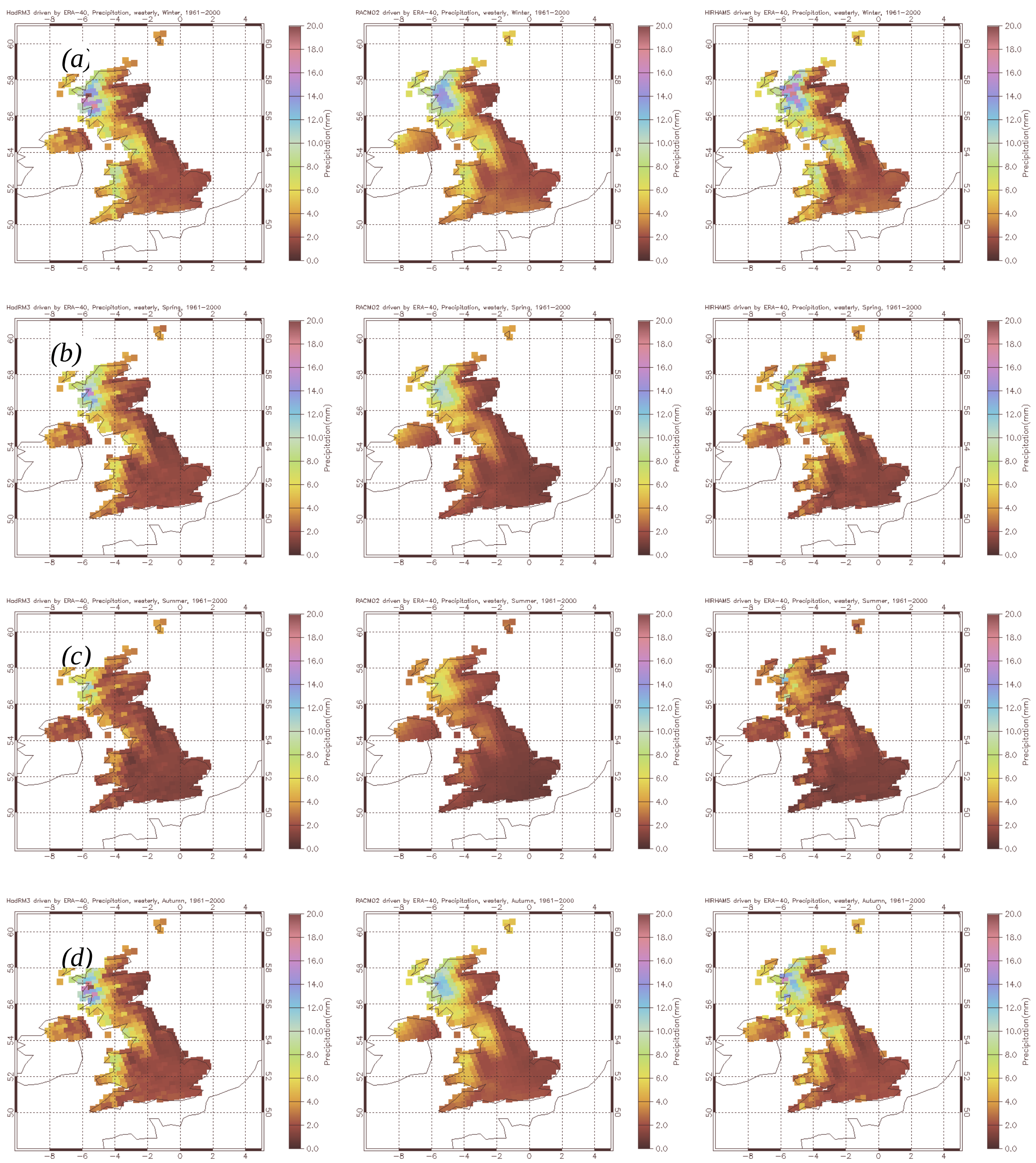


Fig 7.3. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals for westerly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparisons with observed values (Fig 7.4) suggest that, unlike for the south-westerly type, HadRM3 underestimates both mean and extreme 1-day precipitation across a large majority of the country in all four seasons, with the largest underestimates (approaching 50% at some grid boxes) concentrated in the Scottish Highlands and the high ground of Wales. The overestimates along the west coast of Scotland, which were very prominent under the south-westerly type, are less pronounced for mean precipitation in westerly types, although overestimates of 40% and above for mean 1-day maxima still occur in autumn and winter. RACMO2 also underestimates both mean and extreme 1-day precipitation in westerly flows, more consistently across the country than HadRM3, with the exception of East Anglia and parts of south-east England in winter where overestimates of 20% or more occur at some grid boxes. Underestimates are more significant for extreme precipitation than for mean precipitation, with underestimates of 20-40% over large areas of the country. HIRHAM5 produces less consistent results, but both mean and extreme 1-day precipitation is underestimated by more than 50% in most western coastal districts in summer, and otherwise underestimates of approximately 20% occur in most regions except for some western districts and East Anglia and the southeast in winter where overestimates of 20% occur.

Convective precipitation occurs mostly in western areas in autumn and winter according to all three models, but HIRHAM5 again suffers from simulating large amounts of convective precipitation along coastal fringes and little or none inland. HadRM3 and RACMO2 differ considerably regarding summer convective precipitation, RACMO2 shows convective precipitation as contributing up to 30% of the total in East Anglia, south-east England and also western Scotland, while HadRM3 shows a bias towards eastern coastal districts with up to 60% of the total precipitation being convective in those areas. HIRHAM5 shows little or no convective precipitation away from west-coast areas even in summer. As with the south-westerly type RACMO2 projects rather more convective precipitation in western Scotland in autumn and winter than HadRM3, despite projecting far less across most of the country in spring and especially summer.

The correlations with observed values are generally high except in summer. Unlike with the weather under south-westerly types, and all types combined, correlations are highest in winter, rather than autumn, and RACMO2 produces correlations of 0.6 to 0.8 in most parts of the country for winter precipitation with westerly flows. In summer, correlations are in the range of 0.2 to 0.4 in most parts of the country. HIRHAM5 performs almost as well as RACMO2, while HadRM3 produces similar correlations away from eastern Scotland and north-east England, but the latter regions produce much lower correlations, less than 0.4 in spring and autumn as well as in summer. Again the lowest correlations occur to the lee of high ground, as with the south-westerly type.

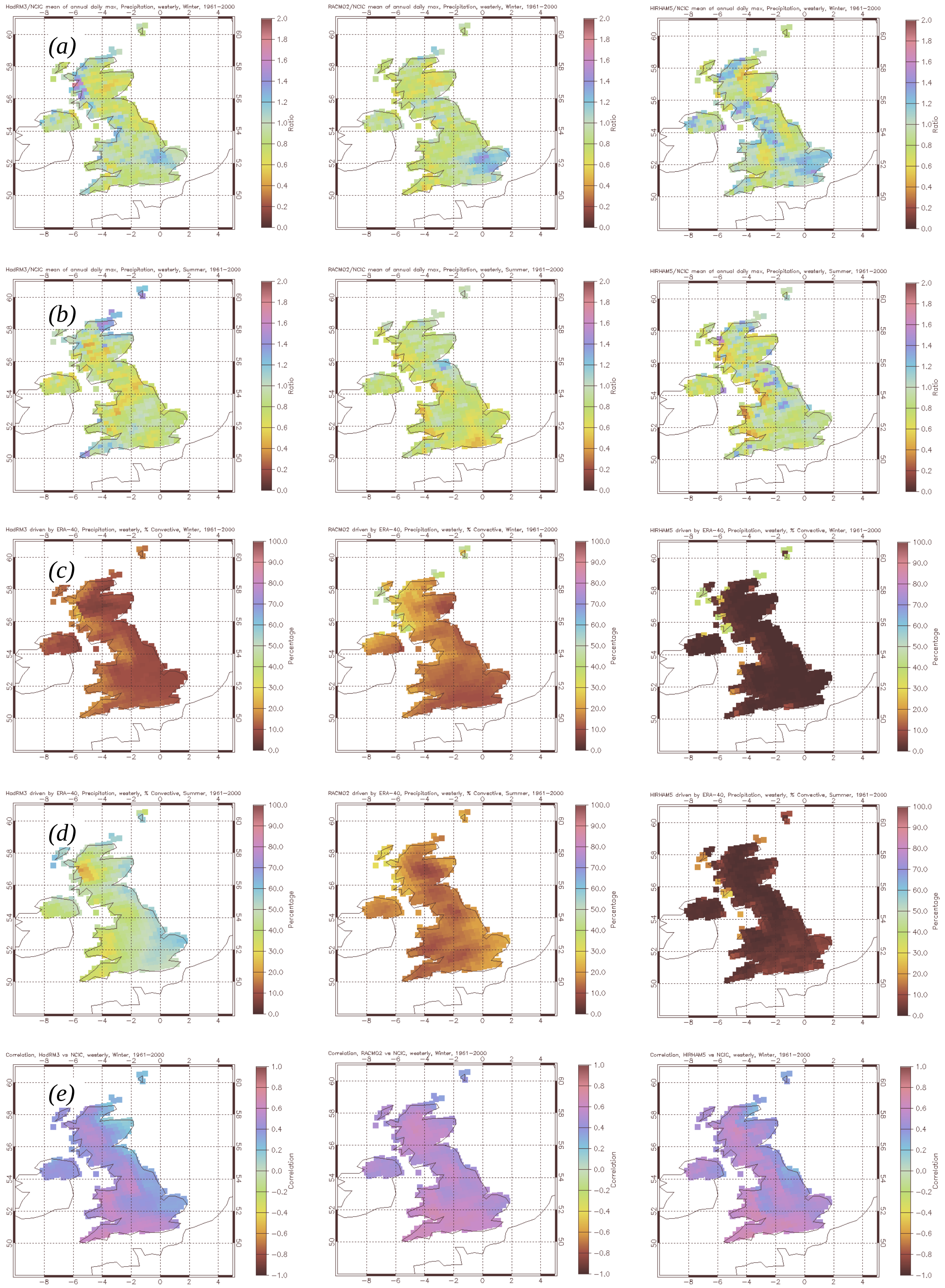


Fig 7.4. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the westerly type. The limit for correlation significance at the 95% level is approximately r = 0.08 (due to large sample size).

7.2.3 The north-westerly type

For north-westerly types (Fig 7.5) simulated mean daily precipitation across the UK shows strong cross-model agreement on the general geographical distribution, with north-west Scotland seeing the most precipitation, but again RACMO2 provides a much smoother distribution than either HadRM3 and HIRHAM5. HIRHAM5 has a less spatially coherent pattern in western Scotland in summer than the other two models, with a scattering of individual grid boxes producing high daily rainfall.

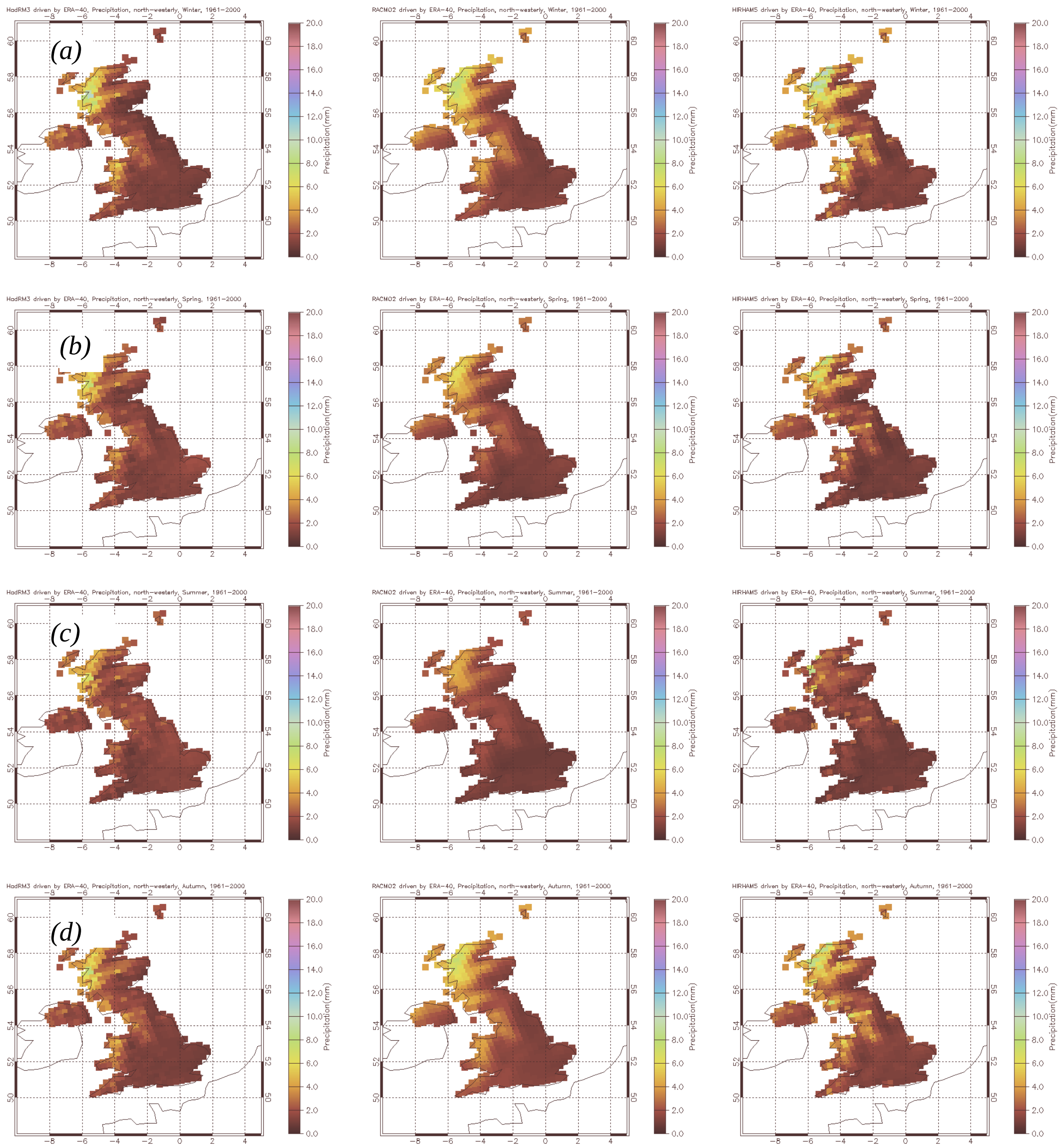


Fig 7.5. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals for north-westerly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed data, the models appear to cope less well with north-westerly (Fig 7.6) types than with south-westerly and westerly types. RACMO2 and HadRM3 generally underestimate precipitation across the British Isles, with HadRM3 performing the worse of the two with underestimates of mean precipitation approaching and locally exceeding 50% over much of Scotland in autumn and winter, and also near the south coast of England in autumn. Conversely HadRM3 overestimates mean spring precipitation in south-east England and overestimates in Lincolnshire and east Yorkshire in summer. RACMO2 also underestimates mean 1-day maximum precipitation consistently by up to 50% in western coastal areas. HIRHAM5 also underestimates both mean precipitation and the mean 1-day maximum in north-westerly flows, with the strongest underestimates again along the west coast in summer.

As with the westerly Lamb type, there are considerable differences between the HadRM3 and RACMO2 projections of summer convective precipitation. Both HadRM3 and RACMO2 show the majority of autumn and winter convective precipitation as being concentrated in western areas, particularly western Scotland (convective fraction of up to 40% in western Scotland), and HadRM3 also has a similarly high percentage of precipitation being of convective origin in west Lancashire (20-30% in winter, 40% in summer). RACMO2 does not project much convective precipitation in eastern districts from north-westerly types in spring and summer, with no more than 30% of the total precipitation being shown as convective, while in contrast HadRM3 projects more than 50% of summer precipitation as being of convective origin, reaching 70% in parts of East Anglia and the southeast.

Correlations with observed values are lower than for the westerly and south-westerly types, except in western Scotland in autumn and winter, and also south-west England in autumn, winter and spring in the case of RACMO2 and HIRHAM5, with HadRM3 producing correlations of 0.2 or less in all four seasons in many eastern areas. Correlations are near zero in parts of eastern Britain in summer for all three models. There is a strong implication that the models are not as good at handling precipitation events from north-westerly flows except in the west of Scotland, adding strength to the possibility that it may stem from good handling of frontal/orographic events and relatively poor handling of other precipitation events.

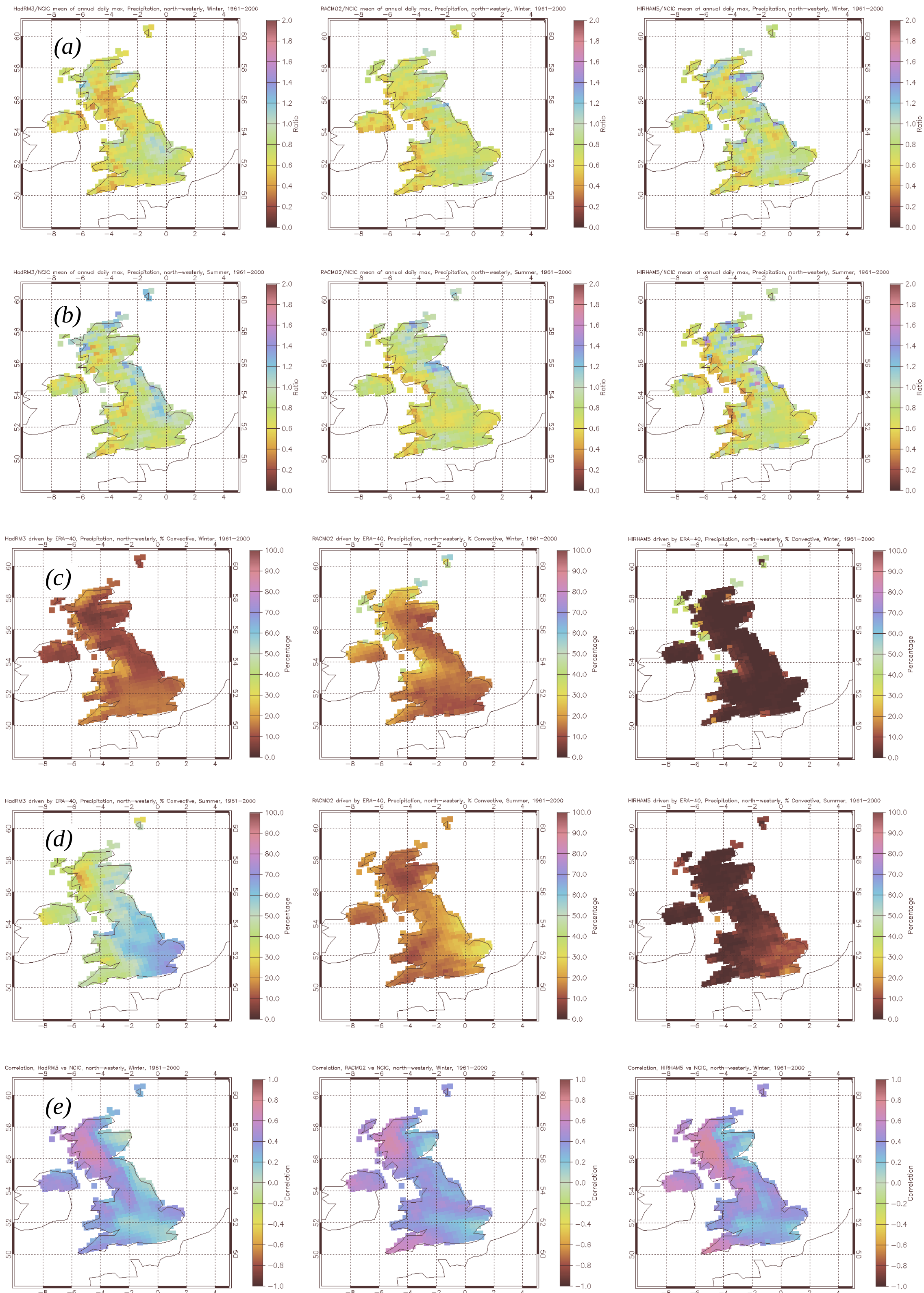


Fig 7.6. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the north-westerly type. The limit for correlation significance at the 95% level is approximately r = 0.11 (due to large sample size).

7.2.4 The northerly type

For northerly types (Fig 7.7), the models differ more in their simulation of mean precipitation across the UK.   RACMO2 shows a maximum near north-facing coasts in winter, spring and autumn, HadRM3 shows a maximum over northern hills, and HIRHAM5 shows a more extreme version of RACMO2's distribution with high totals at scattered grid boxes elsewhere. Again RACMO2's distribution is more smoothed than is the case for the other two models.

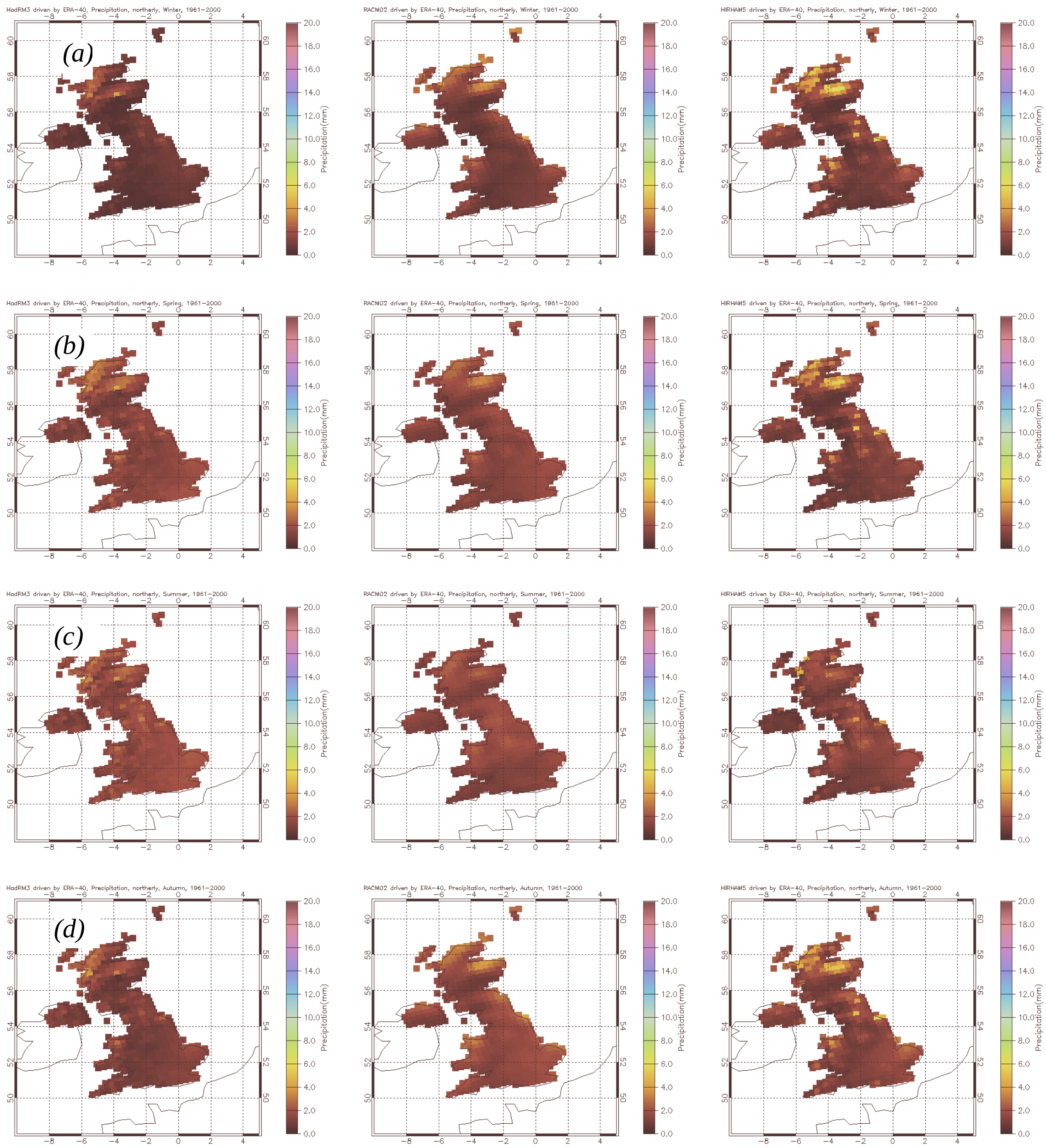


Fig 7.7. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in northerly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values it is clear that the northerly type is handled more poorly by the models than the south-westerly, westerly and north-westerly types previously considered (Fig 7.8). RACMO2 strongly overestimates mean precipitation across much of central and southern England during autumn and winter, especially in winter when overestimates approach 100%, and also around the Firth of Forth (suggesting that the sheltering effects of high ground, or lack of homegrown showers due to weak solar heating of the surface, are underestimated). In contrast there are underestimates of 50% or more in parts of western Scotland. Summer precipitation from northerlies is overestimated by 40-60% over much of Wales, the Midlands and north-west England with an overestimate approaching 100% on the north-west coast of Wales. HadRM3 underestimates autumn and winter precipitation substantially near north-facing coasts, with underestimates widely exceeding 50% in those areas in winter, while significant overestimates occur in winter in the Midlands. Spring precipitation is overestimated by up to 60% in the south, and summer precipitation is overestimated over most of the country. HIRHAM5 has overestimates widely in excess of 100% in central and southern England in winter, and there is low consistency between adjacent grid boxes but accordance with observed values is good at most grid boxes in spring, summer and autumn except for western Scotland and north-west England, where substantial underestimates occur in all seasons. The extreme 1-day maxima are handled better by RACMO2 than mean precipitation but there are still strong anomalies, with overestimates of 60-80% at some grid boxes in southern England in winter. A similar pattern occurs with HadRM3 and HIRHAM5, both of which show similar anomaly distributions to those for mean precipitation, but with less pronounced anomalies.

RACMO2 and HadRM3 show similar distributions of convective precipitation from northerly types, with autumn and winter having the highest amounts of convective precipitation, and the highest proportions of the total, prevalent near north-facing coasts. HadRM3 has a greater emphasis on higher proportions of convective precipitation near west-facing coasts than RACMO2, and a large majority of the convective precipitation is more strongly confined to coastal fringes than is suggested by RACMO2.

Spring and summer precipitation show similar geographical distributions but somewhat higher proportions of total precipitation are given as convective by HadRM3, suggesting proportions of up to 80% in Kent and Sussex, while RACMO2 shows a peak of 40-50% to the west of London, both models suggesting a bias towards the southeast. HIRHAM5 suffers from the problems seen with the other types considered so far, with almost no convective precipitation shown except for some extreme coastal fringes and proportions of up to 20% in southern England in summer.

Correlations with observed values are markedly reduced compared to those seen for the south-westerly, westerly and north-westerly types. All three models show correlations of 0.4 to 0.6 in many parts of Scotland and north-western Ireland in autumn, winter and spring, particularly western Scotland, and in parts of south-west England in spring, but elsewhere there is no consistent pattern between the models, and significant areas of the country have correlations close to zero. The winter correlations of RACMO2 are noteworthy in that correlations are high in Scotland and near north-facing coasts, but near zero in the regions that are heavily sheltered from showery northerly airstreams in winter.

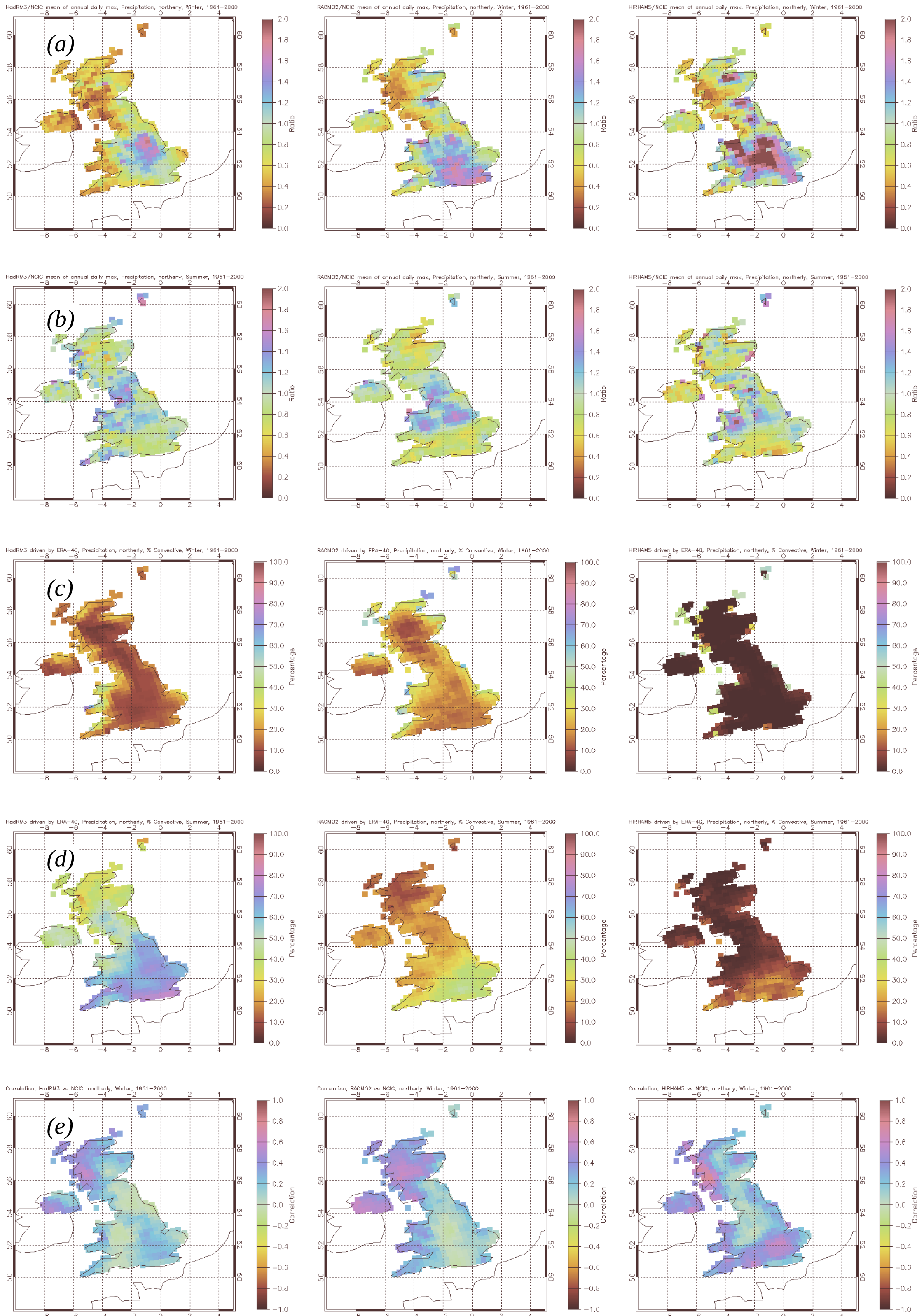


Fig 7.8. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the northerly type. The limit for correlation significance at the 95% level is approximately r = 0.16.

7.2.5 The north-easterly type

The models diverge more significantly in their simulation of the geographical distribution of precipitation in north-easterly regimes (Fig 7.9). In particular RACMO2 gives higher precipitation in central England in summer and in eastern Britain in autumn than the other two models, while HIRHAM5 gives higher precipitation in north-east England in summer and autumn.

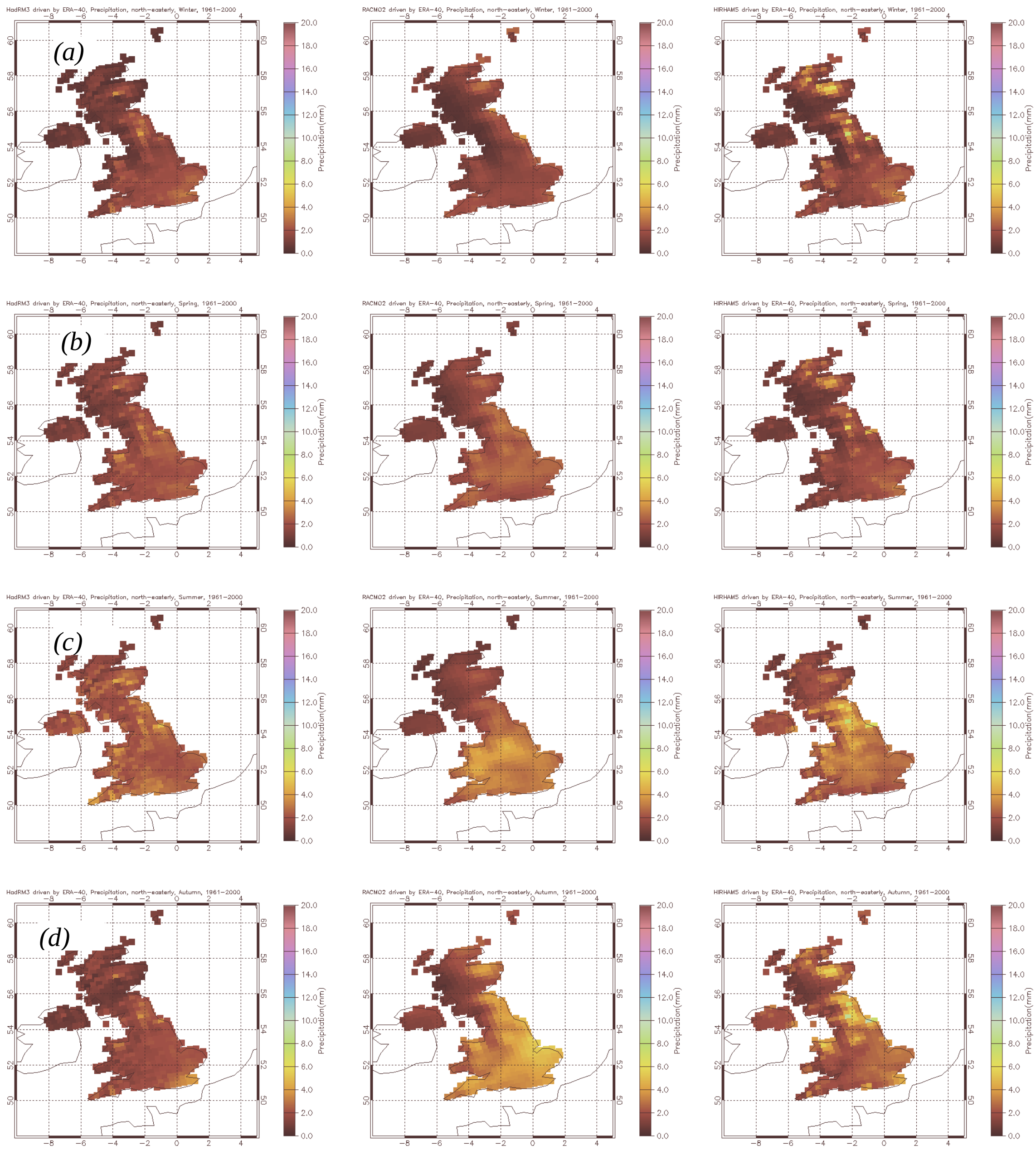


Fig 7.9. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in north-easterly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Precipitation associated with the north-easterly type, in comparison with observed values (Fig 7.10), is poorly handled by all three models. Mean precipitation is overestimated by 100% in winter at a large range of grid boxes for all three models, HadRM3 underestimates precipitation by well in excess of 50% in northern Scotland, and RACMO2 and HIRHAM5 underestimate similarly in western Scotland. Conversely, in summer all three models underestimate in southern England and overestimate (by more than 100%) in some northern and western regions, with RACMO2 performing better than HadRM3 and HIRHAM5 in this case. Spring features overestimates in north-west England for all three models, while autumn has overestimates in western and southern Britain for RACMO2 and HIRHAM5, and underestimates of more than 50% in north-eastern Britain (particularly near North Sea coasts) for HadRM3. The mean 1-day maxima are simulated more accurately by RACMO2 than the mean precipitation, but this is not the case with HadRM3 or HIRHAM5 which show similar anomaly distributions and intensities to those for mean precipitation.

HadRM3 has convective precipitation occurring mostly in southern and south-western Britain during spring and summer with 70% of precipitation given as convective in parts of Devon and Cornwall, while in winter convective precipitation is shown as most common around coastal fringes (even those facing away from the wind). RACMO2 shows a similar distribution in summer but smaller proportions (approximately 30% of precipitation being convective in the most prone south-western areas) while in autumn and winter it has convective precipitation more heavily biased towards north and east-facing coasts than HadRM3. HIRHAM5 again has an unrealistic bias towards autumn and winter convective precipitation being exclusively confined to some individual grid boxes on extreme coastal fringes, but shows up to 30% of precipitation being convective in south-east England in summer, particularly near the south coast.

Correlations with observed values are mostly low. RACMO2 produces correlations of up to 0.6 in parts of eastern England in autumn and winter, and HIRHAM5 produces similarly high correlations in spring in south-west England, but otherwise correlations are mostly between 0 and 0.2, and HadRM3 even produces a small negative correlation in Lincolnshire in summer.

Note that the results for the north-easterly type will be less reliable than for the previous types considered due to the smaller number of days featuring north-easterly types (Table 7.1).

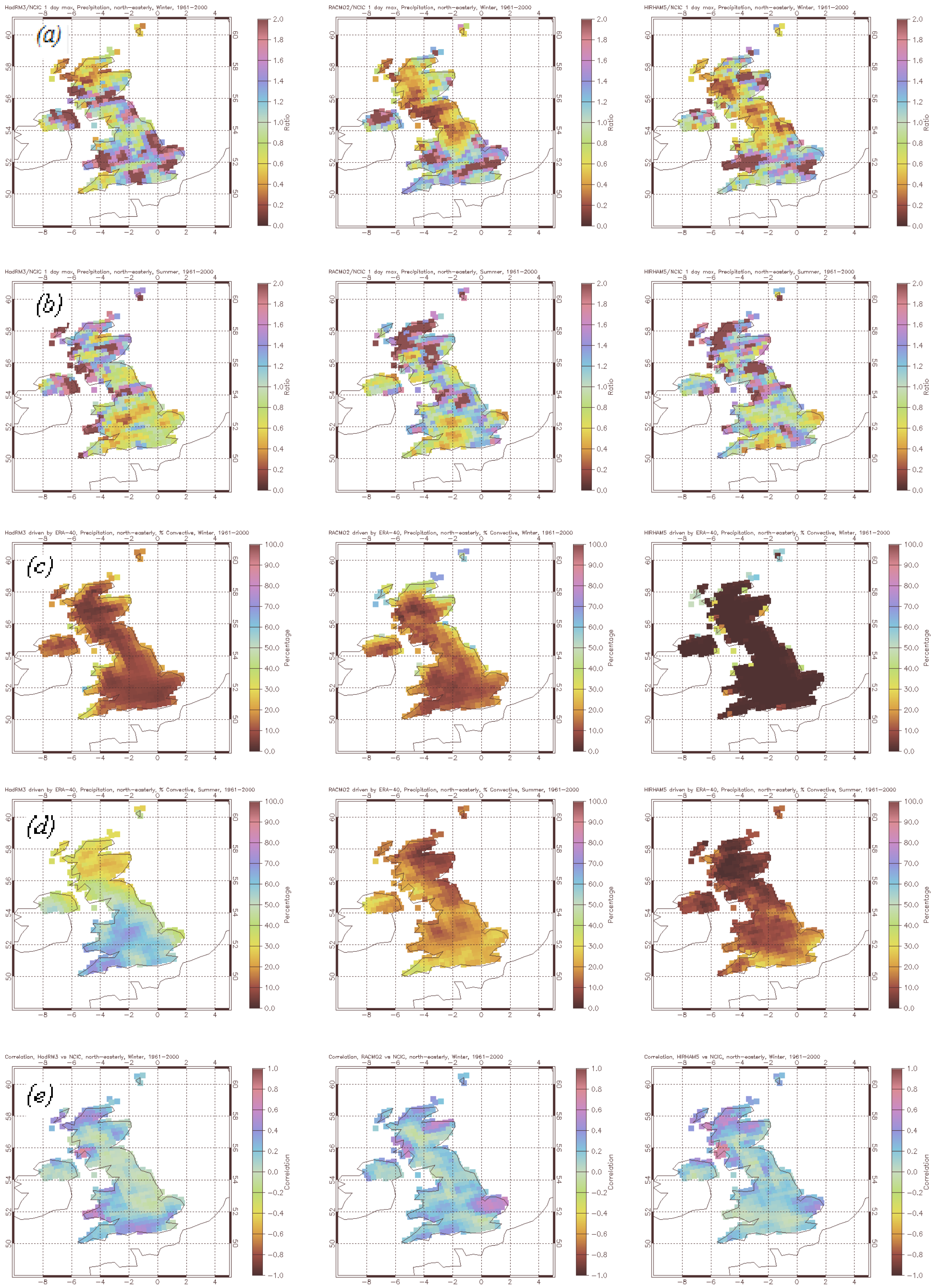


Fig 7.10. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the north-easterly type. The limit for correlation significance at the 95% level is approximately r = 0.22.

7.2.6 The easterly type

For the easterly type (Fig 7.11), the models show a more consistent simulation of precipitation distribution across the UK. However, in winter and spring, RACMO2 simulates a maximum occurring along some North Sea coasts whereas HadRM3 and HIRHAM5 simulate the maximum occurring inland, particularly over the Pennines and eastern Scottish Highlands.

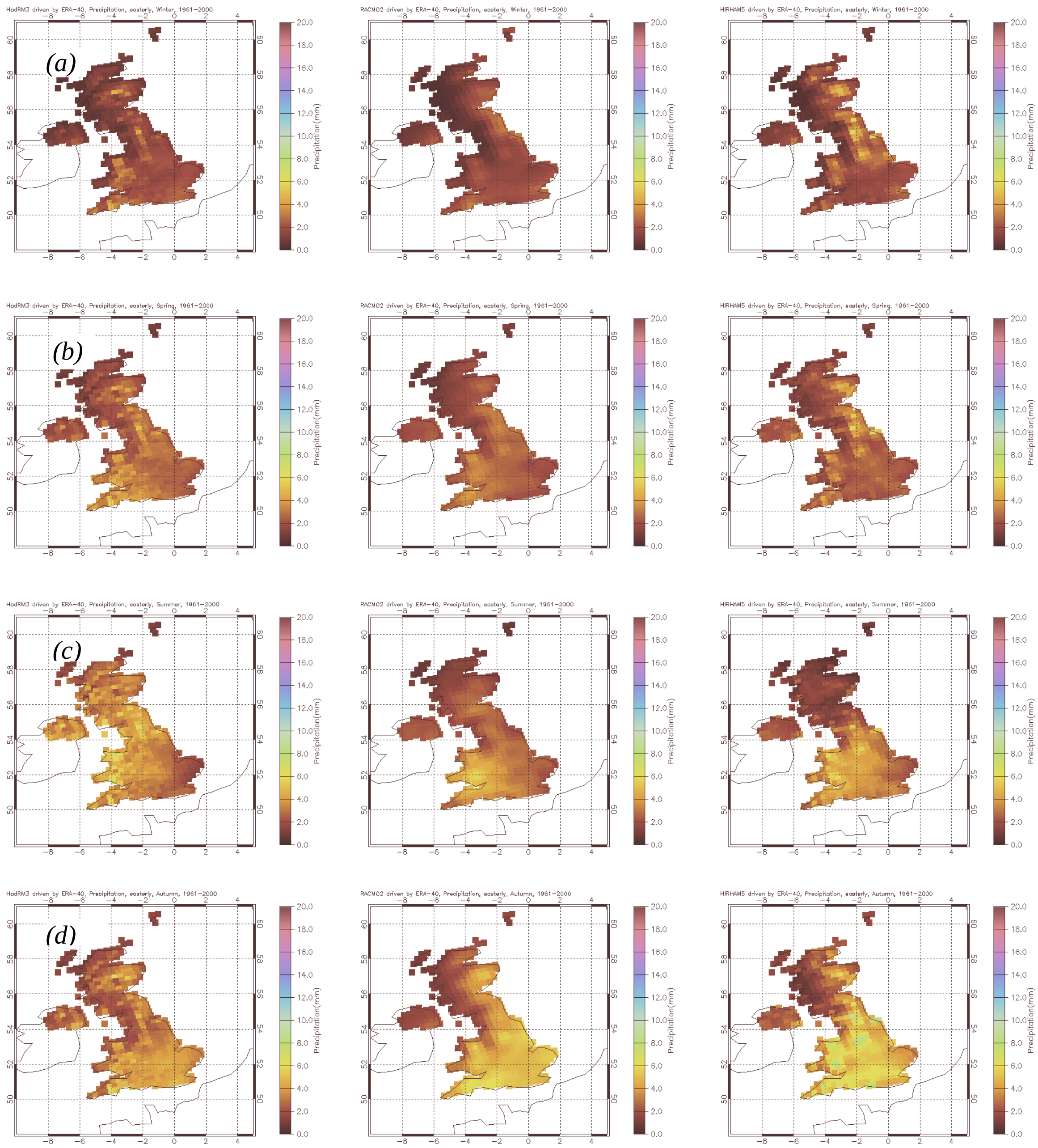


Fig 7.11. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in easterly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values (Fig 7.12), RACMO2 overestimates mean precipitation in most parts of the country in winter (mostly by 40-60%) but underestimates occur over the Pennines and western Scotland. Substantial overestimates occur in Lancashire and Yorkshire in spring, in northern and eastern Britain generally during autumn and in northern Scotland during summer. HadRM3 shows a more extreme version of the same patterns in spring and summer, but in winter overestimates of over 100% occur widely in western areas. In contrast, autumn sees good accordance with observed values over most parts of the country for the HadRM3 outputs. HIRHAM5 has similar anomaly patterns to HadRM3 but with the overestimates in Scotland in summer covering a much smaller area (more confined to the north coast) and with overestimates of over 100% in north-west England in autumn. As with the north-easterly type, RACMO2 performs better at simulating the mean 1-day maxima, while HadRM3 and HIRHAM5 show similar anomalies by this measure to those for mean precipitation.

HadRM3 shows the majority of convective precipitation from easterlies occurring in the southern half of Britain in summer with a proportion of the total as large as 90% in west London, while in winter, most convective precipitation is simulated to occur in southern and western coastal districts, despite the latter facing away from the wind. RACMO2 also shows a bias towards southern England in summer but with proportions of the total only reaching 50%, while in winter convective precipitation is simulated to occur most prominently near the east coasts of Scotland and northern England. HIRHAM5 shows a similar distribution to RACMO2 in summer but shows little or no convective precipitation anywhere in the UK in winter, spring and autumn.

Correlations of simulated precipitation with observed values are lower than for the south-westerly, westerly and north-westerly types, but for RACMO2 and HIRHAM5 they are higher than for north-easterly types. RACMO2 produces correlations of up to 0.6 in western Scotland in winter, while parts of eastern England are in the 0.4-0.6 range, as is much of Northern Ireland in winter, summer and autumn. HIRHAM5 produces correlations of up to 0.6 in Northern Ireland in autumn and in west Wales in winter. HadRM3 produces low correlations (less than 0.4) in almost all regions in all four seasons, with small negative correlations (0 to -0.2) in parts of western and northern Scotland in autumn.

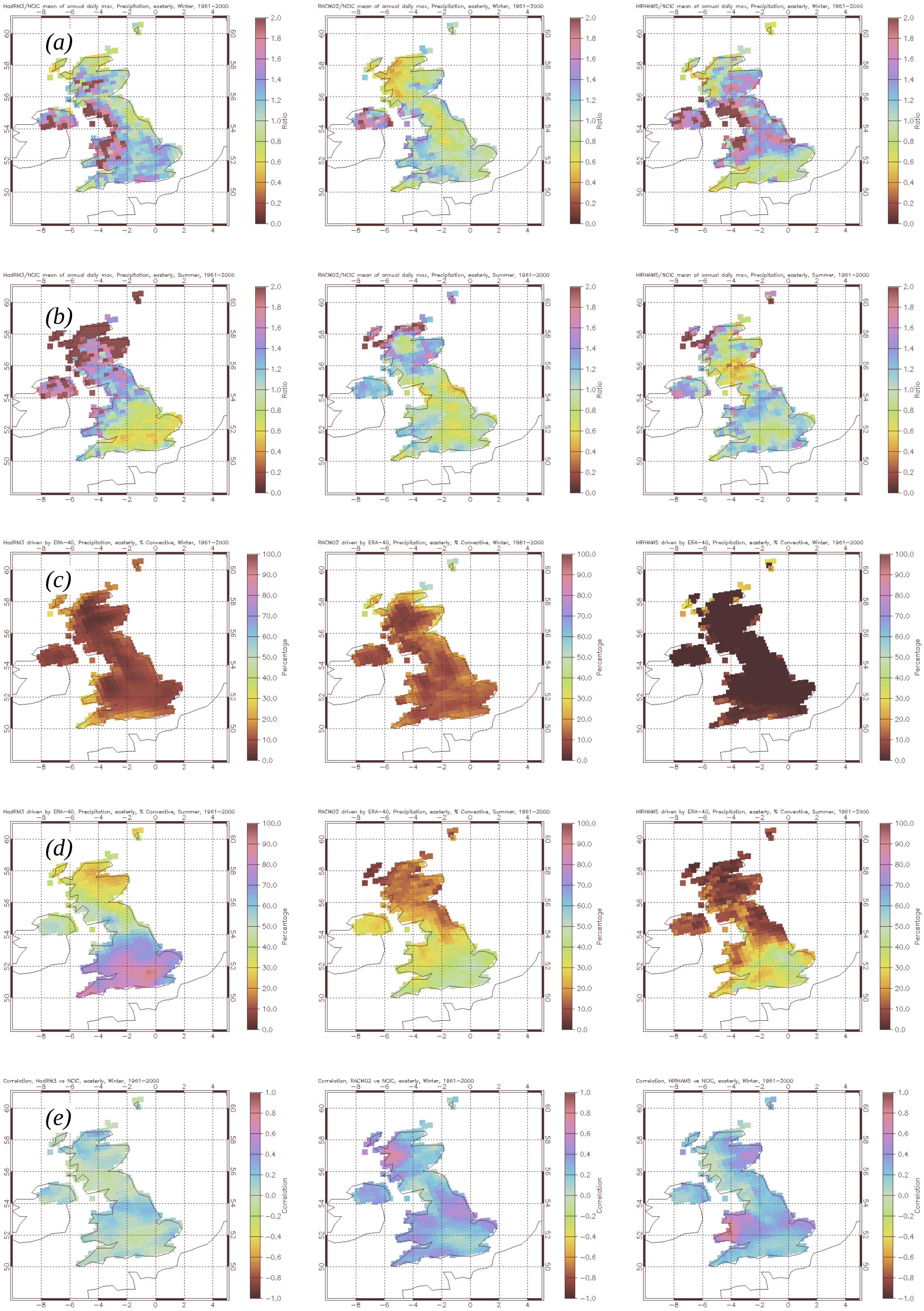


Fig 7.12. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the easterly type. The limit for correlation significance at the 95% level is approximately r = 0.17.

7.2.7 The south-easterly type

For south-easterly types (Fig 7.13) the models again show strong agreement on the distribution of mean precipitation over the UK but with RACMO2 showing a more “smoothed” distribution than the other two models. In contrast to the outputs previously considered for south-westerly, westerly and north-westerly types, HIRHAM5 produces smoother outputs than HadRM3.

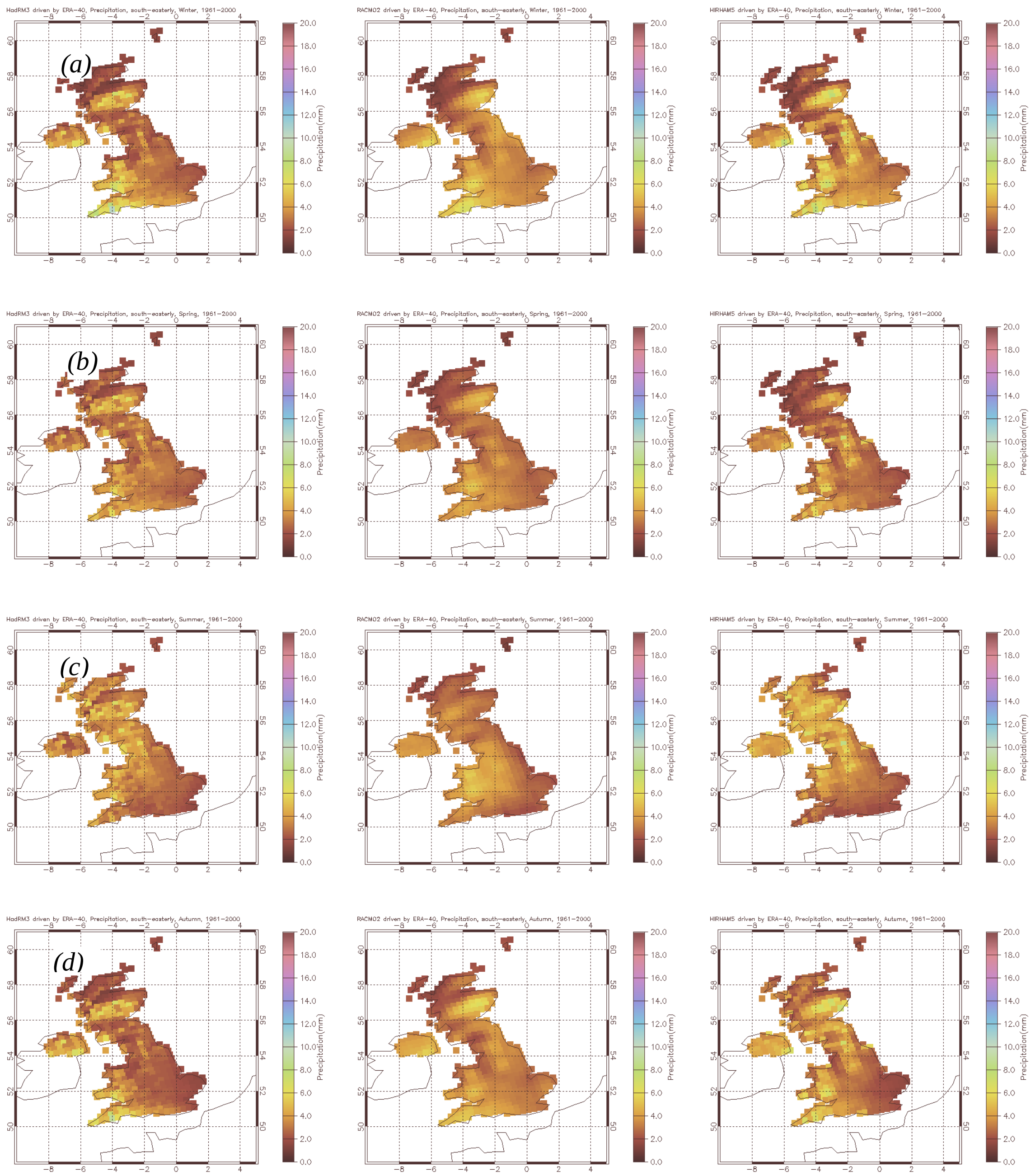


Fig 7.13. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in south-easterly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values (Fig 7.14), RACMO2 overestimates precipitation at most grid boxes in northern Scotland in all four seasons, and in central and eastern England in winter, spring and autumn, especially Norfolk where the overestimate in spring reaches 80-100%. HadRM3 handles precipitation from the south-easterly type better than RACMO2 in autumn and winter, though with some anomalies at individual grid boxes, but precipitation is strongly overestimated in East Anglia and western Scotland in spring, and in northern Scotland in summer where overestimates exceed 100%. HIRHAM5 shows similar anomalies to HadRM3 but overestimates of 40-60% occur widely in autumn and winter, and underestimates occur in south-west Scotland in spring, in contrast to the overestimates of HadRM3. The estimates of mean 1-day maxima show similar anomaly distributions to those for mean precipitation for all three models, with all three models also showing slightly closer accordance with observed values.

Convective precipitation is handled similarly for all three models, with a large majority of convective precipitation in autumn and winter shown as occurring near the south coast of England, with a bias towards south-west England for HadRM3, while spring and summer have a north-south split. HIRHAM5 again has winter convection almost exclusively restricted to a small number of individual grid boxes along coastal fringes. Convective precipitation produces up to 80% of the total in parts of southern England according to HadRM3 while RACMO2 and HIRHAM5 suggest proportions of up to 60%. HIRHAM5 unrealistically shows almost no convective precipitation across the northern half of Britain, whereas RACMO2 and HadRM3 show smaller proportions (between 20 and 40%).

Correlations with observed values are generally high, with RACMO2 producing correlations of 0.4 or higher nationwide in winter, although they are generally lower in summer with values of 0.2 or less in parts of western England in summer. HIRHAM5 and HadRM3 show similar distributions, with HIRHAM5 performing similarly to RACMO2 but HadRM3’s correlations are mostly 0.1-0.2 lower across the country.

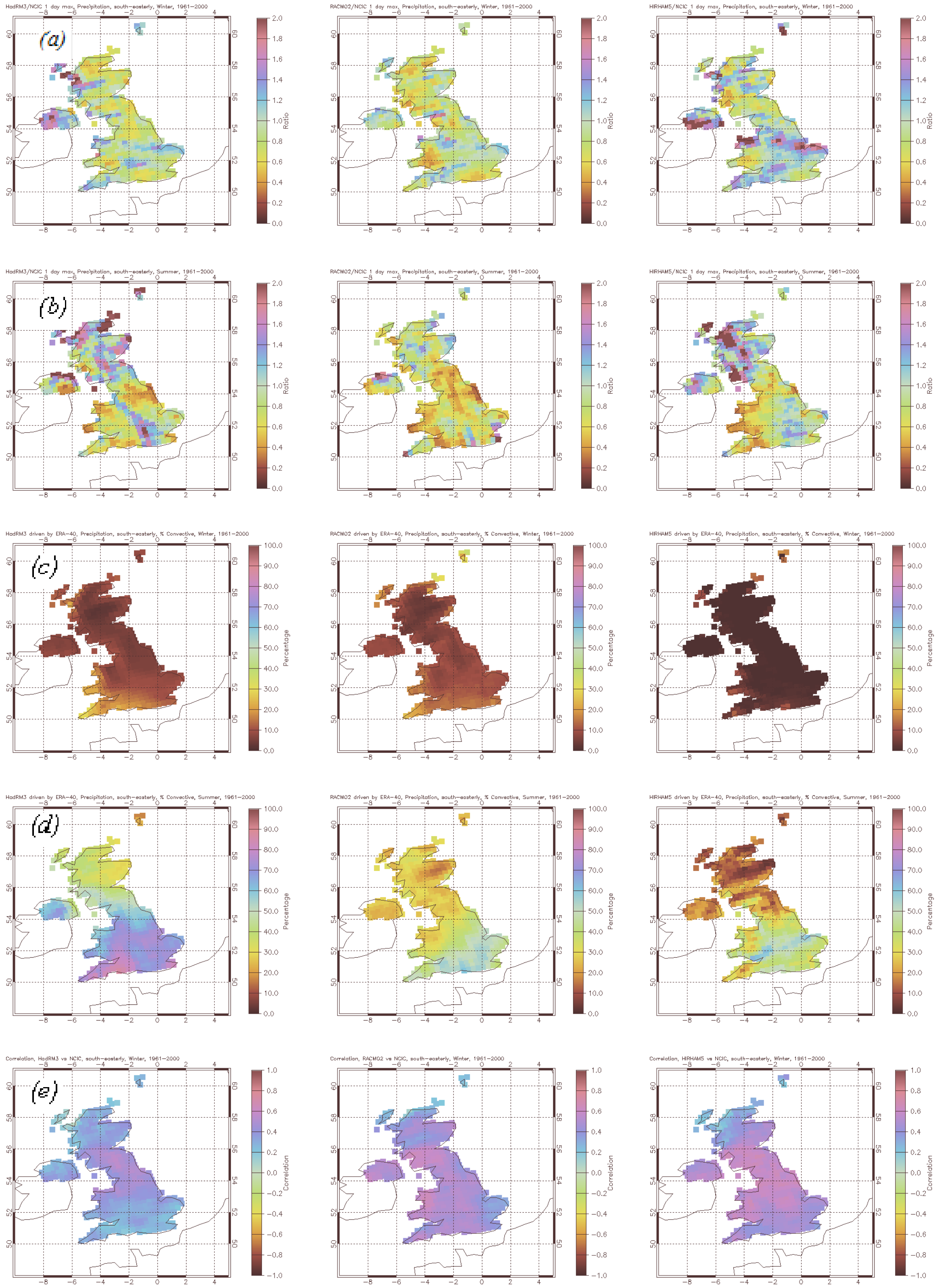


Fig 7.14. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the south-easterly type. The limit for correlation significance at the 95% level is approximately r = 0.14.

7.2.8 The southerly type

The models produce a similar distribution of precipitation in all seasons during southerly regimes (Fig 7.15). As for the south-easterly type, HIRHAM5 produces a more smooth distribution than HadRM3, though RACMO2 continues to produce a smoother distribution than either HadRM3 or HIRHAM5. The projected distribution of precipitation is similar to that for south-westerly types but with significantly less rainfall across northern Scotland.

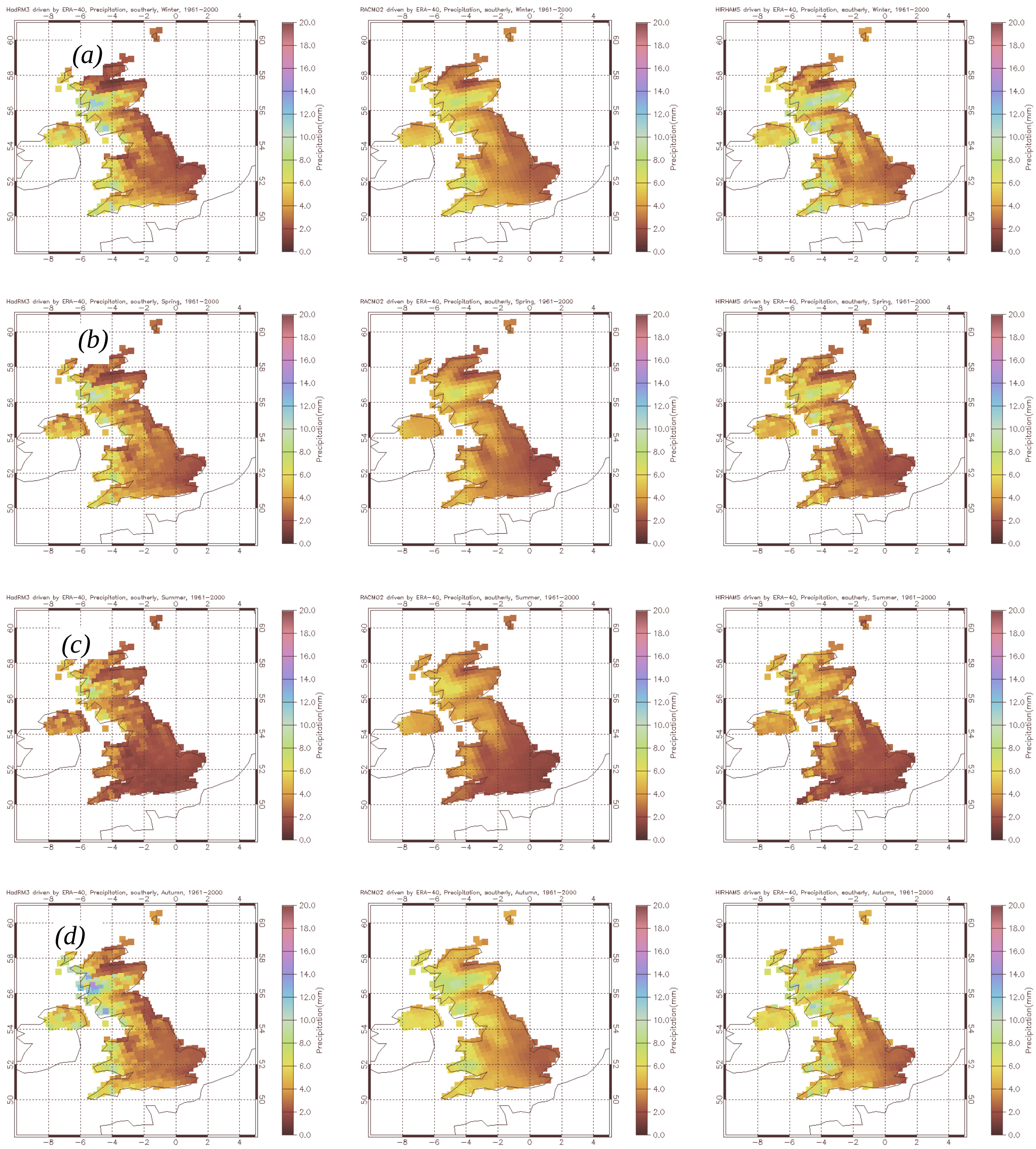


Fig 7.15. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in southerly types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values (Fig 7.16), RACMO2 appears to handle precipitation similarly to the south-easterly type, with overestimates of 40-60% over most eastern districts in winter, spring and autumn (mostly the northeast in spring) but generally good accordance with observed values in summer, although underestimates of 40-60% occur locally in south-west England. HadRM3 performs better than RACMO2 in autumn and winter, with fewer anomalies between adjacent grid boxes than for the south-easterly type, but underestimates by more than 50% in summer in parts of south-western Britain. HIRHAM5 performs similarly to RACMO2, but the anomalous grid boxes noted for the more common wind directions are again strongly evident. The models perform better for 1-day maxima than for mean precipitation, with the exception of HadRM3 during summer, when extreme precipitation in the south and west is underestimated by more than mean precipitation.

HadRM3 shows convective precipitation occurring mostly near south and west-facing coasts in autumn and winter, while RACMO2 has it predominantly occurring near the south coast with relatively little affecting western districts. Summer convective precipitation reaches 40-50% of the total for the RACMO2 summer output, with the highest proportions occurring over Lincolnshire, while HadRM3 has the highest proportion (approximately 60%) occurring up the spine of England and also in northeast Norfolk.

Correlations with observed values are a little lower than for the south-easterly type. RACMO2 and HIRHAM5 both produce correlations between 0.4 and 0.6 over most of the country during winter, but correlations widely fall to approximately 0.2 during summer. HadRM3 again performs less well, although correlations are in the 0.4-0.6 range in most parts of the country during winter, and summer correlations in parts of eastern England fall to zero or below.

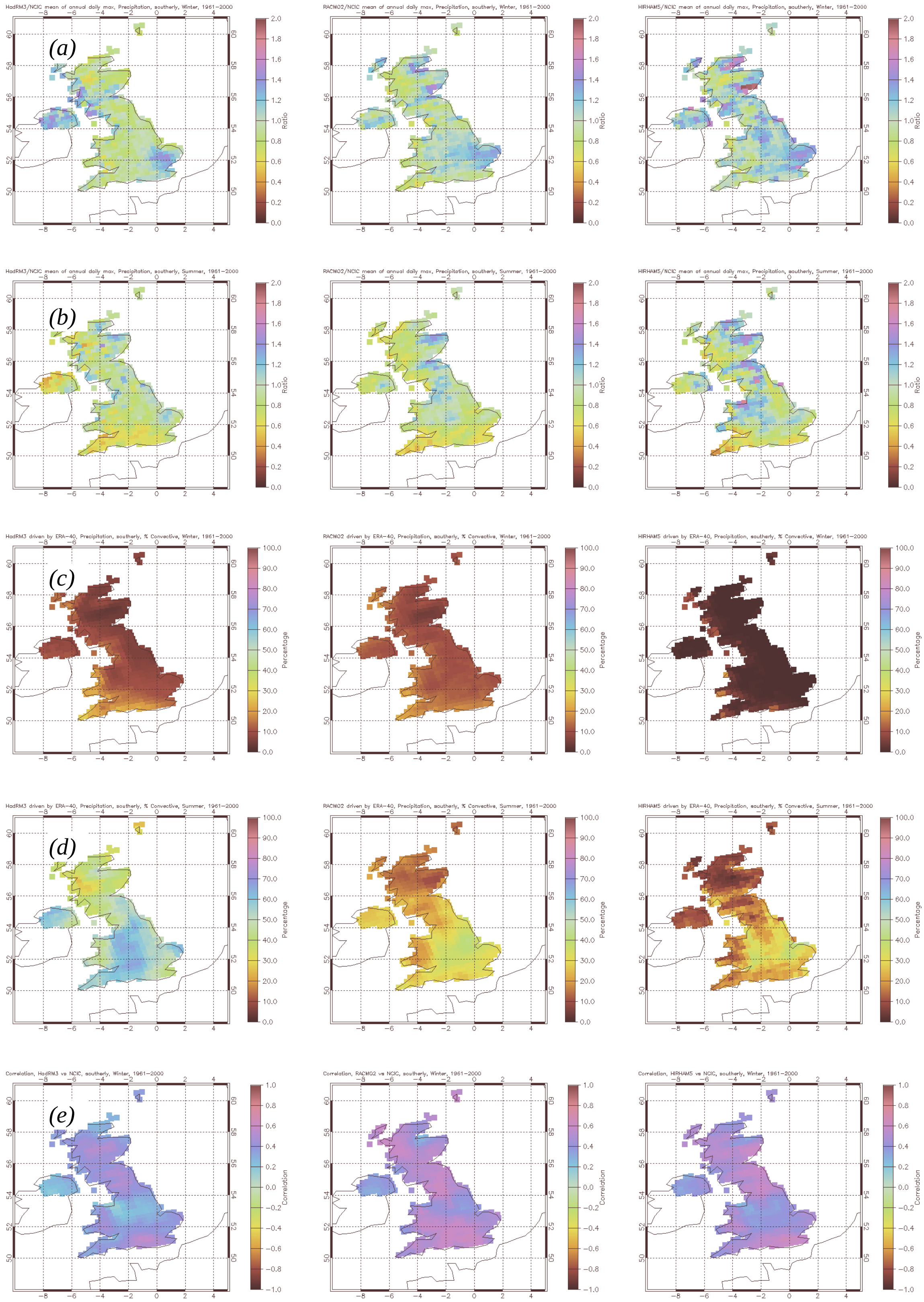


Fig 7.16. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the southerly type. The limit for correlation significance at the 95% level is approximately r = 0.10 (due to large sample size).

7.2.9 The cyclonic type

For the “pure” cyclonic type (Fig 7.17), the models strongly agree on the distribution of precipitation across the UK, with upland parts of northern and western Britain seeing the most precipitation, and southern coastal areas having significant amounts in autumn and winter. As was the case for southerly and south-easterly types, HIRHAM5 produces a smoother distribution of precipitation than HadRM3 but less so than RACMO2.

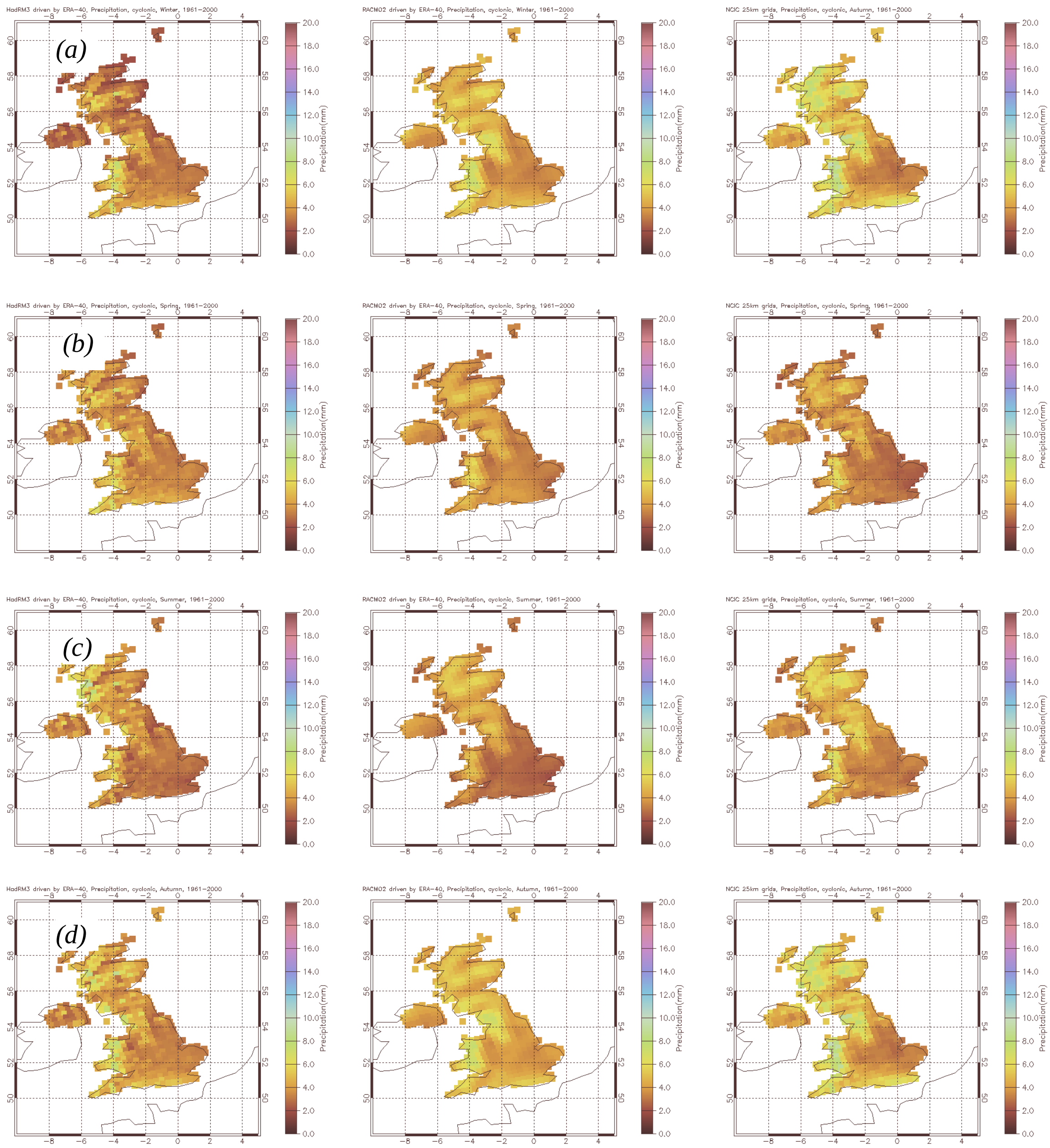


Fig 7.17. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in cyclonic types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values (Fig 7.18), RACMO2 handles mean precipitation very well in summer, with most grid boxes coming out within 20% of the observed values, but overestimates occur in eastern districts in the other three seasons, particularly in winter when overestimations exceed 60% locally in south-east Scotland. Conversely HadRM3 has problems with overestimation near southern and western coasts in spring, and near western coasts in summer, and generally good accordance with observed values in autumn and winter although underestimations of 20-40% occur locally. HIRHAM5 overestimates in north-eastern districts in winter and spring (especially winter) and underestimates by more than 50% in coastal parts of south-western Britain in summer, but accordance with observed values is mostly good in autumn. Accordance with observed mean 1-day maxima is better than for mean precipitation in the case of RACMO2, though with widespread underestimates of 10-20%, but HadRM3 and HIRHAM5 both overestimate extreme precipitation from cyclonic types in eastern England in autumn and winter.

The models all have most precipitation occurring in inland and especially upland areas in cyclonic regimes, but with some inconsistent handling of the west-east split in the observed values (as seen above). Convective precipitation is projected to occur mostly in western and southern areas for all three models, but HIRHAM5 again has most of it restricted to a few individual grid boxes at coastal extremes. In summer, HadRM3 and RACMO2 both point to a north-south split with up to 80% of the total simulated by HadRM3 being convective, and 40-50% simulated by RACMO2. HIRHAM5 shows a bias towards the southeast in summer rather than the south in general.

Correlations with observed values under the cyclonic type are mostly near 0.4 in winter, and in the 0.2-0.4 range in the other three seasons, for the RACMO2 outputs, with HIRHAM5 only slightly behind, and HadRM3 behind both RACMO2 and HIRHAM5 in terms of accuracy with correlations near zero in some parts of the country in summer, and rising to the 0.2-0.4 range in winter.

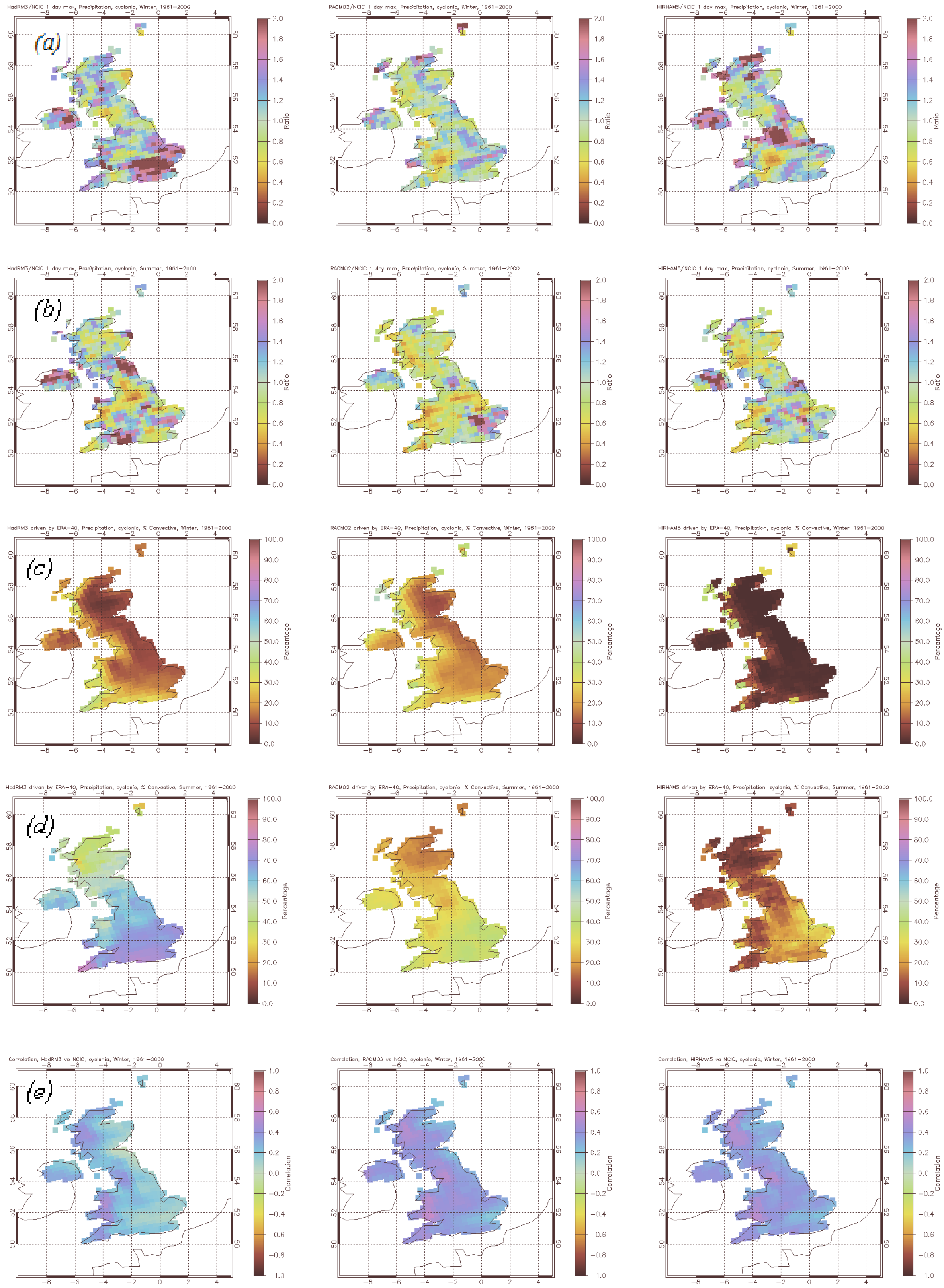


Fig 7.18. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the cyclonic type. The limit for correlation significance at the 95% level is approximately r = 0.10 (due to large sample size).

7.2.10 The anticyclonic type

The models suggest small amounts of precipitation under "pure" anticyclonic conditions (Fig 7.19) except in western Scotland where HadRM3 simulates large precipitation amounts in all four seasons, while HIRHAM5 gives large amounts only at scattered grid boxes, and RACMO2 has a smoothed area of slightly enhanced precipitation.

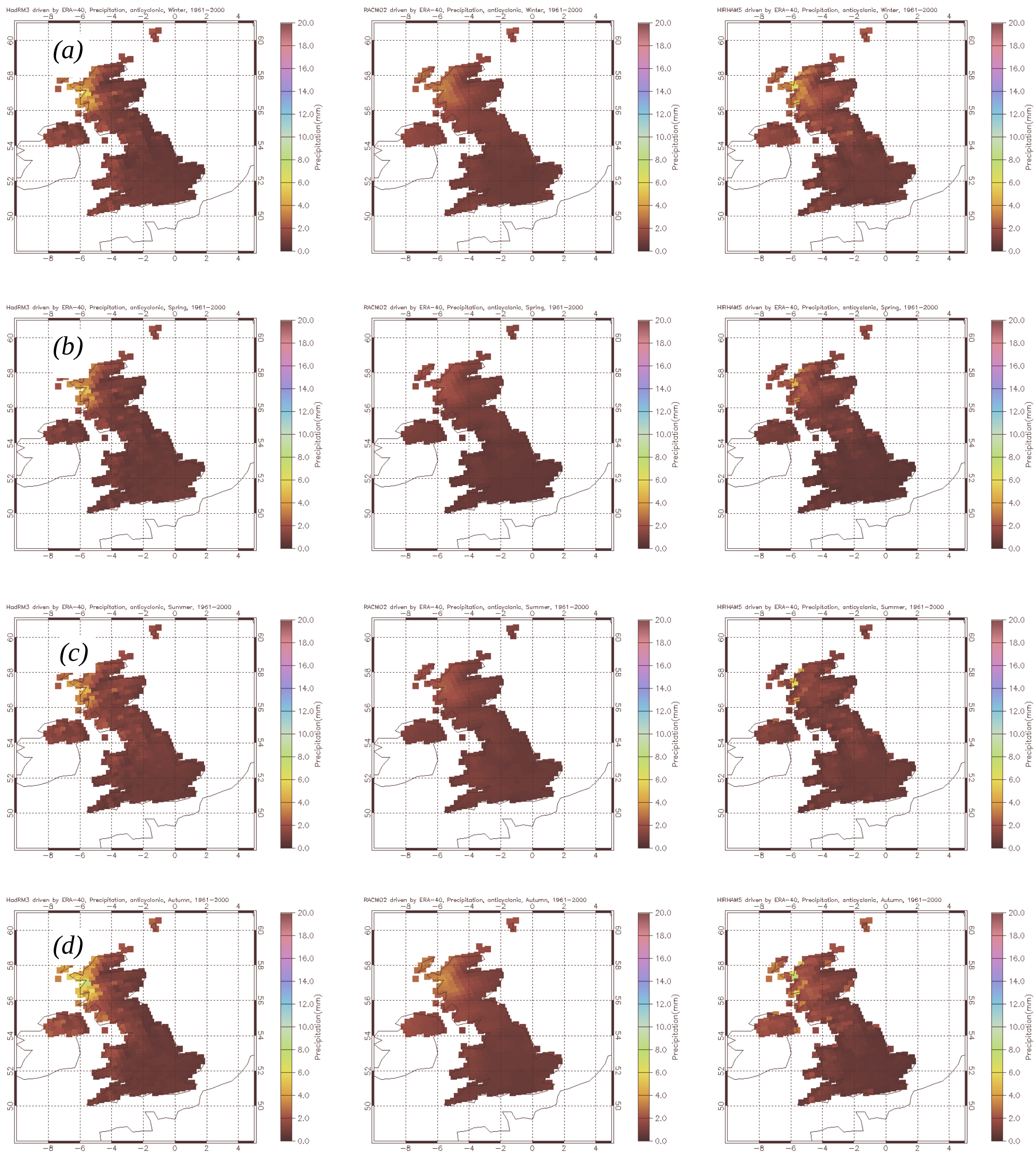


Fig 7.19. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), showing mean daily precipitation totals in cyclonic types for (a) winter (DJF), (b) spring(MAM), (c) summer(JJA) and (d) autumn (SON).

Comparing with observed values (Fig 7.20), precipitation associated with the anticyclonic type is strongly overestimated in eastern areas in most cases. RACMO2 strongly overestimates mean precipitation in most eastern areas in winter, spring and autumn, with overestimates locally exceeding 100%, while underestimates of up to 40% occur in some western coastal areas, while in summer the overestimates (away from western Scotland) are less extreme. HadRM3 handles precipitation better during autumn and winter, with less extreme overestimates than in the case of RACMO2, and the overestimates confined to the southern half of eastern England, but in spring and summer overestimates are more extreme and occur nationwide. HIRHAM5 overestimates in central and eastern areas, especially in winter, and underestimates in some western coastal districts with underestimates well in excess of 50% in summer and autumn. Extreme precipitation under anticyclonic conditions shows a larger bias towards underestimation across much of the UK for all three models, especially in western regions.

Convective precipitation under anticyclonic conditions is simulated to be almost non-existent in winter, but HadRM3 and more especially RACMO2 indicate some convective precipitation occurring around coasts, especially east-facing coasts, implying showers near the east coast in anticyclonic/easterly types. In spring and summer a northwest-southeast split is suggested, with convective precipitation accounting for as much as 60-70% of the total in southeast England according to HadRM3, and 40-50% according to RACMO2, and 30-40% locally according to HIRHAM5.

Correlations with observed values are very high for RACMO2's winter output with values of 0.6 to 0.8 in many parts of the country, and autumn correlations are almost as high, but spring sees the highest correlations confined to western Scotland, and in summer correlations range between 0.2 and 0.4 in most parts of the country. HadRM3 shows a similar pattern but the high autumn and winter correlations are confined to the western two-thirds of the country, while HIRHAM5 falls between the RACMO2 and HadRM3 scenarios.

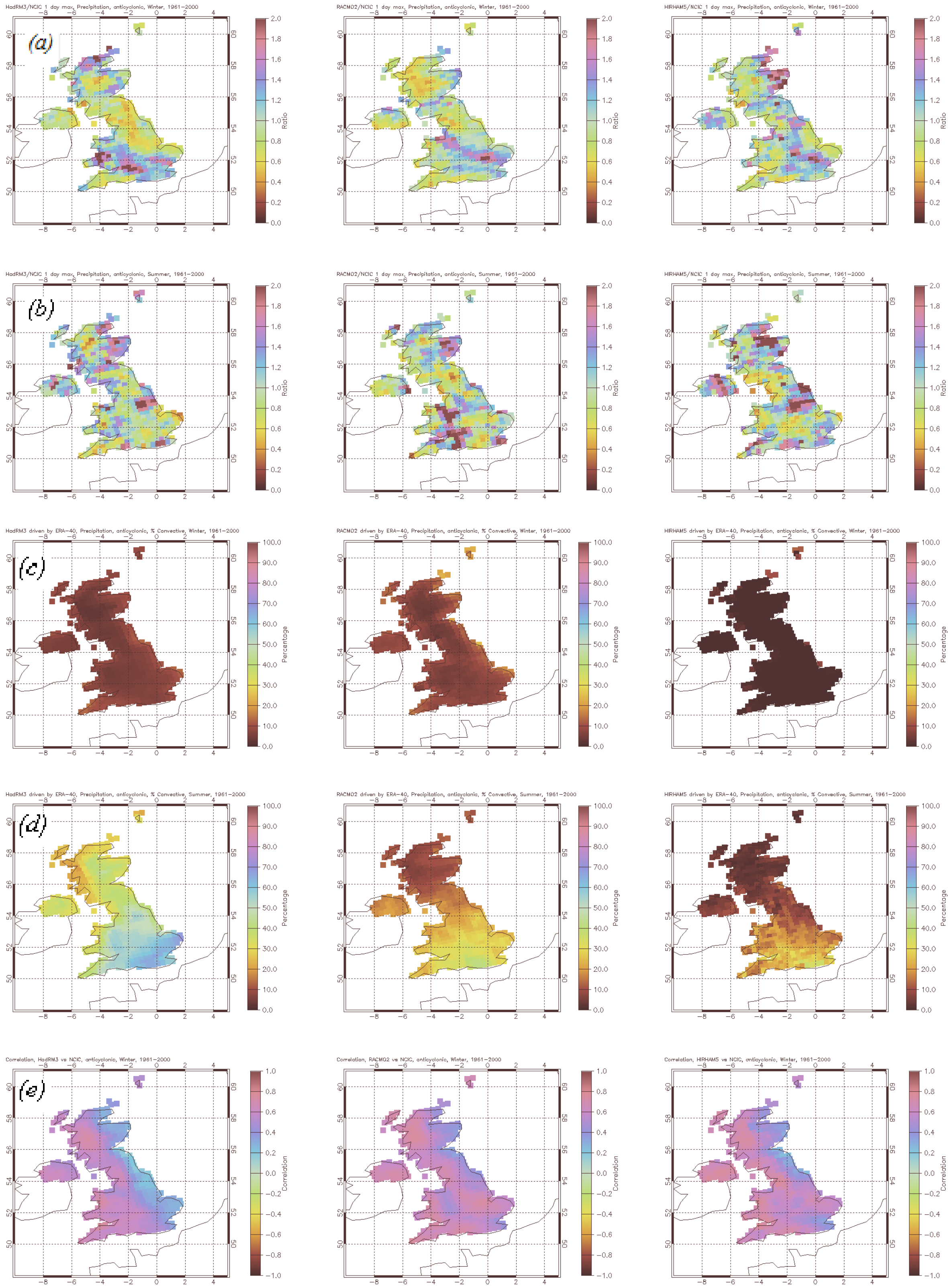


Fig 7.20. Outputs from HadRM3 (left), RACMO2 (middle) and HIRHAM5 (right), for (a) ratio of mean winter (DJF) 1-day maxima to observed values, (b) as (a) but for summer (JJA), (c) percentage of total winter precipitation that is convective, (d) as (c) but for summer, and (e) mean daily correlation with observed winter precipitation values. All models are driven by ERA-40, data are restricted to days with the anticyclonic type. The limit for correlation significance at the 95% level is approximately r = 0.08 (due to large sample size).

7.2.11 Conclusions

The three models considered here perform best in association with westerlies, south-westerlies, southerlies, and south-easterlies, but struggle considerably with north-easterly and easterly types. For all wind vectors between north-west and south, correlations with observed values consistently produce higher values in windward upland areas in autumn, winter and spring than in sheltered areas, and lower values in summer, suggesting a consistent tendency to handle organised frontal and orographic events better than lighter and less organised/convective events. RACMO2 consistently slightly outperforms HIRHAM5 which is significantly ahead of HadRM3 by this measure. RACMO2 also produces a significantly smoother distribution of precipitation across the UK, with HadRM3 performing worst by this measure for southerly and south-easterly types, and HIRHAM5 performing worst for south-westerly, westerly and northerly types.

Both mean precipitation and extreme precipitation shows a bias towards underestimates in upland/windward areas and overestimates in sheltered areas in autumn, winter and spring, which may be related to the “drizzle effect” found in other studies where the models produce too many small rainfall events. The grid boxes that produce anomalously high totals for the HIRHAM5 outputs appear to be anomalous regardless of the circulation type, while the overestimations of HadRM3 for the west coast of Scotland are most prominent on days with southerly, south-westerly and westerly types. Precipitation is widely underestimated across the UK from north-westerly types. Extreme precipitation anomalies consistently show similar geographical distributions to the mean precipitation anomalies, but with a consistent bias towards comparative underestimates of extreme precipitation.

It is difficult to commit to strong conclusions regarding the models’ simulation of convective precipitation given the inability to compare with observed data, but HIRHAM5 maintains a highly unrealistic simulation of convective precipitation regardless of the circulation type. There are hints that RACMO2 may be better at handling convective precipitation than HadRM3, from higher correlations with observed precipitation values in sheltered areas and the fact that autumn and winter convective precipitation is associated more reliably and strongly with windward coasts than for the HadRM3 outputs, and also penetrates further inland.

Hand (2004), who performed an analysis on the occurrence of convective days of "sunshine and showers" across the UK under different Lamb types, produced a set of results that have more in common with the RACMO2 outputs than those of HadRM3, although his results concerned only the frequency of convective precipitation rather than taking account of the intensity. It is possible that the results for the simulation of convective precipitation may be affected by the ERA-40 limitation mentioned by Klepp et al. (2005), the underestimation of post-frontal convective events associated with troughs and polar lows.

Comparing the models' respective performances, RACMO2 is consistently the most accurate of the three models, with HadRM3 and HIRHAM5 both having more flaws (HadRM3 shows relatively low correlations with observed values while HIRHAM5 is poor at handling convective precipitation and significantly overestimates precipitation on some coastal fringes).

7.3 Model projections into the future

The outputs from the three most accurate RCMs (RACMO2, HadRM3, HIRHAM5) coupled with associated GCMs, covering the periods 1961-2000, 2011-2050 and 2051-2090, are used to project the expected changes in mean precipitation and extreme precipitation under the IPCC's A1B scenario. RACMO2 and HIRHAM5 are driven by ECHAM-r5 in this analysis, while HadRM3 is driven by HadCM3. The seasonal precipitation outputs from the models over the period 1961-2000 are compared with those from the observed NCIC data, to determine whether the accuracy of the models is affected significantly when they are driven by global climate models rather than the ERA-40 reanalysis, and to assess downsides of relying upon their projections into the future. Projections for 1961-2000 (all using outputs from ECHAM-r5 and HadCM3-driven models rather than the ERA-40 driven models) are compared with those for 2011-2050 and 2051-2090 to assess the projected patterns of change in mean precipitation and extreme precipitation across the UK, looking at regional as well as national changes, and performing separate outputs for each of the four meteorological seasons. The comparisons use the ratio of the outputs for the 2011-2050 and 2051-2090 periods to the outputs for 1961-2000.

Mean precipitation, together with 1, 2, 5 and 10-day maxima, are used in the analysis, and precipitation is also divided into convective and large-scale components, to determine projected changes in the proportion of precipitation that is of convective rather than large-scale origin. This project focuses on only three models; for more extensive projects see for example UKCIP09 (UKCIP09, 2010).

7.3.1 Accuracy of precipitation simulations of the RCMs driven by GCMs

Fig 7.21 shows two examples of differences between simulated and observed precipitation when HadRM3 is driven by HadCM3 and RACMO2 and HIRHAM5 are driven by ECHAM-r5. The median 5-day maximum is chosen to maintain consistency with the figures in Chapter 6. In the case of HadRM3, the model being driven by HadCM3 rather than ERA-40 makes very little difference to the mean seasonal precipitation anomalies, relative to those described in section 6.1.1, in spite of documented problems with HadCM3 being biased towards high pressure in the Arctic and an underestimation of the strength of the prevailing westerly flow over north-west Europe (Johns et al., 2003) although the pattern of precipitation across the UK is less “smooth” with larger differences between adjacent grid boxes. However, in the case of RACMO2 and HIRHAM5, noteworthy increases in the anomalies occur when those models are driven by ECHAM-r5 rather than ERA-40. RACMO2 overestimates significantly in eastern and central districts, particularly in winter and spring when overestimates in southern England widely reach 60%, but accordance with observed values is better in summer and especially autumn. HIRHAM5 produces significant overestimates of 40-60% in eastern England in winter, and underestimates of over 50% in southern and western Britain in summer and autumn.

Extreme precipitation shows a less consistent pattern. RACMO2 tends to underestimate mean 1-day maxima in western Britain by up to 20%, while overestimating in eastern Britain, with overestimates of 40-60% in eastern England in winter. Winter and spring values show good accordance with observed values for 2, 5 and 10-day maxima, with overestimates of up to 20% in parts of southern England and underestimates of 20-40% in some northern and western districts but most parts within 20% of observed values, but autumn sees underestimates of up to 50% in southern and western areas for 5 and 10-day maxima. Summer sees overestimates in eastern areas for 5-day maxima, underestimates in most parts for 2-day maxima, and very high accordance with observed values for 10-day maxima.

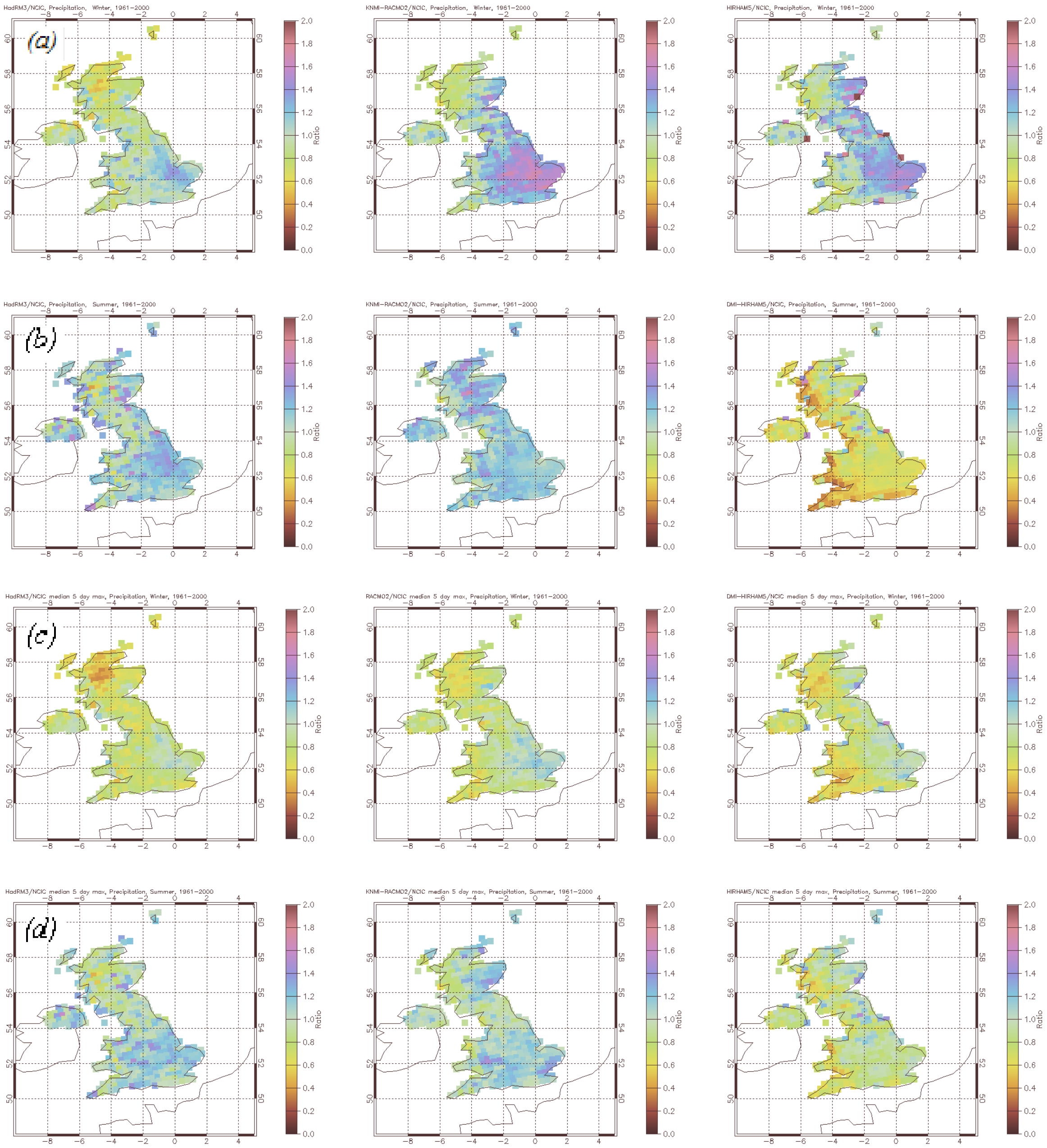


Fig 7.21. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the ratio of simulated to observed precipitation for (a) mean winter precipitation, (b) as (a) but for summer, (c) median 5-day winter maxima and (d) as (c) but for summer.

In the case of HadRM3, 1-day maxima are generally overestimated in eastern areas and also the west coast of Scotland, with close accordance with observed values elsewhere, while 2, 5 and 10-day maxima are underestimated, increasingly so as the time period is increased, with underestimates widely in excess of 50% for 10-day maxima in autumn in western and southern districts. HIRHAM5 overestimates mean 1-day maxima in most regions in winter and spring (especially eastern districts in winter) but performs much better in summer and autumn, except for underestimates of up to 50% in western and southern coastal areas. As the length of the time period is increased, increasingly large underestimates occur in western and southern districts in autumn, spring and summer are handled well with the exception of some individual grid boxes, and underestimates of up to 50% increasingly occur in western districts in winter.

Convective precipitation accounts for a similar proportion of the total relative to when the three models are driven by ERA-40, but with some small differences. The proportions given by RACMO2 and HIRHAM5 are generally reduced, with a maximum of 30% in the southeast in summer according to RACMO2, but as high as 40% in western coastal Scotland in autumn and spring. HIRHAM5 retains the problem observed in the ERA-40 analysis, with convective precipitation in winter, spring and autumn almost exclusively restricted to some individual grid boxes around coastal fringes. The proportion given by HadRM3 is increased slightly, with convective precipitation accounting for up to 70% of the total in south-east England in summer, and being less restricted to coastal fringes in winter.

Overall, switching from driving the models using the ERA-40 reanalysis to using global climate models has generated some differences, particularly a tendency to underestimate extreme 2, 5 and 10-day precipitation in western and southern areas (in all four seasons in the case of HadRM3 driven by HadCM3, and specifically in autumn in the cases of RACMO2 and HIRHAM5 driven by ECHAM-r5). Mean precipitation is overestimated more strongly in the east when RACMO2 and HIRHAM5 are driven by ECHAM-r5, but using HadCM3 rather than the ERA-40 reanalysis to drive HadRM3 appears to make very little difference to the distribution of mean precipitation. The anomalous increases in mean precipitation on the RACMO2 and HIRHAM5 outputs arise from increased large-scale precipitation with a decline in the percentage of precipitation that is of convective origin.

7.3.2 Projected changes in mean winter precipitation for the periods 2011-2050 and 2051-2090 relative to 1961-2000

Fig 7.22 shows the projected changes in seasonal precipitation for 2011-2050 relative to 1961-2000, and Fig 7.23 shows the projected changes for 2051-2090 relative to 1961-2000. RACMO2 projects an increase in winter precipitation, with an increase of approximately 10% in most regions for the period 2011-2050, increasing to approximately 20% in most regions for the period 2051-2090. Upland areas, particularly the Pennines and Scottish Highlands, are projected to have the smallest increases, but with increases of up to 40% projected over northern Scotland. Spring precipitation is projected to increase by up to 20% in western Scotland by 2011-2050, but with no significant change or a small decline indicated for eastern Scotland and most of England and Wales. Between 2011-2050 and 2051-2090, the increase in north-western Britain extends to a larger geographical area, but the further increase is only small. Summer precipitation is projected to decrease except in western Scotland and parts of north-west England, with falls of 20% or more in parts of southern England by 2051-2090. No large changes are projected for autumn precipitation, with increases of up to 10% indicated for some regions.

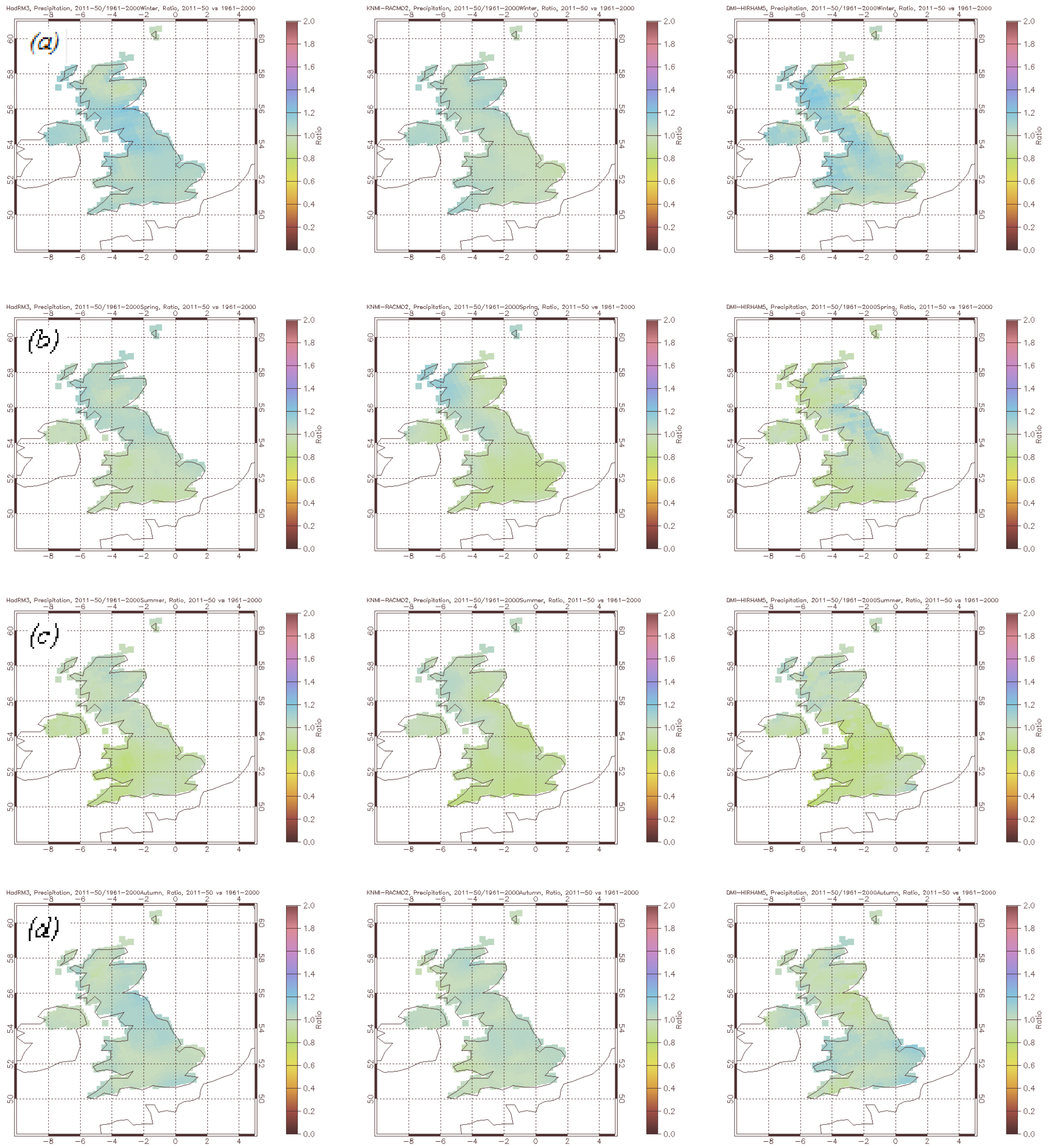


Fig 7.22. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in mean precipitation between 1961-2000 and 2011-2050 for (a) winter, (b) spring, (c) summer and (d) autumn.

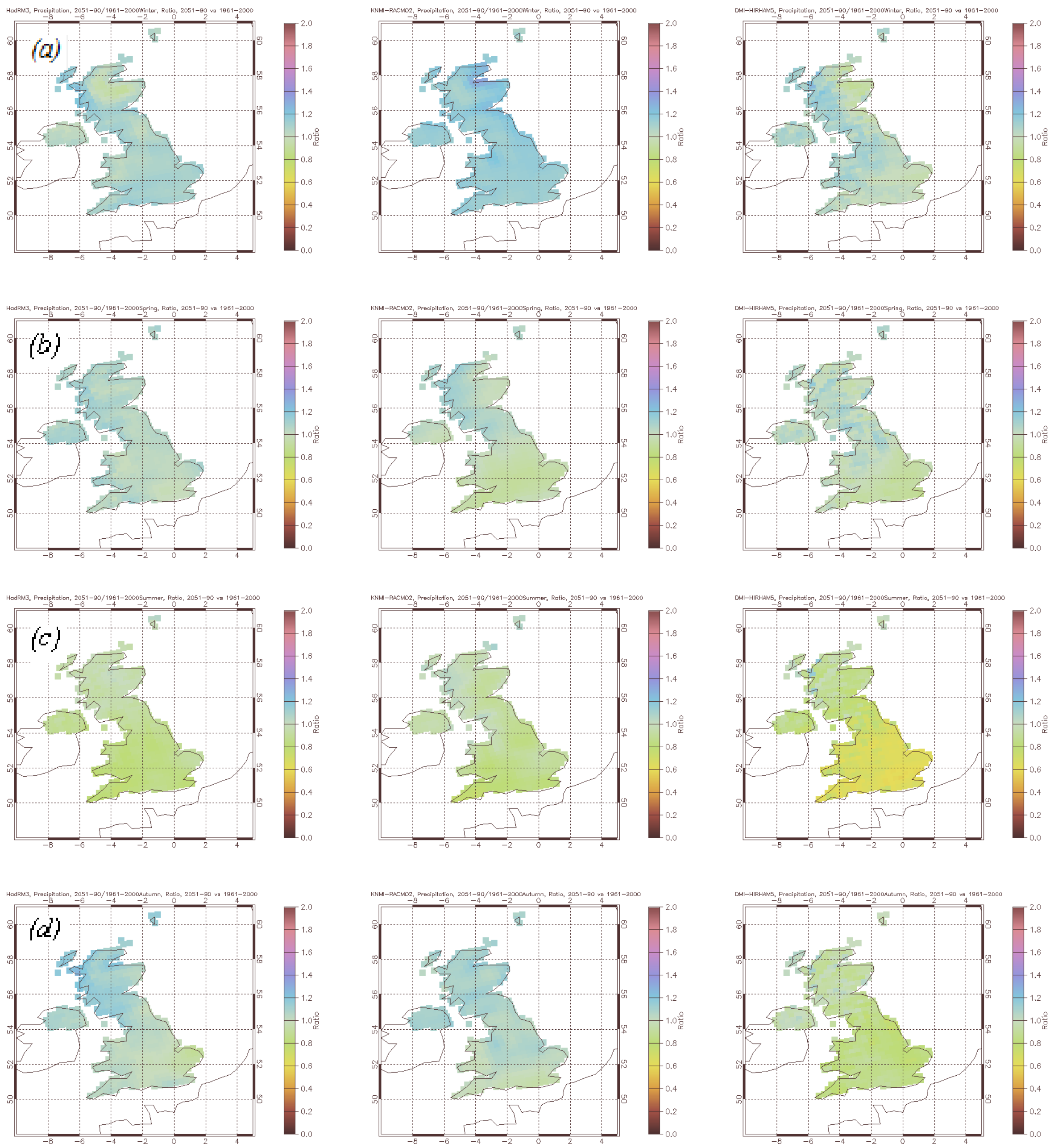


Fig 7.23. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in mean precipitation between 1961-2000 and 2051-2090 for (a) winter, (b) spring, (c) summer and (d) autumn.

The HadRM3 outputs produce some differences relative to the RACMO2 outputs. Winter precipitation is projected to increase in most regions, with increases of 10-20% in many lowland areas by 2011-2050, strongest around the Firth of Forth, but with smaller or no increases in most upland areas. By 2051-2090, the increases become more concentrated towards western Scotland, with other areas of the country not seeing major changes relative to 2011-2050. Spring precipitation shows much smaller changes, with increases of 10% or more in parts of northern Britain by 2011-2050, and then a concentration of small increases in western Scotland for 2051-2090, similar to the winter pattern but far less extreme. Autumn is similar, with increases of approximately 10% in parts of north-east England and eastern Scotland for the 2011-2050 period, and then increases mostly concentrated in western Scotland for the 2051-2090 period. East Anglia is shown as having a small precipitation decline in autumn. Summer precipitation shows no strong changes for 2011-2050 but a decline of up to 20% over much of England and Wales by 2051-2090.

The HIRHAM5 outputs project a 20% increase in spring precipitation by 2011-2050, and a 20% increase in winter precipitation in western areas, and a 20% increase in Norfolk in autumn, while spring sees only small changes. The 2051-2090 outputs are more extreme than is the case for HadRM3 and RACMO2, with a 40% decline in summer precipitation over most of England and Wales, an increase of up to 20% in some western and north-western districts in winter (if anything a small decline in winter precipitation between 2011-2050 and 2051-2090) and a decline of 10-20% in most parts of the country in autumn, amounting to a substantial decline in East Anglia and the southeast between 2011-2050 and 2051-2090.

In conclusion, there is a consensus among the three models for a decline in summer precipitation by the 2051-2090 period, and a weaker signal for a decline by 2011-2050, but there is disagreement on the extent of the decline. Winter precipitation is projected to increase in western, and particularly north-western, districts by all three models, but with mixed results for eastern regions. Spring and autumn outputs produce mixed results, but again with a recurring signal for increases in north-western Britain by 2051-2090.

7.3.3 Projected changes in the proportion of convective precipitation for the periods 2011-2050 and 2051-2090 relative to 1961-2000

The percentage of precipitation that is given as convective over the periods 2011-2050 (Fig 7.24) and 2051-2090 (Fig 7.25) are compared with that over the period 1961-2000, to give an indication of whether the models simulate an increase or decrease in convective precipitation as a proportion of the total.

RACMO2 projects no substantial changes in the proportion of convective (as opposed to large-scale) precipitation in spring and autumn between 1961-2000 and 2011-2050, but this proportion decreases in winter and summer over large areas of the country, by approximately 20% in most western districts in summer and 20-40% over most of England and Wales in winter. For the period 2051-2090, most regions show a decline relative to 1961-2000 in summer and winter, reaching 40% in western Scotland in summer and 40-60% on the east coast of Scotland in winter. Autumn shows a decline of 20-40% in western and especially north-western Britain, while spring does not see any significant changes. In contrast, HadRM3 projects an increase in the percentage contribution from convective precipitation. The largest increases in autumn, winter and spring for 2011-2050 occur in northern Scotland, with an increase of 40-60% in winter in parts of the Scottish Highlands, while there are small increases elsewhere in the UK with the exception of western England and Wales in winter. Summer has small increases in most regions. The same trends continue for the 2051-2090 period, with an increase of 80% relative to 1961-2000 over the Scottish Highlands in winter, and increases of approximately 20% generally across the UK in autumn (except for a 40% increase over the Scottish Highlands) while increases in spring and summer are generally below 20%. HIRHAM5 produces spatially inconsistent results by this measure in winter, though a general decrease is projected in summer, reaching 40-60% in some regions in summer by 2051-2090, with the exception of southern coastal areas and northeast Scotland which have increases of 20-40%. Autumn has a decline of 40-60% in some central and eastern parts of England for 2011-2050, but these reduce substantially for 2051-2090. Spring has reductions of 20-40% for 2051-2090 away from the south and south-west of England where increases of 40-60% occur, and a less extreme version of the same pattern occurs for 2011-2050.

Overall, the signals for changes in convective precipitation are mixed, since RACMO2 projects a decline in most regions while HadRM3 projects an increase, which is especially heavily concentrated in the Scottish Highlands. The results from HIRHAM5 are more variable and thus probably less reliable due to the problems that HIRHAM5 has in resolving convective precipitation that were noted in sections 6.1 and 6.2.

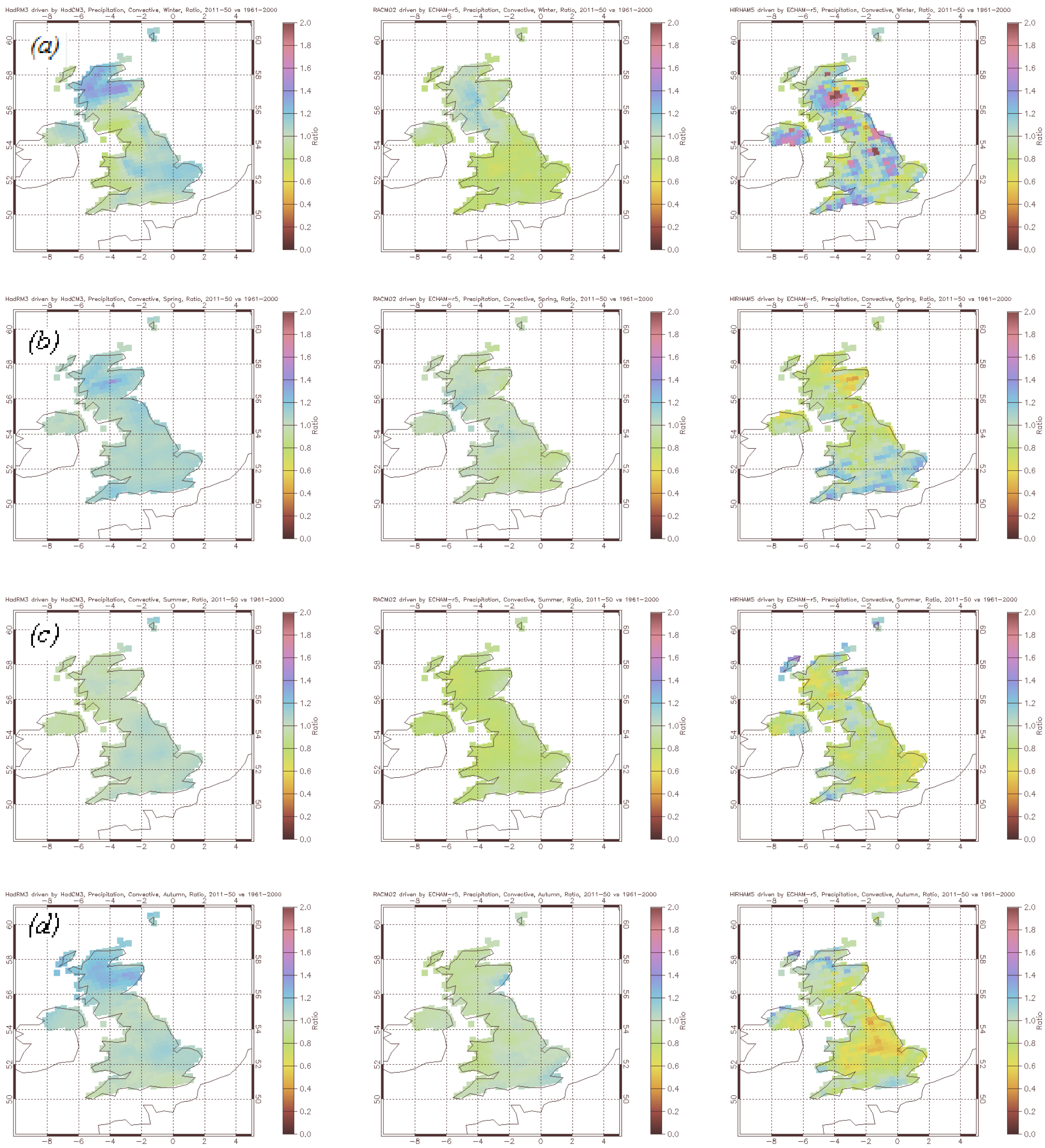


Fig 7.24. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the proportion of convective (as opposed to large-scale) precipitation between 1961-2000 and 2011-2050 for (a) winter, (b) spring, (c) summer and (d) autumn.

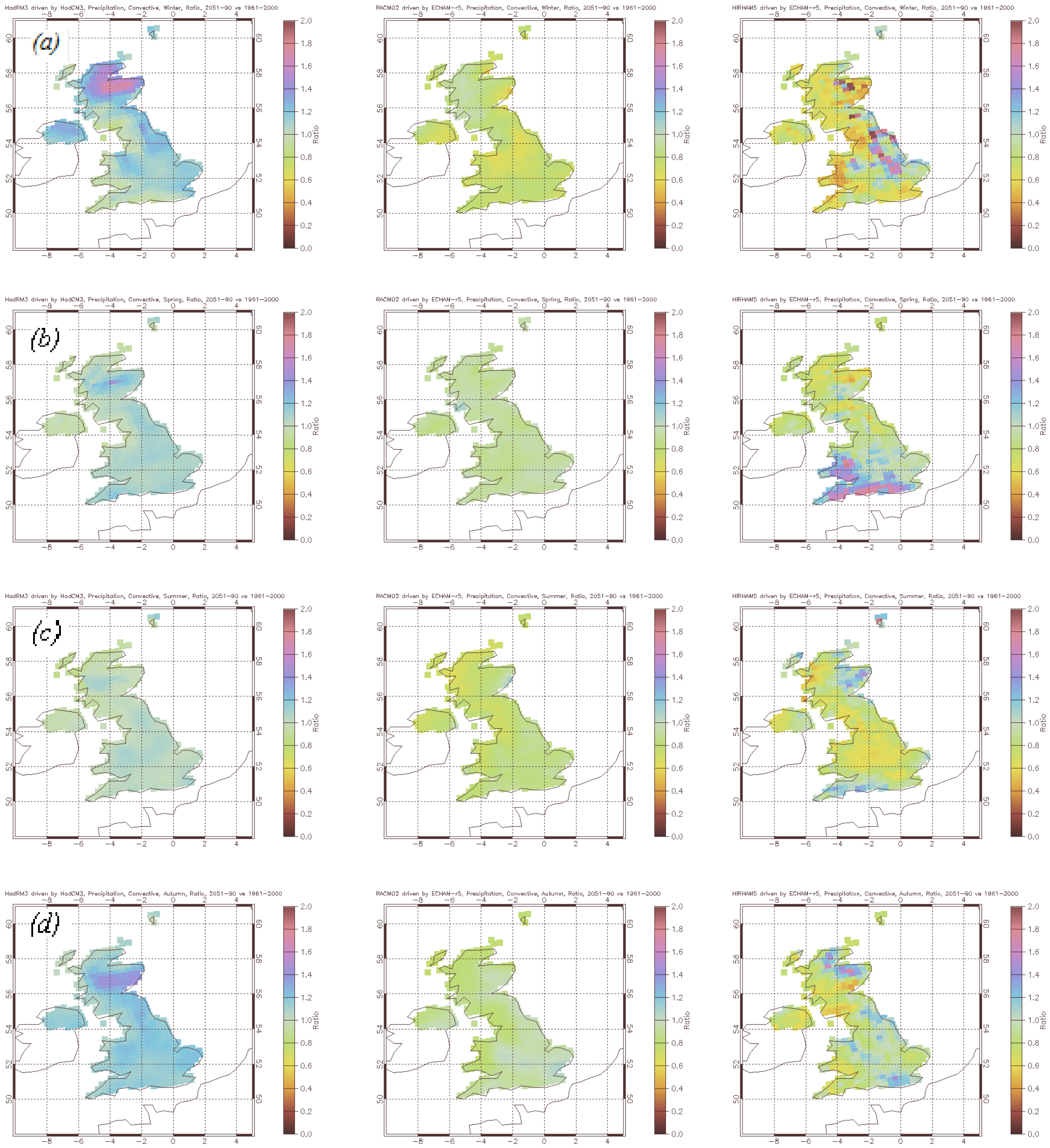


Fig 7.25. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the proportion of convective (as opposed to large-scale) precipitation between 1961-2000 and 2051-2090 for (a) winter, (b) spring, (c) summer and (d) autumn.

7.3.4 Projected changes in extreme precipitation for the periods 2011-2050 and 2051-2090 relative to 1961-2000

Fig 7.26 and 7.27 show projected changes in 1-day maxima for the 2011-2050 and 2051-2090 periods, respectively, for each season for each of the three models. Fig 7.28 and 7.29 show projected changes in 2-day maxima, Fog 7.30 and 7.31 show projected changes in 5-day maxima and Fig 7.32 and 7.33 show projected changes in 10-day maxima. RACMO2 projects increases in the mean 1, 2, 5 and 10-day maxima across most parts of the country in autumn and winter. The increase is only small in most regions for the 2011-2050 period, but approaches 40% in many regions in autumn and winter for the 2051-2090 period. The largest increases in winter are projected to occur in northern and eastern parts of Scotland, while in autumn the largest increases are concentrated towards western Britain. Proportions remain similar for 1, 2, 5 and 10-day maxima, suggesting a significant increase in the amount of prolonged rainfall events which lead to high risk of flooding. No significant changes are suggested for spring, while in summer a decline is projected away from western Scotland, reaching 40-60% for 5-day maxima for the period 2051-2090, though generally near 20% for 1, 2 and 10-day maxima. Again a consistent decline is projected between 2011-2050 and 2051-2090, as well as between 1961-2000 and 2011-2050.

HadRM3 also projects an increase in the mean 1-day maxima across most regions in autumn and winter, with most of the increase occurring between 2011-2050 and 2051-2090. The winter pattern for 2, 5 and 10-day maxima is similar to that for 1-day maxima, but the autumn pattern changes, with large increases (approximately 60%) in southern and western regions for 5-day maxima, and no significant change in 10-day maxima, while 2-day maxima show a decline of 20-40% in southern and central England.. Spring shows an increase for 1, 2 and 5-day maxima but with the increase for 2 and 5-day maxima concentrated in southern England (up to 40% by 2051-2090) and the increase in 1-day maxima concentrated in western coastal districts. No substantial changes are projected for 10-day maxima in spring. Summer extreme precipitation is projected to increase by up to 40% in some northern districts by 2051-2090 for 1, 2 and 10-day maxima, but a decline is projected over most of England and Wales, reaching 20 to 40%. 5-day maxima show a nationwide decline, with a decline of 40-60% across the Midlands.

HIRHAM5 projects a decline in the mean 1-day maxima in summer and autumn across southern areas by 2051-2090, increases in north-western Britain, and no significant changes in spring, while winter has increases of up to 40% in western districts for 2011-2050, but then a small decline between 2011-2050 and 2051-2090. The mean 2-day maxima show a decline in central and southern Britain in summer and autumn, exceeding 40% in some places in autumn by 2051-2090, while winter again has an increase for 2011-2050 which declines for 2051-2090. 5-day maxima show a similar pattern except for autumn for 2051-2090 which has large increases over the whole UK, reaching 100% in western and southern areas, suggesting possible errors in the HIRHAM5 data as this result is strongly at odds with the other results. Mean 5-day maxima in summer decline by 40-60% in many parts of the country for 2051-2090. The mean 10-day maxima also show a similar pattern, except that the decline in autumn is more significant than the decline during summer, with a decline of 20-40% in most parts away from western Scotland in the summers of 2051-2090, but 40-60% in many parts during the autumns.

Thus, the outputs from the three models agree on a general decline in extreme summer precipitation away from western Scotland, with the largest agreement occurring for central and southern England, and a larger percentage decline is suggested for extreme precipitation than for mean precipitation. There is also consistent agreement on an increase in extreme winter precipitation, with a similar or greater percentage increase relative to the projected increases in mean winter precipitation. However, the results for changes in extreme spring and autumn precipitation are mixed.

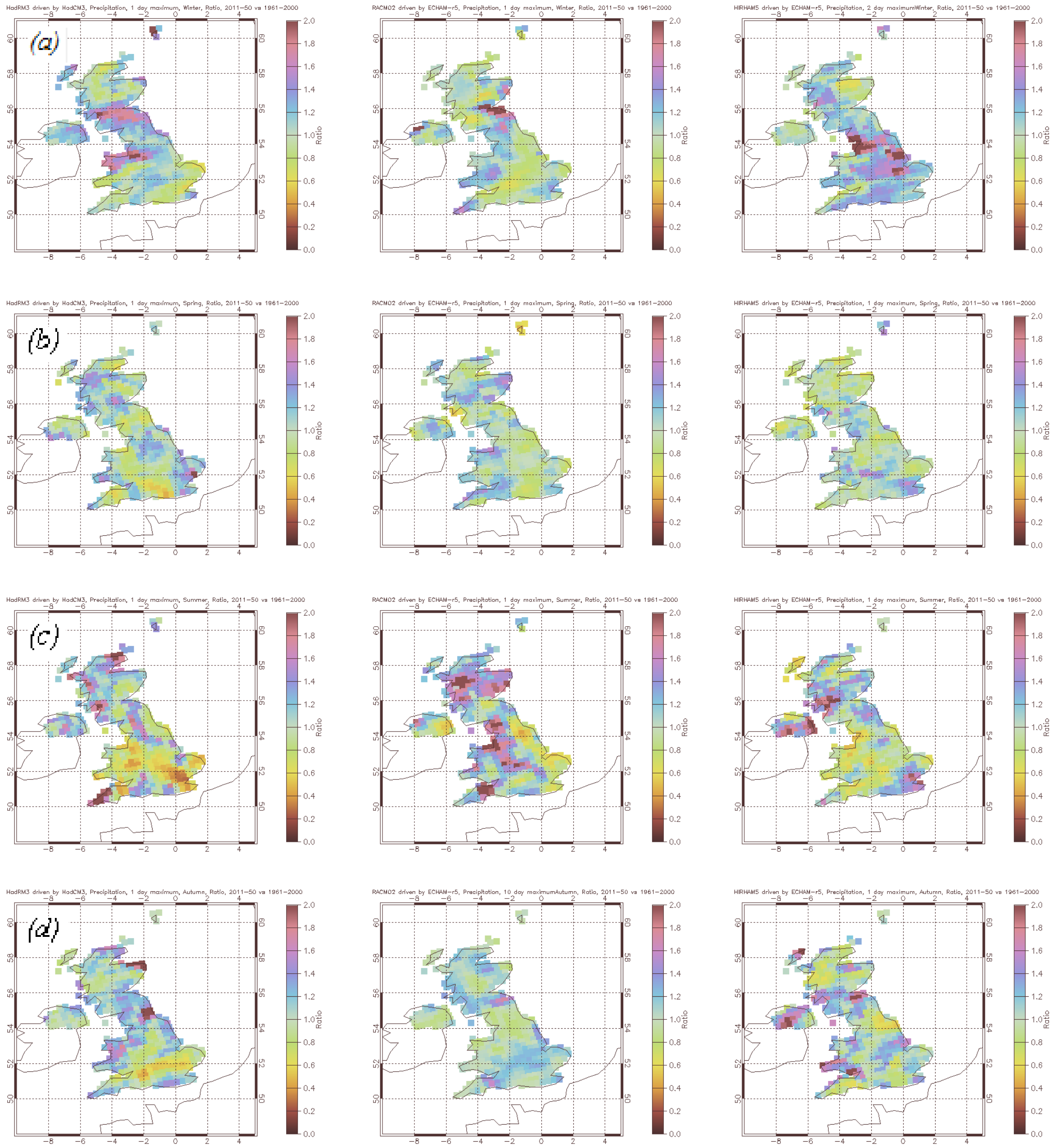


Fig 7.26. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 1-day maxima between 1961-2000 and 2011-2050 for (a) winter, (b) spring, (c) summer and (d) autumn.

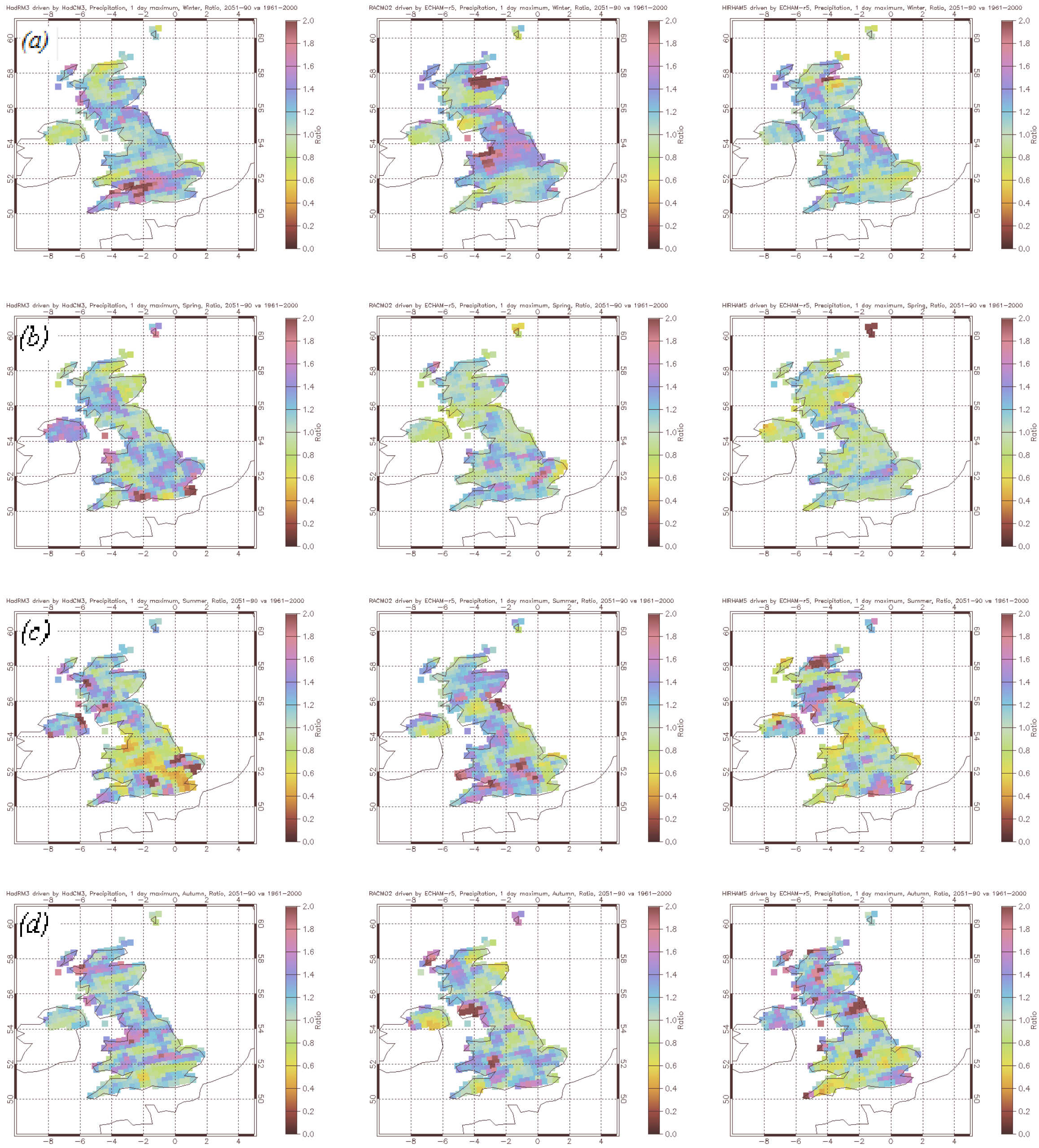


Fig 7.27. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 1-day maxima between 1961-2000 and 2051-2090 for (a) winter, (b) spring, (c) summer and (d) autumn.

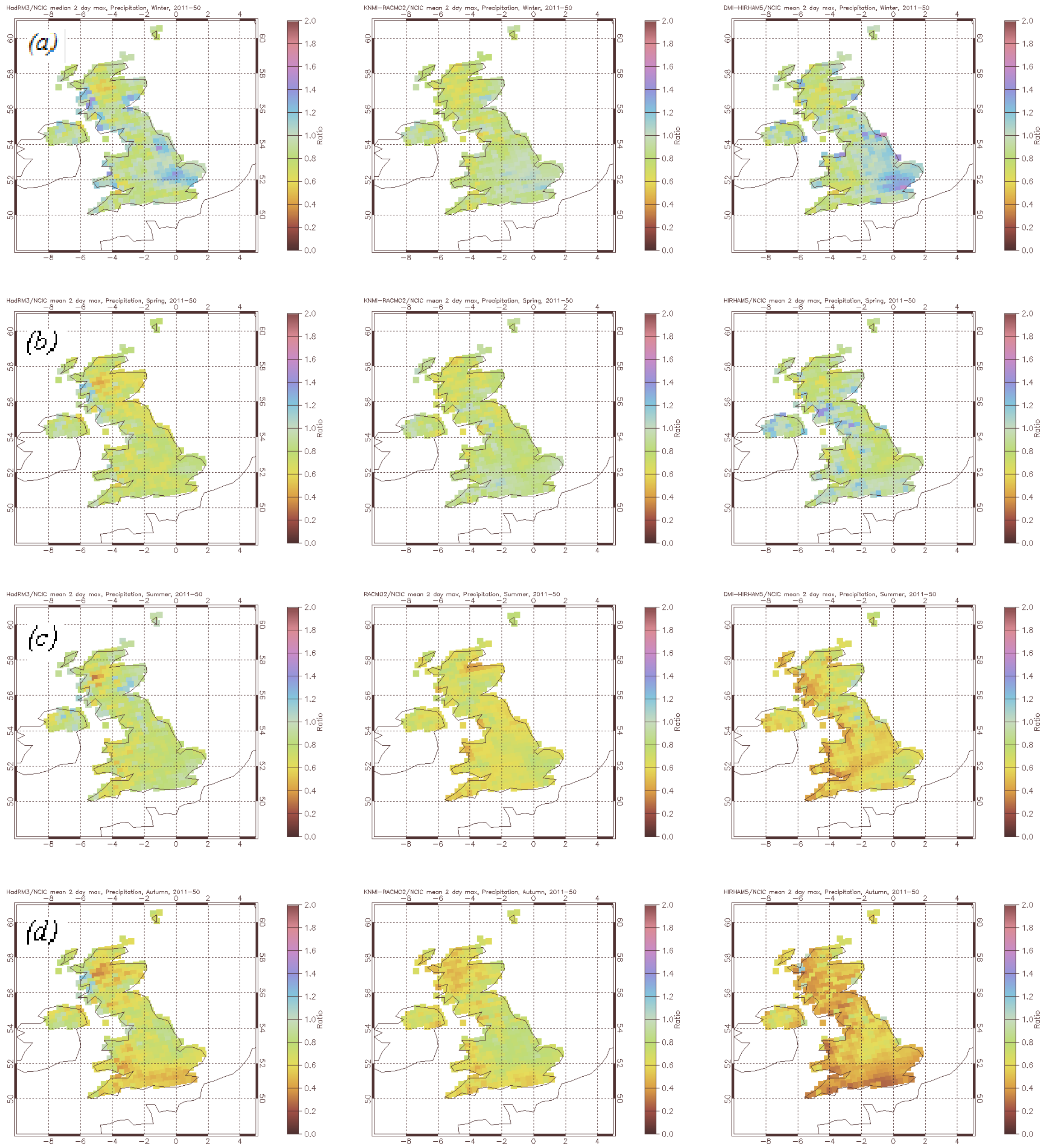


Fig 7.28. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 2-day maxima between 1961-2000 and 2011-2050 for (a) winter, (b) spring, (c) summer and (d) autumn.

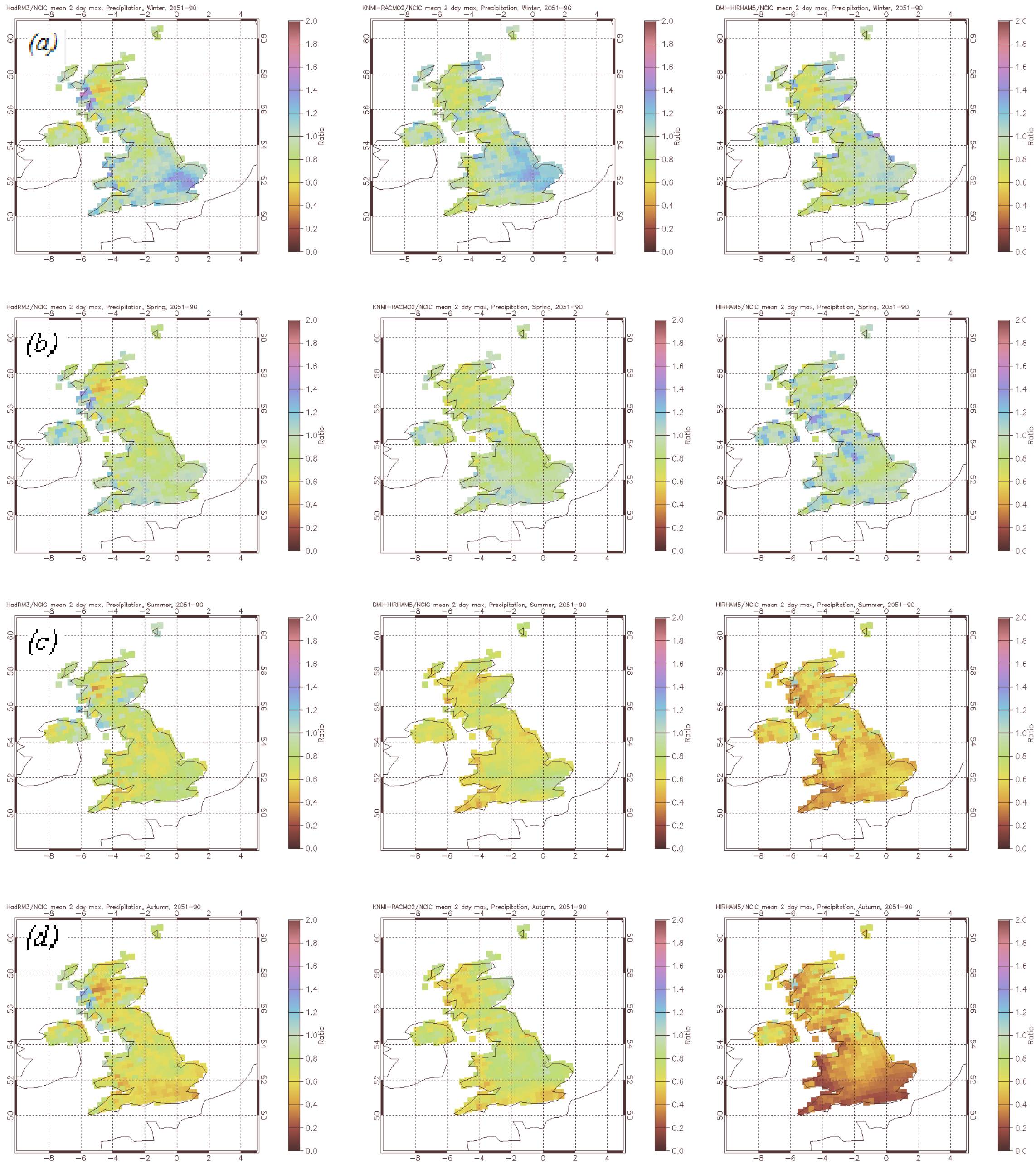


Fig 7.29. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 2-day maxima between 1961-2000 and 2051-2090 for (a) winter, (b) spring, (c) summer and (d) autumn.

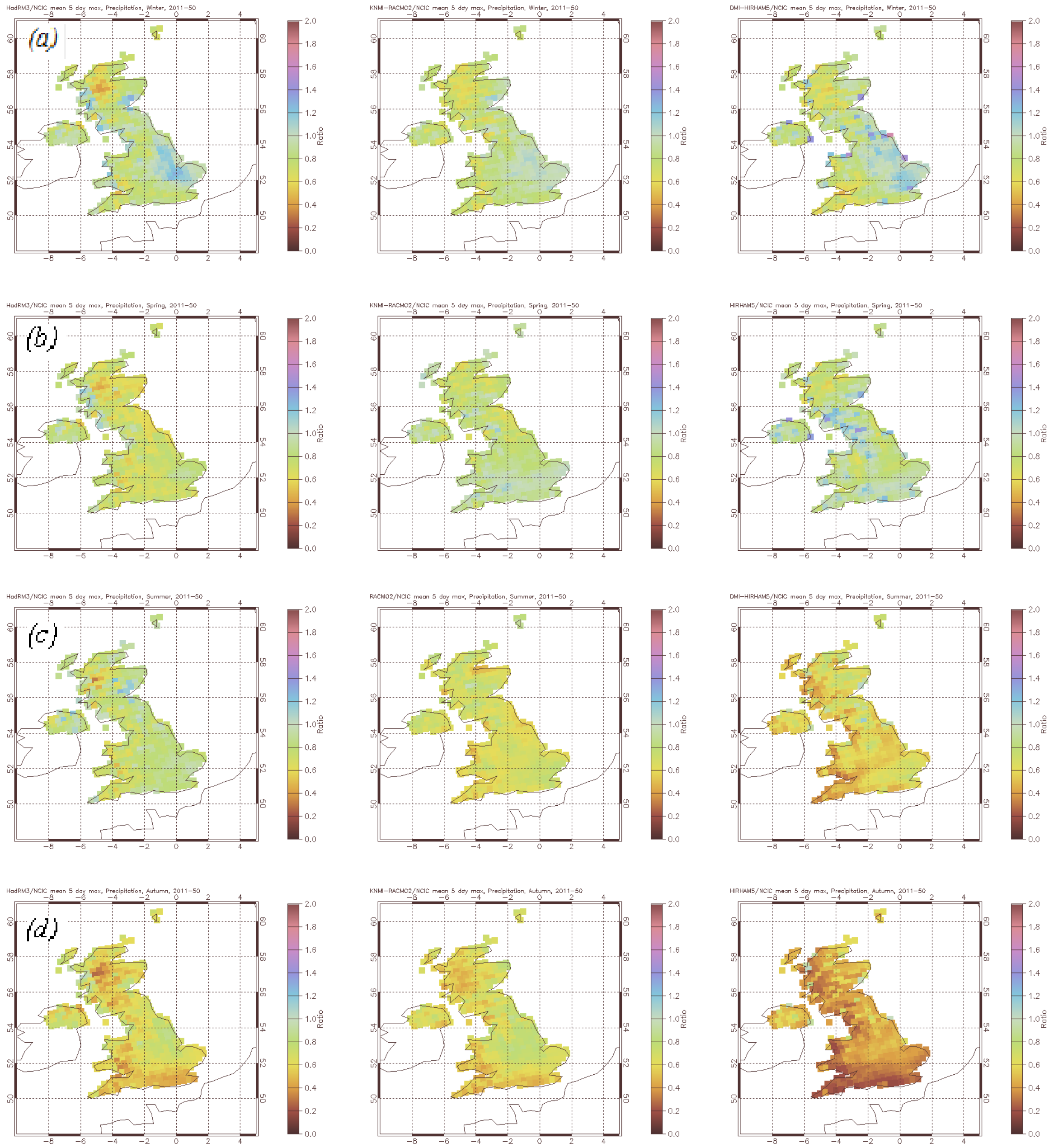


Fig 7.30. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 5-day maxima between 1961-2000 and 2011-2050 for (a) winter, (b) spring, (c) summer and (d) autumn.

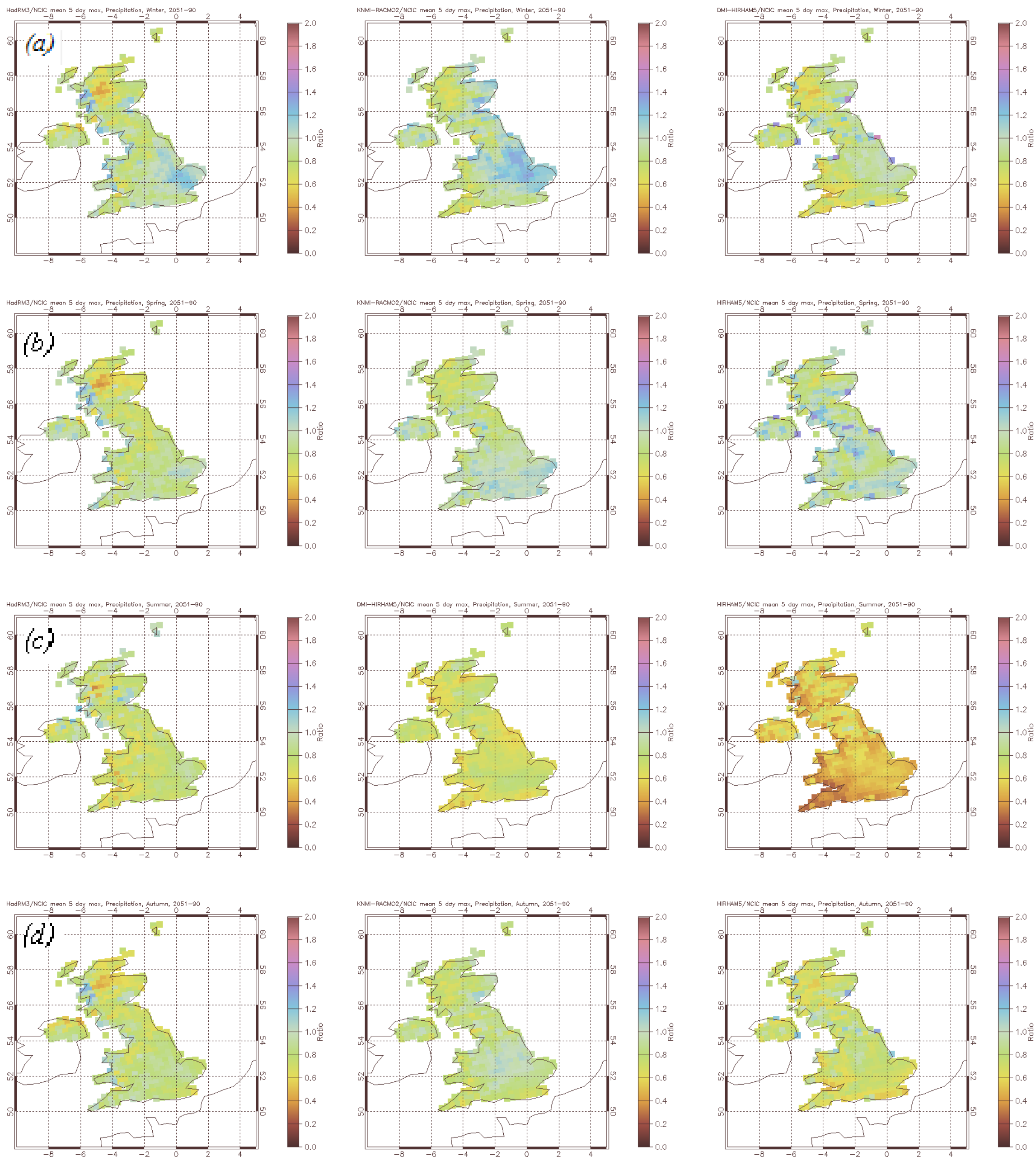


Fig 7.31. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 5-day maxima between 1961-2000 and 2051-2090 for (a) winter, (b) spring, (c) summer and (d) autumn.

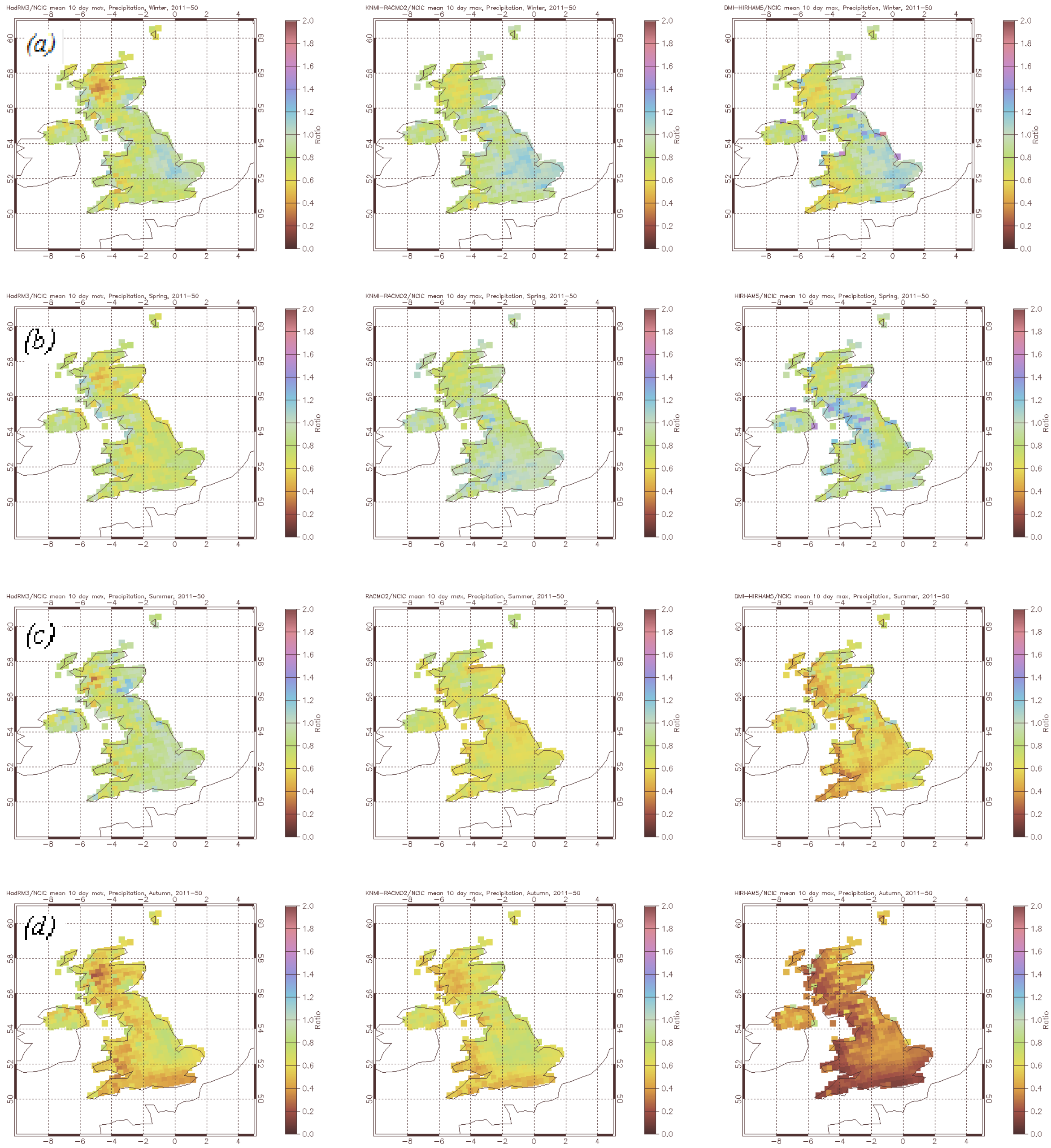


Fig 7.32. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 10-day maxima between 1961-2000 and 2011-2050 for (a) winter, (b) spring, (c) summer and (d) autumn.

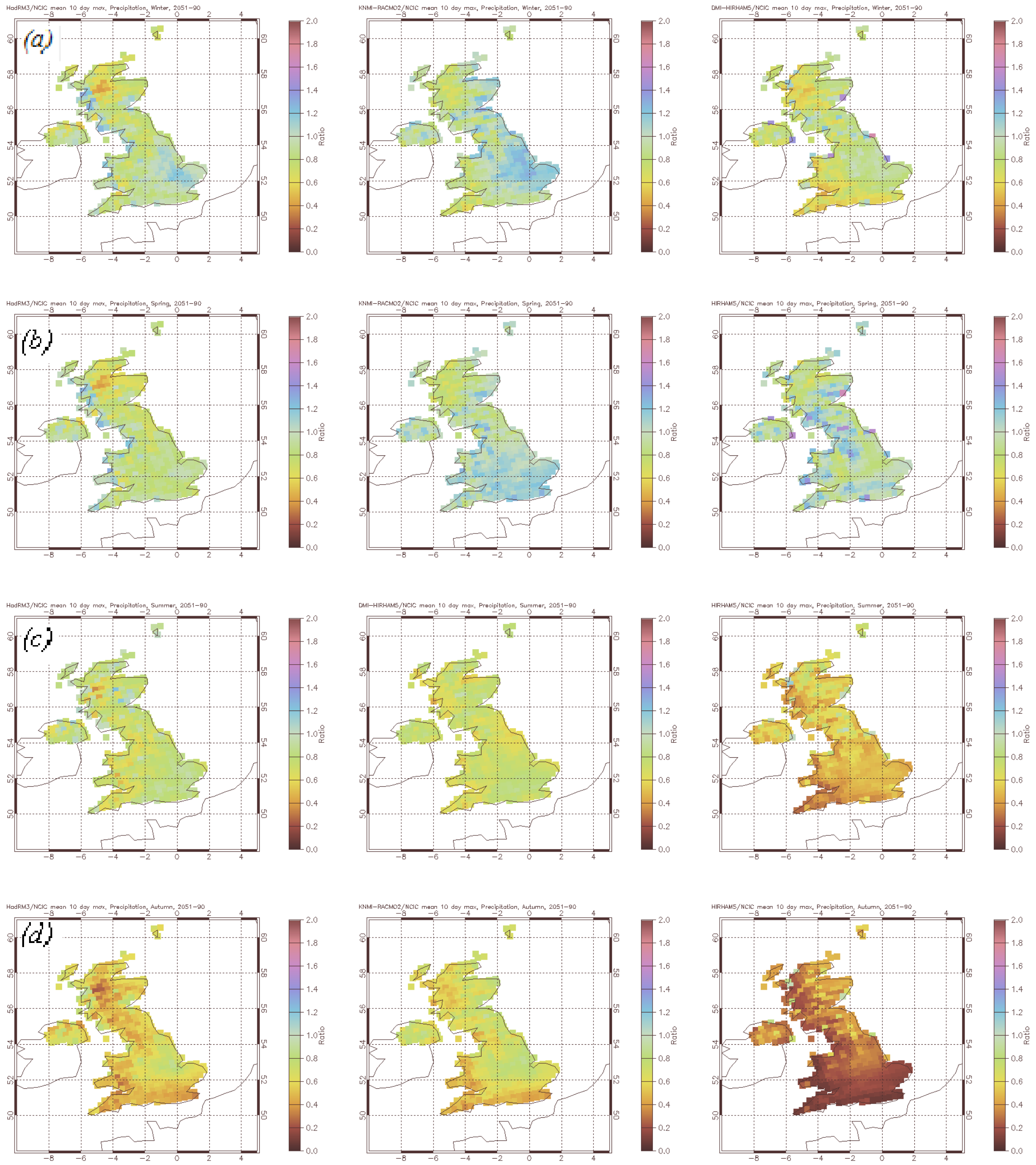


Fig 7.33. Outputs from HadRM3 driven by HadCM3 (left), RACMO2 driven by ECHAM-r5 (middle) and HIRHAM5 driven by ECHAM-r5 (right), showing the change projected in the mean 10-day maxima between 1961-2000 and 2051-2090 for (a) winter, (b) spring, (c) summer and (d) autumn.

7.4 Conclusions

The use of several metrics for comparing model simulations with observations has allowed a detailed analysis of the main strengths and weaknesses of the individual models. The validation work in Chapter 6 strongly suggested that RACMO2 was the best-performing model out of the model considered- a result supported also by van der Linden and Mitchell (2009), Kjellstrom et al. (2010) and Christensen et al. (2010) when covering model accuracy across Europe as a whole. HadRM3 and DMI-HIRHAM5 were the two next most reliable models. The HadRM3 result is consistent with the findings of Kjellstrom et al. (2010), who ranked HadRM3 second-best overall, but DMI-HIRHAM5 did not rank among the best-performing models by any of their measures, including precipitation simulation. The HIRHAM5 result thus suggests that HIRHAM5 performs better at capturing the spatial distribution of precipitation across the UK than across Europe as a whole. The analysis comparing simulations with observations under specific Lamb weather types also showed RACMO2 to be the most reliable of those three models. HIRHAM5 consistently overestimates precipitation at individual grid boxes around the coastline, while HadRM3 consistently overestimates precipitation along the west coast of Scotland in winter in association with westerly regimes. All three models have a tendency to underestimate precipitation in windward areas and overestimate in sheltered areas, and underestimate extreme precipitation relative to mean precipitation, which is consistent with the “drizzle effect” noted in many other studies (models producing too many light rainfall events).

The results when comparing simulations with observations for the period 1961-2000 suggest that using ECHAM-r5 as the driving model instead of ERA-40 leads to an anomalous increase in the amount of large-scale precipitation simulated for central and eastern Britain, and an anomalous decrease in extreme precipitation in southern and western Britain in autumn. Using HadCM3 makes less of a difference, but a decrease in extreme precipitation in southern and western areas is apparent in all four seasons. This implies that the HadCM3 model is more consistent with the ERA-40 reanalysis than ECHAM-r5 regarding precipitation simulation.

Mean precipitation is projected to increase in all regions during winter, and decrease in summer (especially in the south) while autumn and spring show smaller trends, but a tendency for increases in north-western Britain and decreases in south-eastern Britain. Projected changes in extreme precipitation mostly show a similar geographical distribution to those in mean precipitation, with general increases in winter, decreases in summer and mixed signals in spring and autumn. These projected changes are consistent with most of the studies of observed changes considered in Section 3.3, but the fact that there are consistent biases in the current set of global and regional climate models suggests that there is still work needed, particularly in reducing the “drizzle effect” and improving physical simulations of the behaviour of rainfall over topography, in order to make the projections more robust.

Convective precipitation is projected by RACMO2 to provide a reduced proportion of the total precipitation, but HadRM3 projects an increased proportion, and HIRHAM5 gives mixed results. The earlier validation work strongly suggested that the HIRHAM5 simulation of convective precipitation is more suspect than that of RACMO2 or HadRM3, and thus the HIRHAM5 results are less likely to be trustworthy. Thus, the model projections relating to the projected change in the proportion of convective precipitation in the future is inconclusive in view of the disagreement between RACMO2 and HadRM3.

8. Conclusions and suggestions for further work

8.1 UK precipitation observations and trends in variability

A new precipitation series has been generated for the UK based on Met Office gridded data, with daily values available for 1958-2007 and monthly values available for 1914-2006 (see Chapter 4) which builds upon the HadUKP series stemming from Wigley et al. (1984) and updated regularly since the mid-1980s (see Section 2.1). The new series gives a "truer" estimate of the regional mean precipitation across the UK, but the backward extension of the series for EW and its subregions to match the timeframe of the HadUKP series introduces some additional regression errors. These errors are similar in magnitude to, or a little smaller than, the errors resulting from limited spatial sampling in the five sub regions, but larger for EW for data from 1789 onwards, where the greater station coverage used to generate the HadUKP series (up to 35 stations) reduces the error from spatial sampling. Prior to 1789, the original EW series was generated using a much smaller number of stations and the associated errors become larger than the regression errors associated with the new series (see Fig 4.12, Chapter 4). The results strongly suggest that using a limited amount of station coverage to estimate an areal mean becomes less of an issue as the areal size is increased- for example, using 7 well-spaced sites to cover one of the five sub-regions of England and Wales is associated with more error than using 35 well-spaced sites to cover England and Wales as a whole (see Fig 4.11, Chapter 4). This suggests that we can derive accurate estimates of mean global temperature and precipitation from a sparse network of stations provided that they are well spaced, but this is less true of a regional mean such as over a sub region of the UK. The new rainfall series is the first homogenised and long-spanning UK rainfall series based on a dense network of rain gauges, which implies a "truer" representation of the areal mean than via the HadUKP series, though the use of interpolation to generate the Met Office grids means that the series is still not a perfect representation of the true mean.

The results of the analysis of the new series suggest that both mean and extreme winter precipitation have increased across the UK, with the largest increases focused across Scotland, but with small or no increases across central southern England and south-eastern England. The analysis identified a strong positive correlation between both mean and extreme precipitation and the winter NAO, which is strongest for the 50th percentile of precipitation for NS, suggesting that much of the trend is probably associated with changes in the NAO. The fact that the 50th percentile of precipitation increased more significantly than the extreme precipitation indices in the primarily-affected regions is thus also consistent with the recent trends being primarily influenced by the NAO. The exceptionally high winter rainfall of the 1990s in those regions is probably an anomaly, since the positive NAO of the 1990s exceeded the magnitude of the NAO increase projected in climate models associated with a warmer climate (Gillett, 2005). However, since many studies suggest that anthropogenic global warming is likely to be associated with an increasingly positive NAO in future decades (though with some uncertainty over this), it may prove to be part of a long-term trend towards wetter winters in western and northern Britain. Spring precipitation has also increased in northern and western regions, with a significant increase in wet-day amounts across Scotland, and while the recent increase has been concentrated over Scotland, north-west England and north Wales, there is evidence of a longer-term increase in mean precipitation across south Wales and south-west England. There is again evidence that the recent increases may be at least partly due to changes in the NAO.

Summer precipitation has declined in all regions, with a stronger signal for declining mean amounts than declining extremes, which is consistent with the climate models' predictions that extreme amounts may not decline significantly even in regions where mean amounts decline significantly in a warmer world. This result is at odds with the results of some other studies, e.g. Osborn et al. (2000) and Fowler and Kilsby (2003a, 2003b). It is unfortunate that the monthly series only covered 1914-2006, as subsequent summers have produced some significant extreme rainfall events across the UK, in most regions during 2007-09 and in Scotland during July 2010. Autumn precipitation has shown weak upward trends, both for mean precipitation and extremes, but there is insufficient evidence available to support the argument that the exceptional wetness of Autumn 2000 may be part of a long-term upward trend.

The upward trend in winter precipitation and the downward trend in summer precipitation both appear to have reversed since the 1990s, and thus trends that previous studies noted as statistically significant in the 1990s and early 2000s have failed to reach the 95% significance level in this work, particularly in spring, summer and autumn. Overall, there is strong evidence that precipitation patterns across the UK are changing, and in a manner that is generally consistent with projections from climate models on precipitation changes in a future warmer world, but the signal from the observed precipitation data is less convincing (i.e. fewer statistically significant trends) than from the temperature data.   Unlike with the observed increase in UK temperatures, most of the observed changes in autumn, winter and spring rainfall (especially winter rainfall) may be due to changes in atmospheric circulation, which are reflected by an increasingly positive NAO.

8.2 Model simulations of UK precipitation variability

Chapter 6 established that the three best-performing models at handling UK precipitation variability, out of eight RCM integrations from the ENSEMBLES project, are KNMI-RACMO2, HadRM3 and DMI-HIRHAM5, with RACMO2 performing best overall, in line with the findings of van der Linden and Mitchell (2009), Christensen et al. (2010) and Kjellstrom et al. (2010). The analysis used a wide range of metrics to determine model accuracy, including an analysis of the models' representation of convective precipitation (which has not been attempted in previous studies). All models overestimate autumn, winter and spring precipitation in eastern England, with a tendency for underestimation of precipitation over upland and/or western parts of Britain. They also consistently underestimate extreme precipitation relative to mean precipitation, but maintaining the same geographical distributions of anomalies, consistent with the observation of many studies that climate models tend to "drizzle" too much and underestimate extremes (see Chapter 2). HadRM3 overestimates precipitation along the west coast of Scotland and the correlation analysis indicates that it has problems handling the rain-shadow effect in eastern Britain. HIRHAM5 is an improvement over HIRHAM but severely overestimates precipitation at some coastal grid boxes. CLM, REMO, RCA and RCA3 have large problems handling topographical influences across the UK, with CLM and REMO heavily underestimating precipitation in upland areas and RCA and RCA3 heavily overestimating in eastern areas.

Only RACMO2 and HadRM3 simulate a distribution of convective precipitation that corresponds well to that indicated by research on the subject, with upland and western areas mostly seeing the highest absolute totals (except in summer) but East Anglia and south-eastern England having convective precipitation account for the highest percentage of the total (especially in summer). The comparisons between the results from ERA-40 driven models and those from HadCM3 and ECHAM-r5 driven models suggest that HadCM3 and ECHAM-r5 underestimate extreme precipitation in western and southern districts and that ECHAM-r5 overestimates mean precipitation in eastern districts, but HadCM3 appears to simulate mean precipitation with similar accuracy to the ERA-40 reanalysis.

The analysis into the simulation of UK precipitation under different Lamb circulation types (Section 7.2) gives a stronger insight into the strengths and weaknesses of RACMO2, HadRM3 and HIRHAM5, and has not been attempted in previous studies, thus giving a new perspective on how the models perform in association with different atmospheric circulation patterns. All three models struggle at handling precipitation associated with north-easterly and easterly types, and show a consistent pattern of underestimating precipitation in windward/upland regions and overestimating it in leeward regions, suggesting that the pattern of orographic enhancement and rain shadow is underestimated in the current generation of climate models. The RACMO2 simulations of convective precipitation distributions in winter appear more reliable than those of HadRM3 with a more consistent association of convective precipitation with windward coastal areas, due to cold air travelling over warm seas generating instability and showers dying out inland as the airmasses pass over comparatively cold dry land. The patterns indicated by HIRHAM5 are unrealistic, giving convective precipitation as almost exclusively restricted to windward coastal fringes with no inland penetration. It is possible that the simulations of convective precipitation may be limited by the tendency of ERA-40 to underestimate convective activity associated with post-frontal troughs (as pointed out by Klepp et al., 2005).

The projections of future climate based on RACMO2, HadRM3 and HIRHAM5 driven by GCMs (HadCM3 for HadRM3 and ECHAM-r5 for RACMO2 and HIRHAM5) point to a decrease in mean summer precipitation across the UK, particularly the southern half, and an increase in mean winter precipitation, although there is divergence regarding the distribution of the winter change. The results for changes in mean spring and autumn precipitation are mixed but RACMO2 and HadRM3 suggest small increases in autumn for many northern and western regions. Changes in extreme precipitation show a similar projected distribution and sign to changes in mean precipitation but HadRM3 suggests an increase in summer extreme precipitation in northern districts. Changes in the relative proportion of convective (as opposed to large-scale) precipitation show mixed results, with an increase suggested by HadRM3, a decrease suggested by RACMO2 and mixed results suggested by HIRHAM5. These results are generally consistent with the results found in previous studies (see Section 3.5), highlighting the considerable uncertainty over how precipitation patterns will change during the 21st century, particularly changes in convective precipitation events. Although the results from Chapter 5 suggested a general trend towards wetter winters and drier summers, most of the observed trends failed to reach the 95% significance level, suggesting that we are not yet able to claim that UK precipitation is changing in the manner suggested by climate model projections. The suggestion of a decline in extreme summer precipitation across the UK, while consistent with UK precipitation trends since the 1960s up until 2006, is at odds with the expectation for more extreme events even in regions where absolute amounts decline, associated with the Clausius-Clapeyron equation. As with the observational data, there are some consistent signals for how UK precipitation is changing, and is likely to change under enhanced greenhouse conditions, but they are not as strong as those for changes in temperatures.

8.3 Suggestions for future work

The work undertaken in this project has produced some firm conclusions but also thrown up numerous questions that need to be addressed in subsequent studies. It is clear, for example, that winter precipitation across northern and western Britain has been declining during the first decade of the 21st century (associated with a reversal of the recent trend towards a more positive winter NAO) and also that there have been some extreme rainfall episodes in the summers of 2007-2010, and so this extreme precipitation analysis will need to be repeated in the future to determine whether the trends identified here are reversing, or whether these recent reversals are only temporary. It is also clear that the winter NAO index does not carry across well to the representation of the behaviour of the summer NAO index, and thus it is worth correlating mean and extreme UK precipitation in high summer (July and August) with a specifically derived high summer NAO index, such as that used by Folland et al. (2009) and determining whether recent changes in summer precipitation can also largely be explained by changes in atmospheric circulation as reflected by the SNAO.

The model performance analysis can be extended to a wider range of models, as the results show that RACMO2 is the best performing model out of the range of models considered in this analysis, but not necessarily better than other models not considered in the analysis. Similarly, the methods used in Chapter 7 can be extended to test a wider range of driving models, to assess the strengths and weaknesses of different driving GCMs at simulating precipitation. The analysis over the UK can also be extended to cover other regions of the globe, e.g. for an analysis of the spatial distributions of simulated mean and extreme precipitation across Europe as a whole, to determine whether the results across Europe produce similar results to the UK-based analysis.

For the purposes of this thesis it was not possible to access categorisations of daily weather into “convective precipitation days” and “large-scale precipitation days”, thus preventing direct comparisons from being made between model simulations and observed data when split into occurrences of convective and large-scale precipitation. Thus, one possible way of advancing this work is to develop a means of categorising observed precipitation data into convective and large-scale precipitation, enabling more quantitative comparisons to be made with the observed model data.

Another approach to extreme events may be to use case studies of individual extreme events and use the model outputs analysed in this thesis to determine how accurately the individual models, when driven by ERA-40, simulate the intensity and distribution of the extreme precipitation, which may help towards determining the key limitations of the current generation of RCMs in simulating extreme precipitation.

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