The size of the grid boxes is limited by the amount of computer power available. Halving the size of the grid boxes in the horizontal and vertical direction makes the model more than 10 times slower to run. A balance must be achieved between resolution and run-time to ensure that enough model experiments can be performed to cover a range of future possibilities. The resulting grid boxes in a global climate model are a few hundreds of kilometres wide in the horizontal. Even in the regional version of the climate model (RCM) they are 25 km, so they cannot resolve all the atmospheric motions and interactions in a single cloud which evolve on much smaller scales. For this reason, small-scale processes must be parameterised, i.e. the effect of the small-scale processes on the grid-box scale variables must be simplified in some way.

The critical aspect for climate prediction is that many of the physical processes that are parameterised in climate models are also involved in the physical feedbacks which determine the effect of increasing greenhouse gases on climate, and set some of the regional aspects of climate change. Also important are interactions between the parameterised processes and the coarsely resolved dynamical motions. Parameterisations are necessarily simplified estimates of how the real-world works; hence there is inherent uncertainty in the modelling approach. In UKCP09 we systematically explore these uncertainties by varying parameters in the Met Office Hadley Centre climate model and include information from other climate models in order to quantify the uncertainty in climate predictions arising from parameterised processes.

A3.2 Some basic assumptions and common misconceptions in climate modelling

Critical examination of the performance of climate models, leading to revision and improvement of the models, is a necessary and ongoing activity within climate modelling (see below). Nevertheless, it is worth stating some the inherent features of all models.

1. Climate models are based on fundamental physical laws (at the very basic level, for example, Newton’s third law of motion) expressed in terms of mathematical equations. They are not, as in some prediction endeavours, statistical fits to past observations.

2. Each component of a model is thoroughly tested; often using data from field experiments or dedicated process models representing, for example, the detailed structure of a cloud. Models and their components are subject to scientific peer review.

3. In short-term prediction areas (weather forecasting, for example) model predictions can be validated or verified against a large sample of past cases. In long-term climate prediction (for example, 50 yr into the future), direct verification of this type is impossible. However the suitability of models as tools for long-term prediction can be established, to some degree, by assessing their ability to pass a range of tests of their physical credibility, including replication of recent climate statistics, historical changes in climate (see Figure A3.1, opposite), or performance in shorter-term predictions of weather for days and weeks into the future and in making predictions of climate on monthly and seasonal time scales.

4. Models cannot be adjusted to give any answer a climate modeller might wish to get about climate change. The complexity of the system precludes

> this. Many features of the past and future climate produced by models, for example, the climate sensitivity — the global mean temperature change for a doubling of CO_2 — could not have been predicted or somehow set when the model was put together. During model development it is the case that optimisation occurs to make the model's fields best fit observations of present-day climate. However, this is often somewhat *ad hoc*, and only in the case of some reduced complexity models has it been attempted systematically.

In the UKCP09 methodology, ensembles of simulations of variants of the Met Office model, have been used to quantify physical relationships between aspects of historical model performance and simulated future changes. That is, to identify the observational tests, in terms of different mean-climate variables and trends, which are most strongly related to the projection of future climate change. These relationships are then be used to determine weights which calibrate the relative contribution of different ensemble members when quantifying uncertainties in predicted future changes. The weights are set according to the strengths of correlations between the simulated values of observable historical variables, and non-observable future variables. The use of the perturbed physics approach allows, in some sense, the *de-tuning* of the model in order that the fit with observations, which may have been used during the model development phase, may then be used in the weighting scheme (describe in more detail in Chapter 3 and Annex 2). This ameliorates the impact of *double counting* the observations, i.e. using the observations to first tune the model and then using them again in the weighting scheme, which may over-constrain the predictions.

Models will never be able to exactly reproduce the real climate system; nevertheless there is enough similarity between the climate model and the real world to give us confidence that they capture (albeit with uncertainty) key processes known to be important in determining the sign and magnitude of predicted future changes. We can be confident that the models can provide some inference about the real world, as is done in, for example, successive IPCC reports. Nevertheless, we do recognise that there are uncertainties and that there are deficiencies common to all models, including the Met Office model. The whole point of the UKCP09 probabilistic projections is to express the credibility of the model projections in terms of the probability of different outcomes. The model deficiencies are taken account of in the probability or credibility limits of the probabilistic projections.

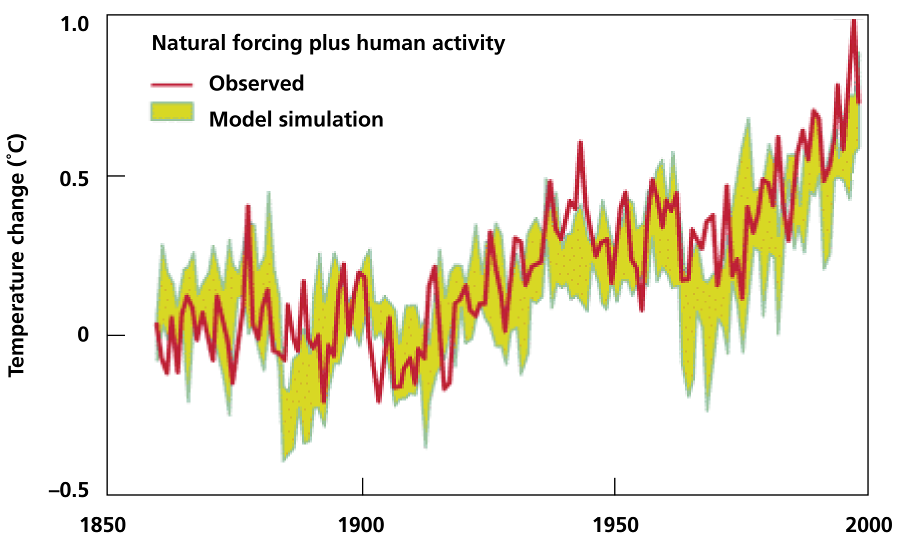


Figure A3.1: Observations of changes in global mean temperature, 1860–2000 (red) compared to the simulation using the HadCM3 climate model driven by observed changes in man-made forcing (greenhouse gas and sulphate aerosol concentrations), natural forcing (solar radiation and volcanic aerosol) and including natural variability (green band). Decadal-scale variability and trends are reasonably well simulated by the model Stott *et al.* (2000).

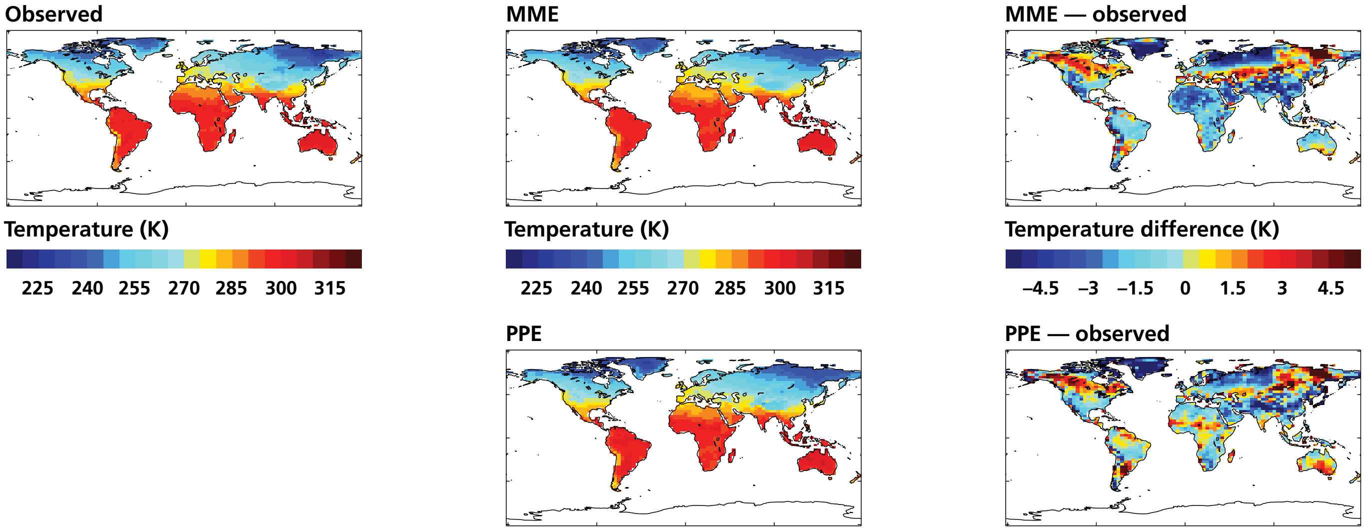
A3.3 Large-scale and small-scale processes and climate change

The current generation of climate models can capture the broad-scale features of present day climate (Figures A3.2 and A3.3) and historical climate change (Figure A3.1). This is particularly true for surface variables such as temperature and mean sea-level pressure and for those three-dimensional fields which capture the large-scale structure of winds and temperatures throughout the atmosphere. Even for fields such as mean precipitation, the models are able to reproduce many of the large-scales features with some fidelity. These features are generated by the dynamical and physical processes in the model and are not prescribed.

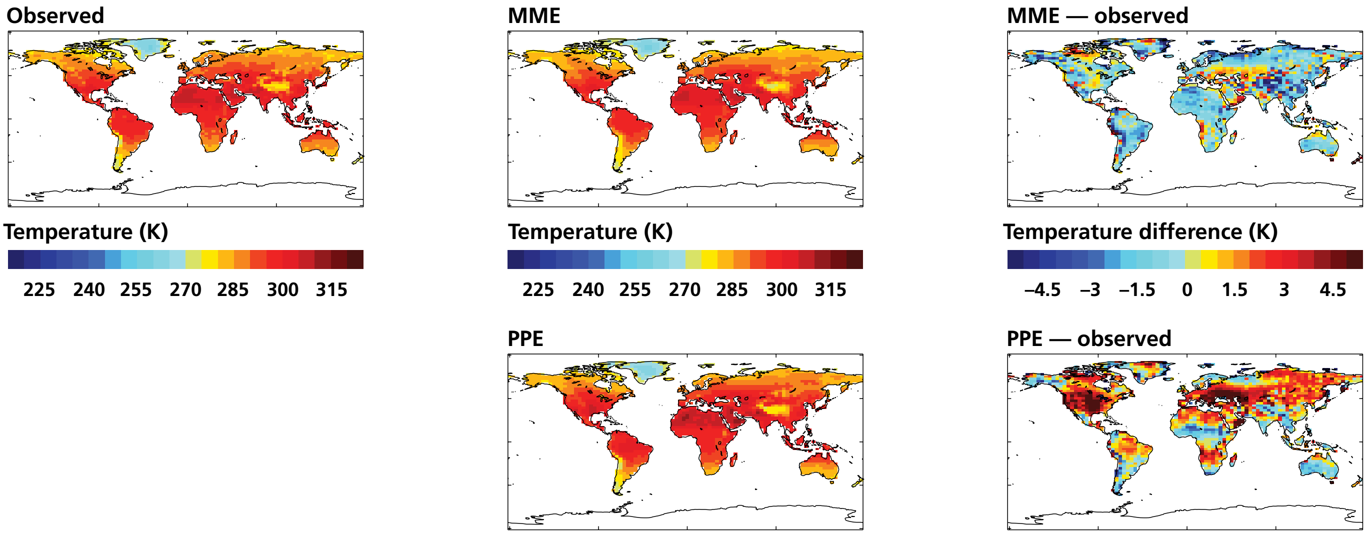
Nevertheless, models are certainly not perfect even on large-scales, as evident in Figures A3.2 and A3.3 which show differences between the model ensemble mean fields and the observations. For example, the ensemble mean of the HadCM3 ensemble with perturbations to atmosphere-component parameters (PPE_A1B — see Chapter 3) shows a clear warm bias in summer Northern Hemisphere continental regions (which we discuss later). In addition, there are biases which are common to both the perturbed physics and multi-model ensembles. Models tend

Figure A3.2: Winter (top two rows) and summer averaged surface air temperature 1961–1990 in K from observations (left column), absolute values from the multi-model ensemble (MME) mean of all the CMIP3 climate models and from the mean of the versions of HadCM3 with perturbations made to atmospheric parameters (PPE_A1B middle column) and model ensemble mean minus observed mean (right column). The model fields are plotted only where the observational data exists. The multi-model ensemble is those models from the Third Climate Model Intercomparison Project (CMIP3). The members are not the same subset of models as the multi-model ensemble used to generate the UKCP09 PDFs, referred to in Chapters 1–3, which employ data from models coupled to simple mixed layer oceans.

Winter mean temperature



Summer mean temperature

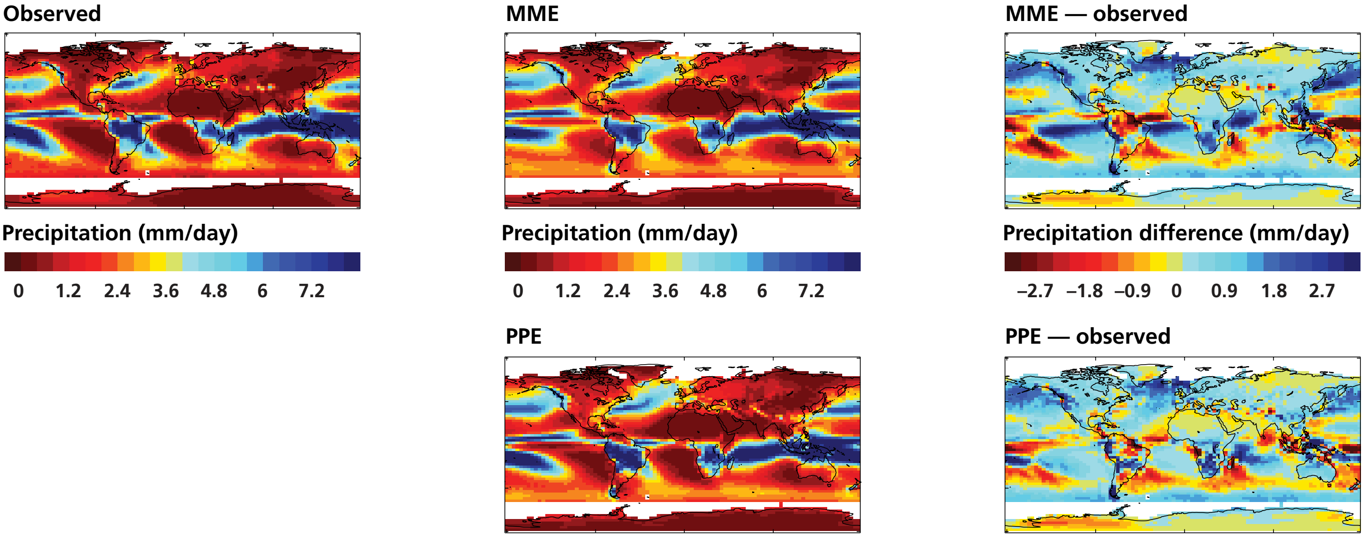


to produce a *double ITCZ* (Intertropical Convergence Zone) in the Pacific whereby zonally-oriented large-scale rain bands appear in both hemispheres, where in reality, the southern hemisphere rain band is oriented NW–SE. In addition, variables such as convective (shower) precipitation can be highly localised so are harder to model, as are fields such as surface winds. When regional factors are important — for example in highly mountainous regions — global models may find it hard to capture the small-scale details of the present day climate. Hence there is plenty of room for improvement in climate models and this is an extensive field of research, both within the Met Office Hadley Centre and internationally. (Further discussion of model evaluation is presented below and can also be found in, for example, Chapter 8 of IPCC AR4. Discussion of the mean climates of the regional model versions can be found in Chapter 5 of this report.)

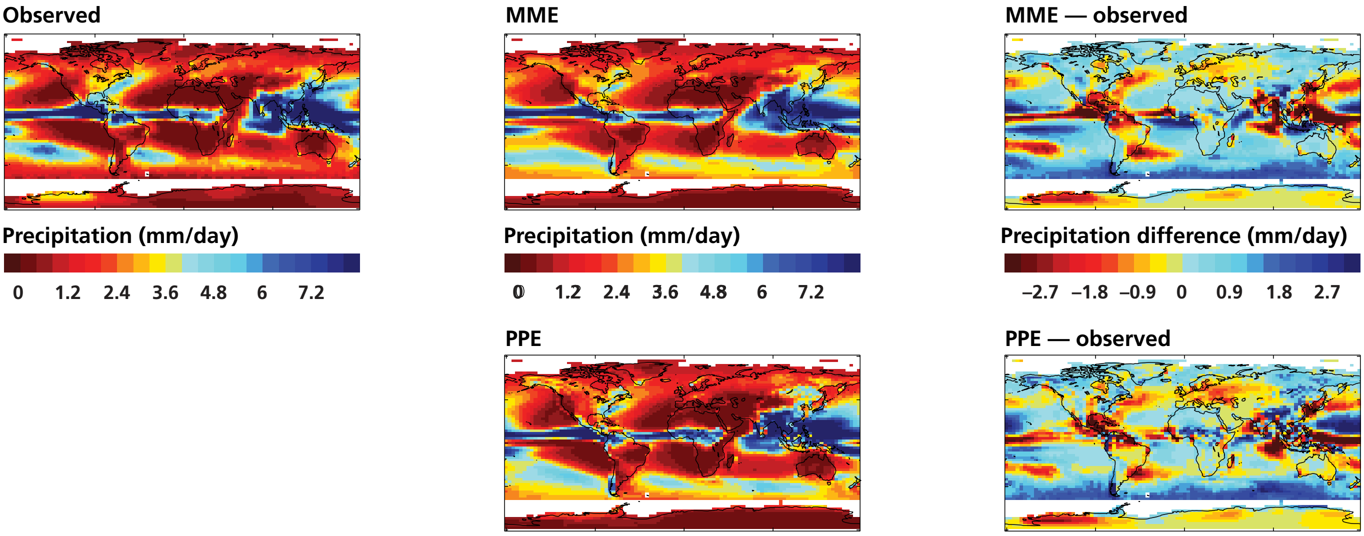
A critical issue for prediction is how these model errors and biases affect the pattern and magnitude of climate change. The main drivers of climate change are global in nature in terms of their radiative forcing and there is a significant degree of commonality between models in terms of their large-scale projections of mean future change (Figure A3.4). The commonality is stronger in the case

Figure A3.3: Winter (top two rows) and summer averaged precipitation 1961–1990 in mm/day from observations (left column), from the multi-model mean of all the CMIP3 climate models and from the mean of the versions of HadCM3 with perturbations made to atmospheric parameters (PPE_A1B middle column) and model ensemble mean minus observations (right column). The model fields are plotted only where the observational data exists.

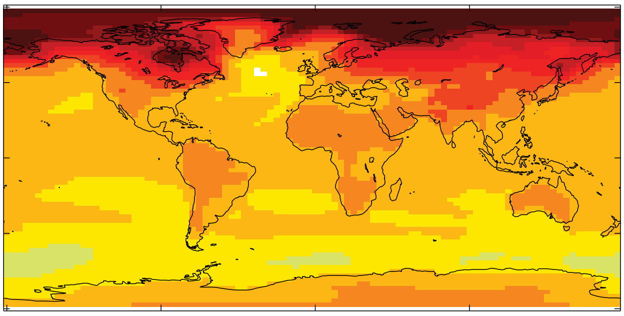
Winter mean precipitation



Summer mean precipitation

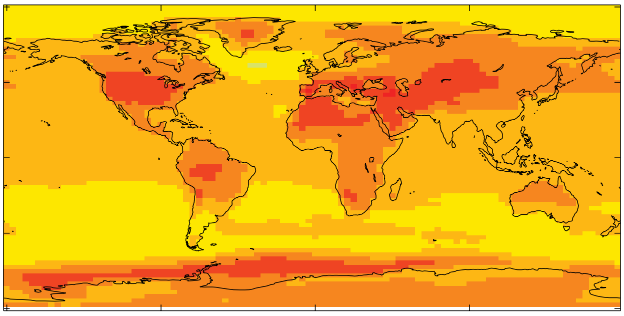


Winter MME

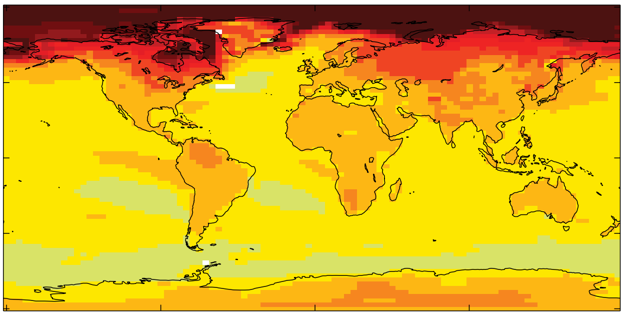


Change in temperature (°C)

Summer MME

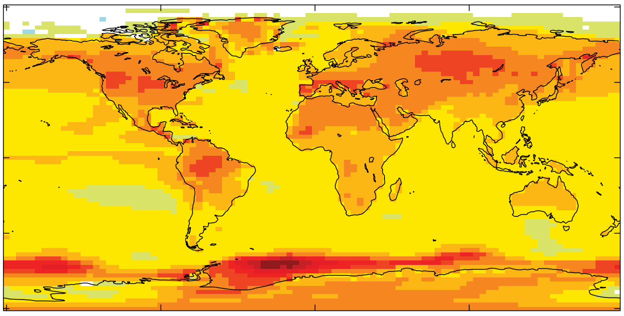


Winter PPE

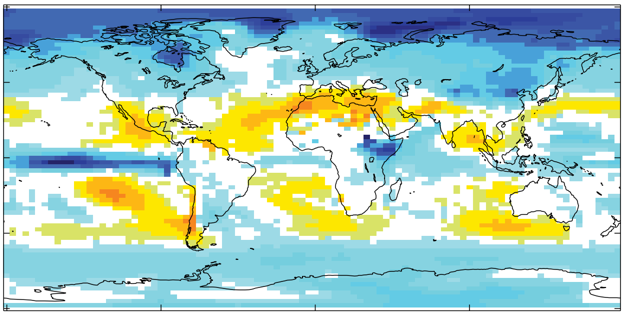


Change in temperature (°C)

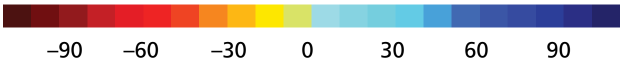
Summer PPE



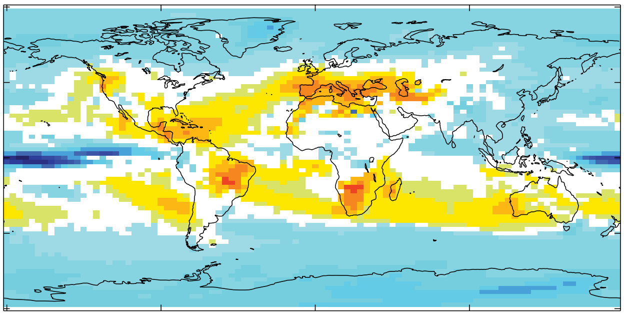
Winter MME



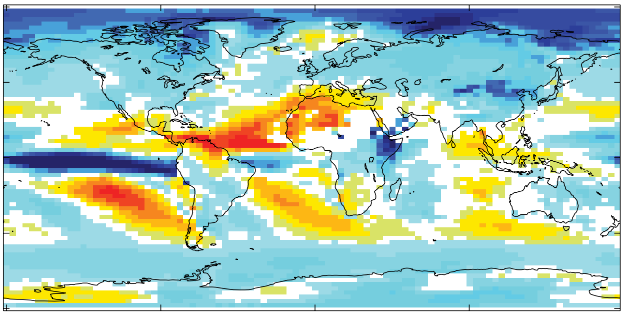
Change in precipitation (%)



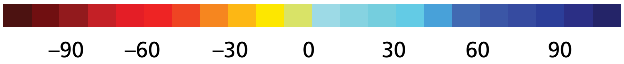
Summer MME



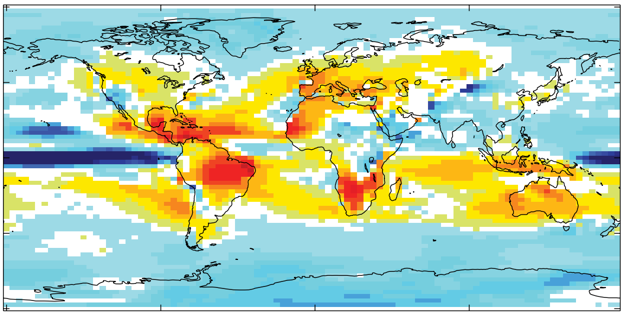
Winter PPE



Change in precipitation (%)



Summer PPE



of temperature, but there are also similar patterns of response in terms of the mean precipitation in models. Different models all show greater warming over land compared to over the ocean and greater warming at high-latitudes in comparison with the tropics in the winter hemisphere. The latter may be understood in terms of simple physical reasoning: in this case, albedo feedbacks whereby snow or ice covered regions become exposed as the planet warms and, as a result, more sunlight is absorbed by the underlying surface. Other important feedbacks include the positive water-vapour feedback; water vapour (a potent natural greenhouse gas) will increase as air temperature increases. The directions of such feedbacks are relatively well understood but their absolute magnitude is still under investigation. Feedbacks from clouds represent a significant source of uncertainty in total global feedbacks and these may also drive variations in local climate changes (clouds remain one of the most-complex and most-studied of feedbacks under climate change). Because of these global-scale uncertainties, the PDFs presented in this report are (a) constructed from a relatively large number of ensemble members which explore uncertainties in large-scale feedbacks and (b) constrained by a number of observed large-scale fields; the relative likelihood of each model version in its ability to simulate the large-scale nature of climate and historical climate change is taken into account (see Chapter 3).

Looking more locally, we see similar patterns of warming in both summer and winter in region of the UK and NW Europe, with the multi-model ensemble mean showing a slightly greater ensemble mean warming than in the case of the perturbed physics ensemble mean. Perhaps more surprising is the similarity of the patterns of precipitation change in the two different ensembles, with increased precipitation during the winter over much of NW Europe and a drying in the Mediterranean region in summer. This indicates common physical mechanisms for the change between different models. Nevertheless, those physical mechanisms may act in subtly different geographical areas and with different strengths in different models. In the summer case, the perturbed physics ensemble drying extends more into the north and over the UK, whereas in the multi-model ensemble the line of zero mean change cuts the UK. This is why it is so important to include information from other climate models in UKCP09.

For some variables the response to climate change may be quite different in different perturbed physics or multi-model members and the resulting PDFs of change quite wide. We should not necessarily assume that the use of the multi-model ensemble in generating the PDFs provides some kind of upper-bound uncertainty in the predictions. The existence of common errors in multi-model and perturbed physics ensembles may, for example, impact the pattern or magnitude of the climate change response seen in all ensembles. There may be other possible formulations of models which could give rather different responses that could affect the level of uncertainty in the PDFs. Nevertheless, without any evidence of the possibility of very different climate change, the most defensible approach is to look to the multi-model ensembles to provide evidence for a *discrepancy* in PDFs generated from the perturbed physics ensembles (see Chapter 3 and Annex 2 for more details). The impact of model formulation (e.g. horizontal and vertical resolution) on the magnitudes and patterns of climate change is a very active area of research.

In general, regional aspects of climate change may be influenced by local regional processes such as the enhancement of rainfall on the windward-side of mountainous regions. Hence the use of the ensemble of regional-model simulations and statistical downscaling techniques in generating the PDFs presented here. Importantly, the regional models are driven by output from the

Figure A3.4 (opposite): Ensemble mean response in the years 2071–2100 minus the mean climate averaged 1961–1990 under SRES scenario A1B from two different types of global climate model ensembles. Left panels from the CMIP3 multi-model ensemble, right panels from the 17-member HadCM3 ensemble (PPE_A1B in Chapter 3) with perturbed atmospheric parameters. The fields are only shaded when greater than 66% of the ensemble members agree on the sign of the projected change. Top row, winter (DJF), surface air temperature. Second row, summer (JJA) surface air temperature. Third row, DJF precipitation. Fourth row, JJA precipitation. A similar figure appears as Figure TS.30 in the IPCC AR4 Technical Summary.

global models that represent the large-scale pattern of climate change. Hence there is an internal consistency in the information which is derived completely from model output.

A3.4 The ability of models to represent modes of variability

A3.4.1 The North Atlantic Oscillation

Modes of variability like the NAO do occur spontaneously in climate models. Causes of long-term variations in the NAO are still under investigation.

The North Atlantic Oscillation (NAO) is one of the dominant modes of variability of Atlantic-European winter climate. It can be broadly described as a see-saw of atmospheric pressure between the Azores and Iceland and is sometimes discussed in relation to a hemispheric mode of variability, the Northern Annular Mode (NAM), with the see-saw between polar and mid-latitude bands of air. When the NAO is positive, winters in the UK tend to be milder and wetter. When it is negative, winters tend to be colder and drier. HadCM3 does simulate the broad spatial and temporal characteristics of NAO variability reasonably well and is certainly competitive when compared to other climate models (e.g. Stephenson *et al*. 2006).

Of particular research interest has been the long term trends in the NAO observed in recent times (see Figure A3.5) that cannot be easily explained in terms of long-term natural internal variability in climate models (e.g. Gillett, 2005). There are conflicting theories about the causes of these trends in the climate literature. They may be related to variations in sea-surface temperatures in the N. Atlantic or remote ocean basins (Rodwell *et al*. 1999; Hoerling *et al*. 2001; Sutton and Hodson 2007), or be related to trends and variability in stratospheric winds (Scaife *et al*. 2005) or both. They might even be explained in terms of chance year-to-year fluctuations which are in no way predictable. None of the models in the 17-member ensemble of HadCM3 with perturbed atmosphere parameters (PPE_A1B) capture the exact observed low-frequency temporal behaviour of the NAO — no free-running climate model does. Yet the general level of variability in each of the members is similar to that seen in the observations and one member (highlighted in red in Figure A3.5) does capture some low-frequency trends in the period around 1950–2000 which are reminiscent of those seen in the real world (quite by chance of course).

None of the perturbed physics ensemble members show significant NAO trends into the future. Some sub-sets of the multi-model archive have been shown to produce positive NAO trends (e.g. Osborn *et al*. 2004) and the recent IPCC

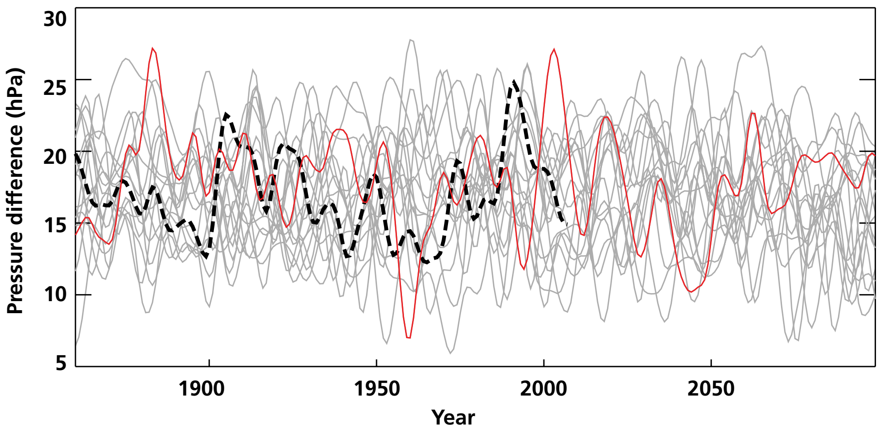


Figure A3.5: Gibraltar minus Iceland mean sea level pressure difference averaged in the winter seasons from observed (thick dotted line) and from the 17 member ensemble of HadCM3 with perturbations to parameters in the atmospheric (PPE_A1B in Chapter 3) component of the model (grey lines). A low-pass filter has been applied to remove year-to-year variability and highlight low-frequency NAO behaviour. An ensemble member with similar magnitude variability to that observed (occurring by chance) is highlighted in red.

assessment concluded that the most recent models showed a trend towards positive NAM and NAO, but with considerable spread among models in the latter. Clearly there is some uncertainty and possible dependence on what index is used to define the NAO/NAM and which models are examined. A corollary of this is that the coherent aspects of future climate changes in winter in the N. Atlantic sector (e.g. Figure A3.4) thus appear to be largely driven in the models by the direct response to the radiative forcing from greenhouse gas increases, rather than any response involving coherent changes in the NAO. This radiative response is the dominant response and no models show changes in dynamical modes of variability such as the NAO which might oppose or severely alter this response.

A3.4.2 Storm tracks and blocking

HadCM3 does simulate the main hemispheric pattern of storm tracks and some aspects of Atlantic-European blocking.

(a) Storm tracks

Greeves *et al*. (2007) show that HadCM3 does capture the main large-scale features of the northern hemisphere circulation, with storm activity concentrated in regions of the Pacific, Atlantic and Mediterranean. These storm tracks are not prescribed in the model but rather evolve as a consequence of the location of mountainous regions, the land–sea contrast and because of preferred regions for development of weather systems. The simulation of storm tracks shows only a modest improvement when model resolution is doubled for example, so the need to quantify uncertainties, achieved in UKCP09 through the use of ensemble simulations of HadCM3 and other contemporary climate models, is unlikely to be removed in the foreseeable future; the computing cost of a high resolution model would have prohibited the use of large ensemble simulations for UKCP09. However, some benefits of higher resolution are achieved in the regional-model downscaling step. A notable generic feature of regional models is their ability to generate many more weather features such as troughs and frontal waves.

It is possible to investigate the behaviour of storms and storm-tracks in climate models using a variety of model outputs. Sophisticated tracking techniques which identify individual cyclones and anticyclones and produce summary statistics of their behaviour may be contrasted with more simple approaches which use time-filtered daily mean-sea-level-pressure fields. Care should be taken in the interpretation as different analysis techniques can sometimes produce subtly different results.

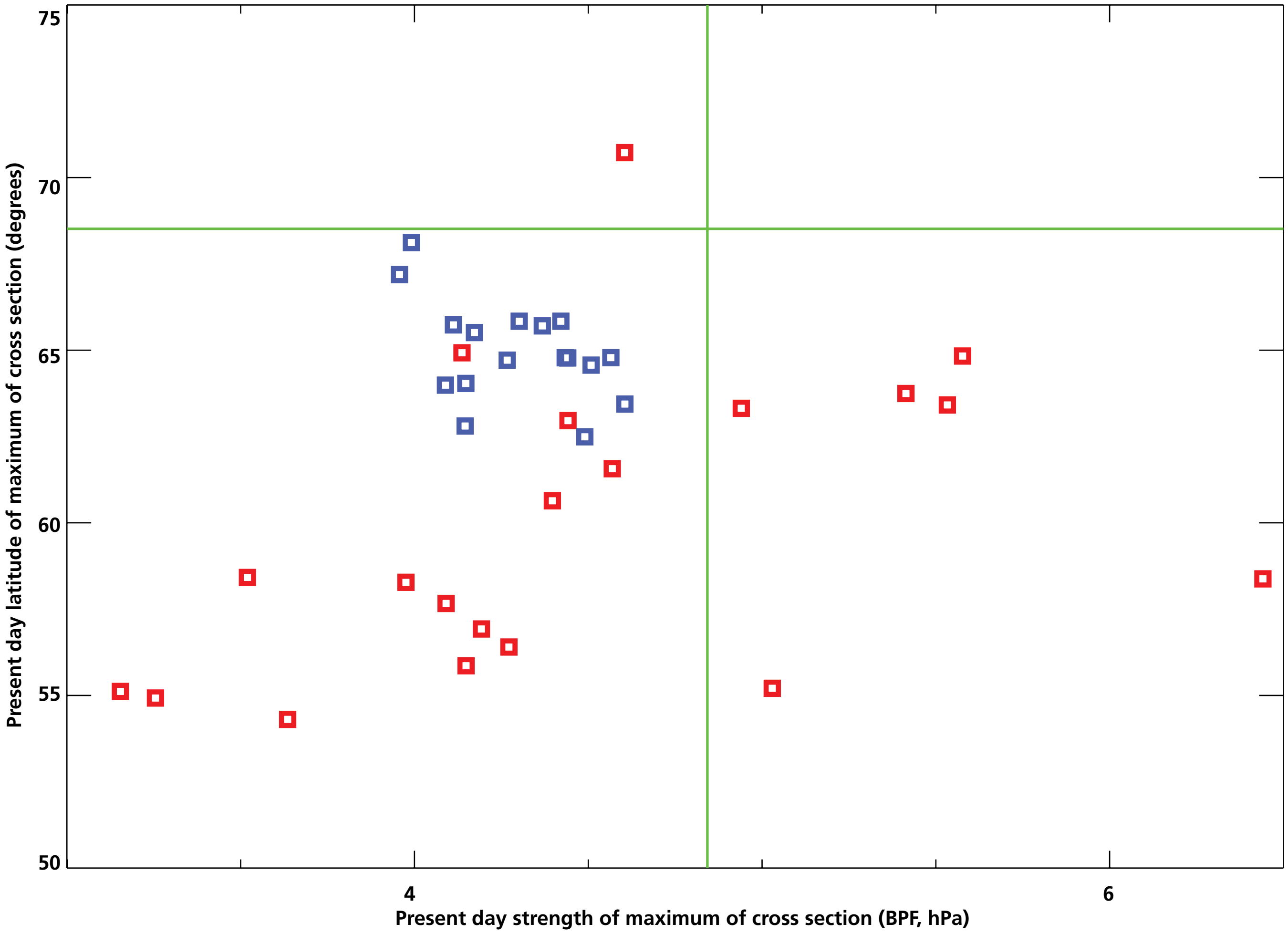
Here we use a simple analysis of mean-sea-level-pressure anomalies, time filtered to retain 2–6 day variability, from the 17-member HadCM3 ensemble with Medium emissions and with perturbations to atmospheric parameters, which are used to drive the regional model simulations. For UK winter, the ensemble mean track of cyclone activity in the models (blue squares in Figure A3.6) is somewhat to the south of its observed position (as given in the ECMWF ERA40 re-analysis of observations). Nevertheless, the track position is closer to that observed than many of the equivalent simulations performed with the CMIP3 models red squares. In addition, the Met Office perturbed physics ensemble has a tighter cluster of storm track strength which, for each member, is only slightly weaker (~10%) than observed. The same southerly track extent is true of the position in other seasons in the ensemble mean, but in those cases the cyclone count is down by around 5–20% (figure not shown). The perturbations to HadCM3 do result in some spread in the position and intensity of the cyclone track between model versions, with ensemble members between 0 and 6 degrees too far south and some having strengths as much as 20% too low. However, this spread is smaller than that seen in the CMIP3 multi-model ensemble, where the equivalent range is from 2 degrees too far north to14 degrees too far south, and range in intensity from 35% too low to 33% too high (Figure A3.6).

Feature-tracking software has also been used to investigation of storms and storm-tracks in these rather coarse-resolution climate models (see Annex 6). Experience tells us, however, that much higher resolution numerical models, such as those used for weather prediction with grid-lengths of the order of 10s of kilometres rather than 100s of kilometres, show much greater fidelity in their ability to simulate the details of individual storms, fronts, etc. that are familiar from looking at daily weather maps. Tropical cyclones which may re-curve into mid-latitudes and become intense storms cannot, for example, be simulated by the current generation of climate models. That is not to say however that such storms are likely to form a major component of the climate change signal. At present, such storms are relatively rare (although may have large consequences) and there is no robust evidence that their frequency will change in the future. Nevertheless, without a number of relatively high-resolution climate model simulations, which will take many years if not decades to realise, it is almost impossible to make any reliable assessments of such phenomena.

(b) Anticyclones and blocking

NW Europe, and in particular the UK, are preferred regions of the globe for anticyclonic events by virtue of being at the end of the Atlantic storm track. The examination of anticyclones turns out to be more complex than the case of

Figure A3.6: Present-day location and intensity of the North Atlantic storm track at the longitude of the UK. The blue squares are from the 17-member HadCM3 perturbed physics ensemble (PPE_A1B in Chapter 3) and the red squares are from the CMIP3 multi-model ensemble. The green lines are from ERA40, and can be thought of as the observed position and strength.



cyclone activity and three different measures have been used to evaluate the ensemble. The inconsistency of the three diagnostics makes it difficult to make a clear statement about the ability of the perturbed physics ensemble to simulate anticyclones, but in general the HadCM3 ensemble is competitive with other climate models.

Further information may be gleaned from the analysis of a particular anticyclonic phenomenon, that of atmospheric blocking. Blocking situations, whereby areas of relatively immobile high atmospheric pressure tend to dominate weather patterns for many days, result in relatively cold, still conditions often accompanied by fog in winter. In summer they tend to be accompanied by dry sunny conditions and heatwaves.

The mechanisms for atmospheric blocking are only partially understood, but it is clear that there are complex motions, involving meso-scale atmospheric turbulence, and interactions that climate-resolution models may not be able to

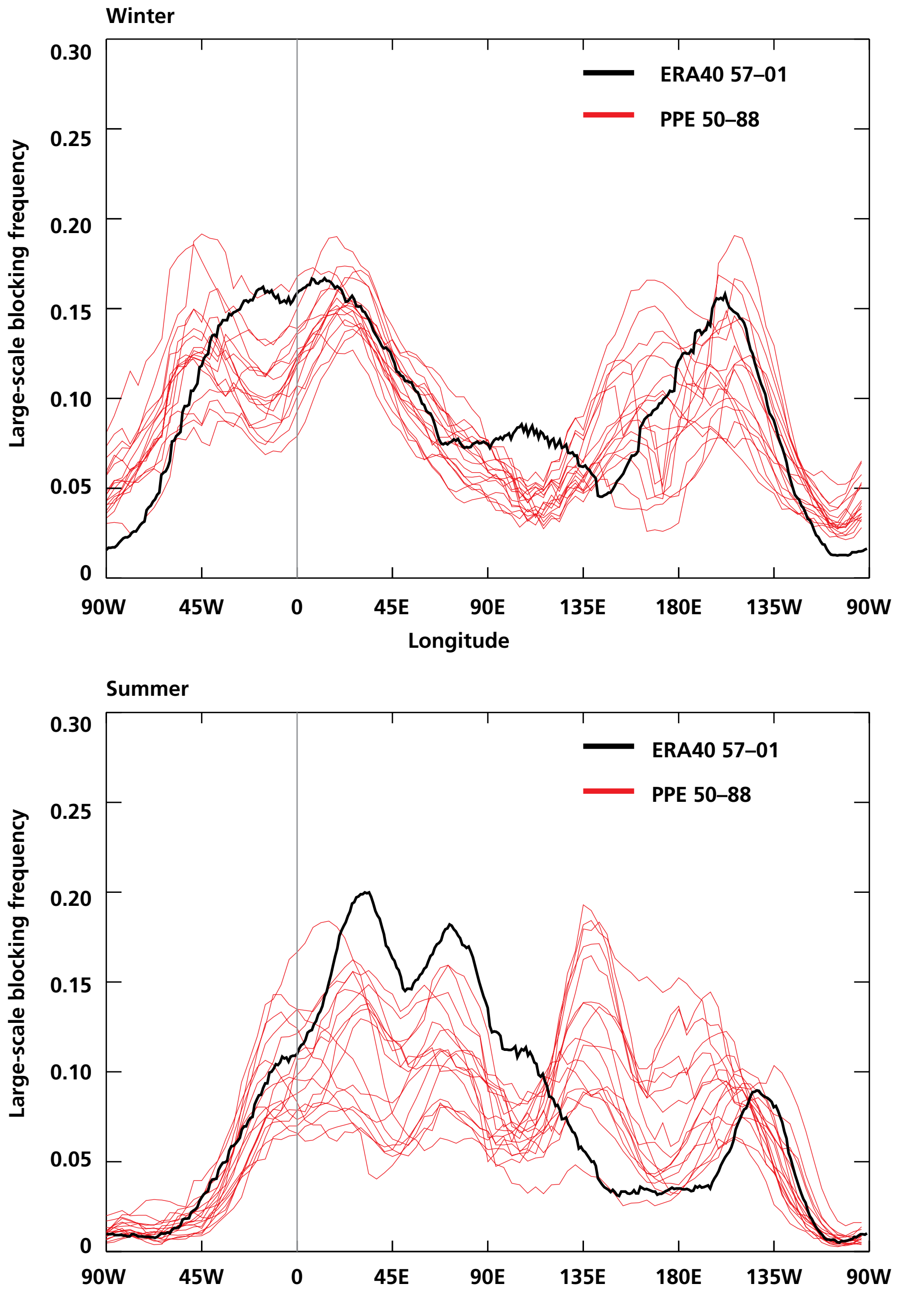


Figure A3.7: The frequency of blocking events in the perturbed physics HadCM3 ensemble (PPE_A1B, red lines) for winter (DJF, top) and summer (JJA, bottom) together with that estimated from ERA40 (thick black lines). The blocking index is calculated following Pelly and Hoskins (2003) and uses a variable latitude to track the location of the model storm track (in contrast to other indices which used a fixed latitude).

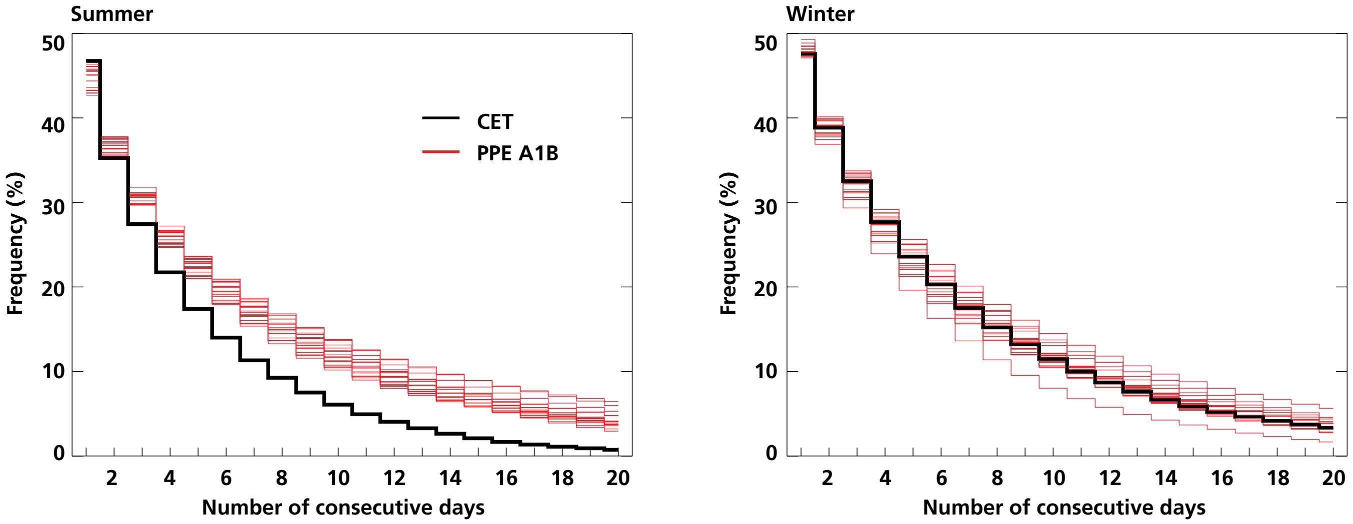


Figure A3.8: The frequency of occurrence of consecutive days of same-sign temperature anomalies from the Central England Temperature (CET) record (black line) and from an equivalent diagnostic from the 17-member ensemble of perturbed physics HadCM3 (PPE_A1B – red lines). On the left panel there is, by definition, a near 50% chance of a day being warmer than average, a 35% of getting two consecutive warm days, etc. On the right panel, the chance of getting consecutive cold days in winter is plotted.

represent fully. The prediction of the intensity and duration of blocking events is one of the most difficult weather forecasting situations. The HadCM3 model does represent, with reasonable fidelity, some aspects of present-day atmospheric blocking in the North Atlantic region (see Figure A3.7) with the performance in summer better than that in winter. At other longitudes the model shows less fidelity, in particular in the Pacific sector. (An additional complication is that it is not clear that simply doubling the resolution of a climate model automatically produces a better simulation of blocking — in the case of one Met Office Hadley Centre model, this results in a degradation).

The role of atmospheric blocking under climate change is currently a major topic of research. Might current model errors severely limit the reliability of climate change projections (e.g. Palmer *et al*. 2008; Scaife *et al*. 2008)? Might large changes in blocking, that current models cannot simulate, cause large changes in the frequency of occurrence of summer heat waves for example? Of more practical interest than the diagnosis of blocking frequency is perhaps is the frequency of occurrence of blocking-like weather in the models used in UKCP09. Figure A3.8 shows a diagnostic of occurrences of periods of cold winter and warm summer days in the UK in the PPE_A1B ensemble. For the winter case, each model in the ensemble does a reasonable job of simulating the relative frequency of occurrence of cold spells. In the summer, the model versions overestimate the frequency of occurrence of warm spells (despite the blocking frequency diagnostic being close to that observed around the Greenwich Meridian in Figure A3.7 — other processes are important). Careful evaluation of such diagnostics from the RCM simulations and the weather generators is recommended in cases where such variability is important to the individual user. It should be noted that the UKCP09 PDFs of mean changes and extremes include, by definition, the effects of blocking and changes in blocking from both perturbed physics and multi-model ensembles. Changes in the storm-tracks and blocking are presented in Annex 6.

A3.5 The effect of mean biases in models

The probabilistic approach quantifies uncertainties in the processes and feedbacks associated with summer drying and related impacts.

As highlighted above, biases in present-day summer climates in models are an issue and may effect the response of the model under climate change. Rowell and Jones (2006) examined the different mechanisms for future summer drying and Jones (2006) examined the different mechanisms for future summer drying under climate change using a matrix of global and regional model experiments. They found that the primary drivers for summer drying in continental Europe are the direct warming coming from enhanced greenhouse gases, coupled with a tendency for a more rapid decline in spring soil moisture which pre-conditions the soil to be dryer prior to the onset of summer. If the soil is moist, then some of the solar heating will be channelled into evaporating this moisture. If the soil is drier, then more of the solar heating will be available to increase temperatures. They also found that the summer soil moisture feedback, whereby reduced soil moisture leads to an increase in surface sensible heating which further reduces soil moisture, was important. Hence future changes in regional climate are driven by a complex array of processes, dependent on both local and remote factors which are included in climate models. Systematic local and remote errors might impact the response derived only from HadCM3 ensembles, but by including results from other models through the discrepancy terms ameliorates this possibility.

In the model experiments used to produce the PDFs presented in this report, a number of processes which control these various feedbacks are perturbed (for example, the number of soil levels accessed for evapotranspiration). Thus we have attempted to explore the uncertainties in the mechanisms for summer drying by using model output from perturbed physics and from multi-model ensembles.

A3.6 Discussion

This annex gives a flavour of some of the issues in climate modelling, with some focus on physical processes that have been major topics of discussion in recent times. A key point is that the UKCP09 PDFs are designed to sample much of the uncertainty introduced by deficiencies in climate models by the use of perturbed physics and multi-model ensembles which in the case of PPEs are weighted by their ability to simulate historical mean climate and climate change. The PDFs represent a measure of the credibility of our current ability to predict climate change.

Much work in climate change research is directed towards both improving climate models and understanding how model deficiencies might impact the magnitude and spatio-temporal pattern of climate change. This research will eventually feed-through to more credible predictions, i.e. PDFs with less uncertainty. Nevertheless, there is a possibility that changes and improvements to models might reveal extreme or very different patterns of climate change outside the range of the UKCP09 PDFs. While we have endeavoured to capture the major feedbacks and their uncertainties and to account for the major deficiencies in models, only future research will be able to tell us if this is the case.

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Annex 4: Probabilistic projection data

Ag Stephens, British Atmospheric Data Centre

The maps and graphs shown in this report, and others available from the UKCP09 website, are generated from a large dataset of probabilistic projections. Chapter 3 describes the methodology developed to produce the projections, and in particular Section 3.2.11 describes the various stages of the procedure. Out of this emerge two products which are described in this annex.

A4.1 Cumulative distribution functions

The first product from the User Interface is a series of cumulative distribution functions (CDFs). Each of these consist of a set of 107 values of future climate changes corresponding to a set of 107 pre-defined probability levels. These CDFs are provided for each variable at each location, temporal average, future time period and emissions scenario. This is the data which is used to form the CDF or PDF graphs (and plume plots) available from the User Interface, such as those shown in Chapter 4. The set of CDFs for every 25 km square in the UK is used to form maps at the 10, 50 and 90% probability levels, such as those also shown in Chapter 4.

Different probability levels have different levels of robustness. We believe data for probability levels between 10 and 90% to be robust. Probability levels between 1 and 9% and 91 and 99% are to be used with caution as these are less robust and the level of robustness will vary according to which variable is being used. Probability levels less than 1% and greater than 99% are only included so that users can generate plots of PDFs estimated from this CDF data to a similar standard found in the UKCP09 User Interface.

A4.2 Sampled data

Users require values sampled from CDFs to input into their impacts models. For one variable of interest this could be sampled from the appropriate CDF. But most impact models will require more than one variable and it is important to capture in the sampling procedure how these variables depend on each other. The second product described in this annex, referred to as *sampled data* satisfies this requirement and can be thought of as a spreadsheet (Table A4.1); there are actually two* spreadsheets (known as Batch 1 and Batch 2) for each 25 km grid square and aggregated region (per emissions scenario and per future time period). Each spreadsheet has 10,000 samples (rows), which have been sampled according to weight (a relative measure of how well an individual model variant compares to observations) from a much larger number generated by the probabilistic statistical methodology (see Chapter 3, Section 3.2.11). Each row can be thought of as representing projections at a single location from a single model variant; so the sampled data can be used to look at a consistent set of changes in the seasonal cycle of a climate variable but not at a consistent set of changes at different locations. As the sampling was done by weight, each row can be considered as equi-probable; sampling allows the better model variants to be selected several times within the sampled data set, and rows from the same model variant have the same mean climate change but differ in how the noise was sampled. The columns of each spreadsheet consist of a number of variables for each temporal averaging period. Figure A4.1 shows schematically the variables, emissions scenarios, locations, time periods and temporal averages.

Smaller numbers of rows can be sub-sampled randomly, but the smaller the sub-sample, the greater the chance of the distribution diverging from that of the full sampled population of 10,000. Also, rows can be specified by sample i.d. but this approach requires careful consideration and justification and could lead to a biased decision if used incorrectly. Similar spreadsheets are available for some variables as future climate, rather than climate change, in which the changes have been combined with an observed 1961–1990 climatology. Data sampled from this spreadsheet (for example, changes in precipitation and temperature for a particular 25 km square) can be used as input to an impacts model.

Note that the sampled data has been clipped using the 1 and 99% probability levels from the CDF data for all available variables. That is, for a given combination of variable, location, time period, averaging period and emission scenario, the values of sampled data below the 1% probability level are set to the value of the 1% probability level from the corresponding CDF, and values above the 99% probability level are set to the value of the 99% probability level.

The User Interface will allow downloading the sampled data directly; as this is about 0.5 Tbytes in all, users are guided towards defining a suitable subset for their needs. The user could download the data from this request as a csv or CF-netCDF file; the csv option would allow the data to be imported into, and manipulated using, a standard desktop spreadsheet package.

A typical request might be:

- **Variables?** *Mean temperature, mean precipitation*
- **Climate change or future climate?** *Climate change*
- **Emissions scenario?** *High*
- **Location?** *25 km grid box 1628 (London)*
- **Time period?** *2070–2099*
- **Temporal average?** *Winter and Summer*
- **Number of subsamples?** *Random selection of 1000 (of the 10,000 possible samples)*

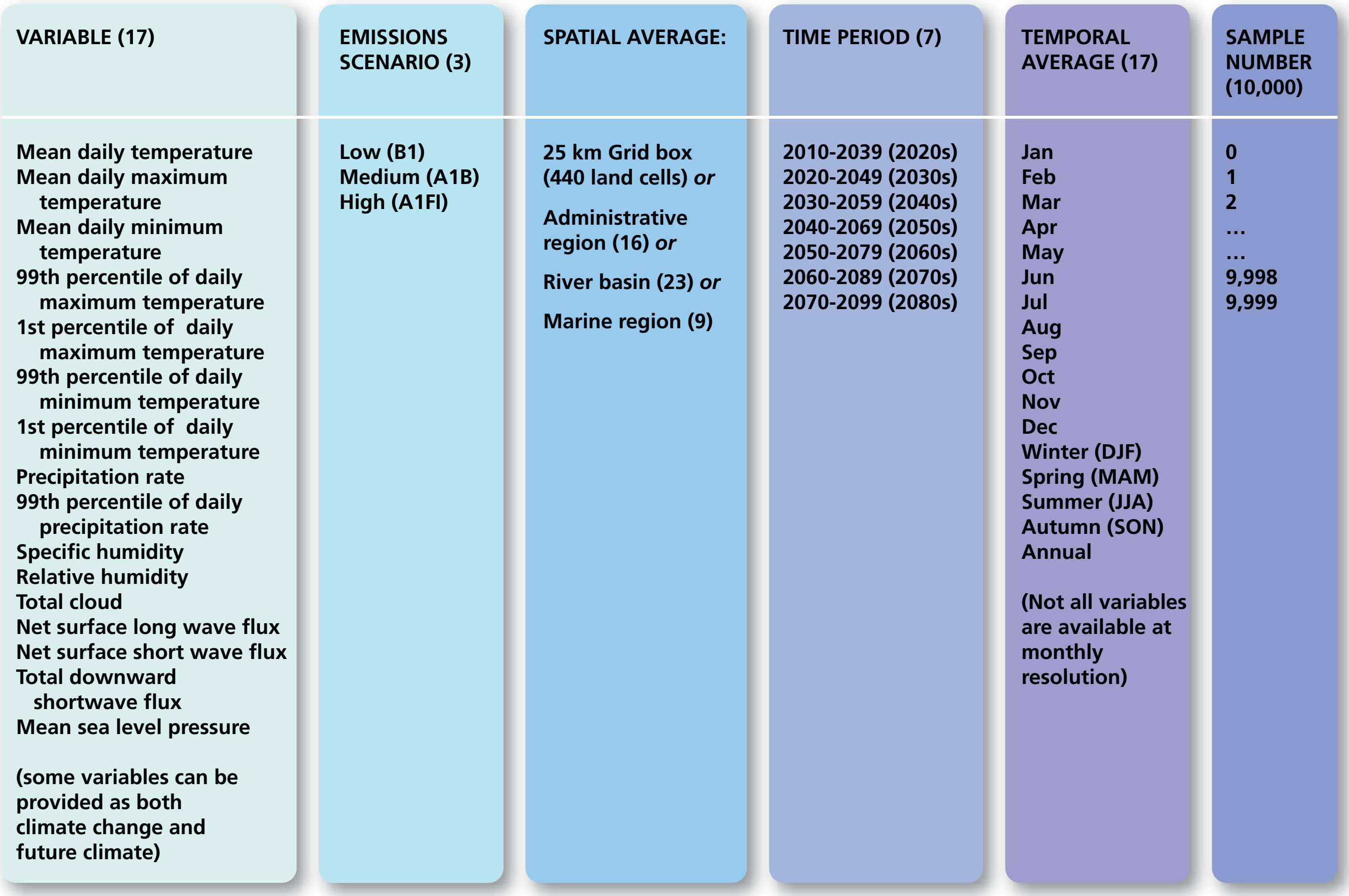
---

* Due to limitations in processing, all the variables cannot be included in a single spreadsheet and each location is processed separately.

Low emissions, Grid box 1234, Batch 1					
2020s					
January					Feb…Dec
Sample i.d.	Tmean	Tmax	Tmax99%	Tmin…	Tmean, Tmax…
0	3.3	4.4	5.5		
1	3.8	4.8	5.8		
…					
9999	2.9	4.1	5.1		

Low emissions, Grid box 1234, Batch 2			
2020s			
January			Feb…Dec
Sample i.d.	MSLP	RH…	MSLP, RH…
0			
1			
…			
9999			

Table A4.1: Diagrammatic representation of a segment of the two batches of data for one 25 km grid square under one emissions scenario and for one future time period.



VARIABLE (17)	EMISSIONS SCENARIO (3)	SPATIAL AVERAGE:	TIME PERIOD (7)	TEMPORAL AVERAGE (17)	SAMPLE NUMBER (10,000)
Mean daily temperature Mean daily maximum temperature Mean daily minimum temperature 99th percentile of daily maximum temperature 1st percentile of daily maximum temperature 99th percentile of daily minimum temperature 1st percentile of daily minimum temperature Precipitation rate 99th percentile of daily precipitation rate Specific humidity Relative humidity Total cloud Net surface long wave flux Net surface short wave flux Total downward shortwave flux Mean sea level pressure (some variables can be provided as both climate change and future climate)	Low (B1) Medium (A1B) High (A1FI)	25 km Grid box (440 land cells) *or* Administrative region (16) *or* River basin (23) *or* Marine region (9)	2010-2039 (2020s) 2020-2049 (2030s) 2030-2059 (2040s) 2040-2069 (2050s) 2050-2079 (2060s) 2060-2089 (2070s) 2070-2099 (2080s)	Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Winter (DJF) Spring (MAM) Summer (JJA) Autumn (SON) Annual (Not all variables are available at monthly resolution)	0 1 2 … … 9,998 9,999

Figure A4.1. Structure of the UKCIP09 Probabilistic Sampled Data for one batch. Some variables can be provided as both climate change and future climate. Not all variables are available at monthly resolution.

Table A4.2: Allocation of variables between the two batches; joint probabilities can be calculated between variables in the same batch only.
*** These variables are required to condition the Weather Generator (UK Climate Projections Science report: Projections of future daily climate for the UK from the Weather Generator). # These variables are not available from the User Interface.**

Batch 1	Batch 2
Mean temperature*	Specific humidity
Mean daily maximum temperature	Net surface long wave flux
Mean daily minimum temperature	Net surface short wave flux
99th percentile of daily maximum temperature	Total downward shortwave flux
1st percentile of daily maximum temperature	Mean sea-level pressure
99th percentile of daily minimum temperature	Lag-1 correlation of daily precipitation* #
1st percentile of daily minimum temperature	
Precipitation rate (percentage change)*	
99%ile of daily precipitation	
Relative humidity*	
Total cloud	
Variance of daily precipitation* #	
Skewness of daily precipitation* #	
Probability of a dry day* #	
Variance of daily mean temperature* #	

Changes (a) with different emissions scenarios, (b) at different locations and (c) in different batches, are not coherent and therefore cannot be combined. If users require a joint probability of changes in two variables, then plots can be provided directly by the User Interface (see Chapter 4, Section 4.6). If users require the joint probability of changes in more than two variables, they can download the variables and perform the necessary calculations offline using their own statistical packages. Joint probabilities (see example in Chapter 4, Section 4.6) can only be created for groups of variables in the same batch; the variables in each batch have been selected to cater for the combinations of variables needed to run the Weather Generator; see Table A4.2 (overleaf). Examining joint probabilities between variables in different batches is inadvisable, and hence the User Interface will not enable this.

Annex 5: Changes to the Atlantic Ocean circulation (Gulf Stream)

A5.1 How does the Atlantic Ocean circulation influence UK climate?

Richard Wood, Met Office Hadley Centre, and Craig Wallace, National Oceanography Centre

The climate of the UK is influenced by its proximity to the North Atlantic Ocean. The ocean acts as a buffer, absorbing heat in the summer and releasing it in the winter, and so moderating the seasonal cycle of temperature. The ocean also supplies moisture to the atmosphere, some of which falls as precipitation over the UK. These climatic influences are expected to continue under plausible scenarios of climate change.

A further influence of the ocean, which is susceptible to change in future, comes from the *Meridional Overturning Circulation* in the North Atlantic (MOC, sometimes less precisely referred to as *thermohaline circulation*, *conveyor belt circulation* or *Gulf Stream circulation*). Surface circulation in the North Atlantic brings warm and relatively salty water northwards from the subtropics. During transit northward, some of the heat is lost to the atmosphere, particularly in the Northwest Atlantic and Nordic Seas. The resulting cold, salty (and hence dense) water sinks and returns southwards several kilometres below the surface. The MOC thus supplies heat to the atmosphere at higher latitudes.

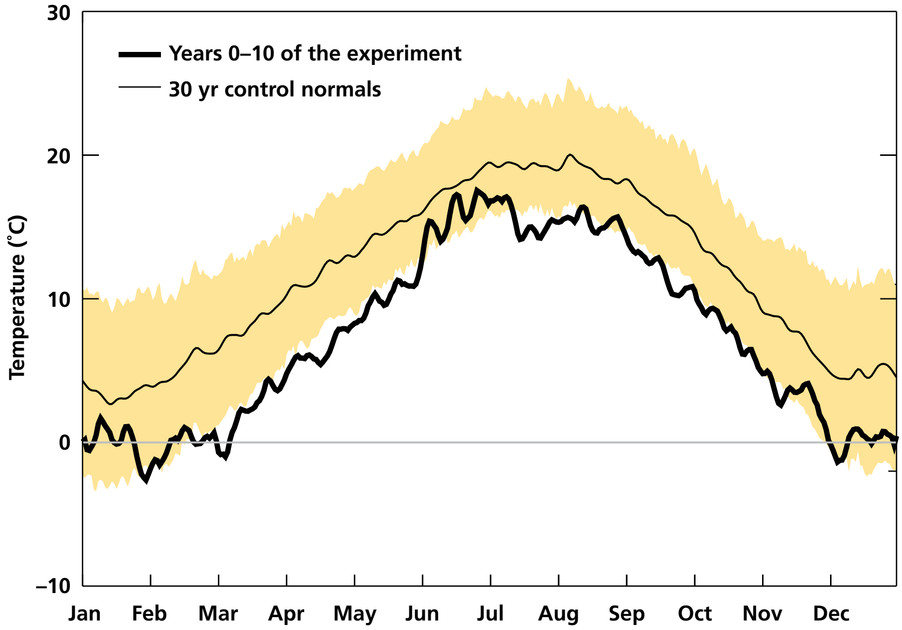


Figure A5.1: Daily maximum Central England Temperature from an experiment using the HadCM3 model in which the MOC is artificially switched off (thick curve). Average values over the 10 yr immediately following the switchoff are shown. This is compared with the same quantity in a control run (thin line), with the 5th and 95th percentiles shown by shading. Greenhouse gases are fixed at pre-industrial values in both model runs. Note that the temperatures are derived directly from the global model without downscaling. From Vellinga and Wood (2002).

The effects of the MOC on climate can be estimated using model simulations in which the MOC is artificially switched off by adding fresh water to the North Atlantic. Figure A5.1 shows the modelled impact of a THC shutdown on daily maximum Central England Temperature, relative to the preindustrial climate. A cooling of around 4°C is seen on average, somewhat more in winter than in summer. In spring and autumn this means that the average daily maximum is less than the coldest 5% of days in the pre-industrial climate.

The model also suggests that without the MOC precipitation would be reduced (by around 20% in both summer and winter, averaged over Western Europe as a whole), but that in winter over high ground more precipitation could fall as snow. The MOC also affects regional sea level by redistributing water within the global ocean (without any change in the global average sea level); without the MOC sea level could be around 25 cm higher over some parts of the UK coastline.

Climate models suggest that the MOC will weaken gradually in response to increasing greenhouse gases (see section below). The effects of such a weakening are included in the UKCP09 projections. However concerns have been raised that the MOC might undergo a more rapid decline, or pass a threshold beyond which it will eventually shut down effectively irreversibly. These concerns are based on a range of modelling and theoretical results and on palaeoclimatic evidence. A number of climate models have an MOC that can exist in both a strong, positive state (as today), and in a weak or reversed state. In many of these, if large scale patterns of precipitation and evaporation strengthen beyond a certain threshold, only the weak/reversed state can exist. A number of abrupt changes to the climate of the North Atlantic and adjacent regions in the past have been linked to fluctuations in the strength of the MOC, believed to have been driven by changes in regional fresh water input. Two marked episodes of rapid change, the *8.2 kyr Event* and the *Younger-Dryas Event*, occurring approximately 8200 and 13,000 yr ago respectively, are particularly apparent in recovered ice and sediment core records (e.g. Taylor *et al.* 1997; Thomas *et al.* 2007). Regional temperatures over Greenland are known to have fallen, by ~6°C during the 8.2 kyr Event and by as much as ~15°C during the Younger Dryas Event. Recent work (e.g. Ellison *et al.* 2006) continues to support the hypothesis that the 8.2 kyr Event was driven by the abrupt discharge of fresh glacial melt water from two dammed lakes over continental North America, Agassiz and Ojibwa. In both these past cases, there was more fresh water locked up in land ice than at present, so these periods may not be exact analogues of the present day, but the palaeoclimatic evidence does point to the sensitivity of the MOC to fresh water input.

Since UKCIP02, progress has been made in both observations and modelling of MOC changes.

A5.2 Is the Atlantic Meridional Overturning Circulation changing?

A number of recent observational studies have attempted to detect signs of recent changes in the MOC. One assessment (Bryden *et al.* 2005) suggests that the overall MOC strength may have decreased by approximately 30% since 1957 (Figure A5.2). However, the sparse nature of the observations used in this study (5 measurements over 5 decades), the possible errors of these observations and the large day-to-day variability of the MOC recently discovered (Cunningham *et al.* 2007; Kanzow *et al.* 2007) highlight the need for additional data to support this conclusion. Furthermore, analyses using Atlantic sea surface temperature patterns as an indirect measurement of MOC strength also conflict with the conclusion of Bryden *et al.* (2005), citing the recent warming seen in the North Atlantic as indication of a stronger MOC during the 1990s (e.g. Latif *et al.* 2006; Knight *et al.* 2005), although this indirect observational method is based on links identified in climate models rather than directly from observations.

Additional observations farther north also provide evidence for widespread change or variability. For example whilst some studies indicate that, in recent decades, the transport of deep water, forming the return leg of the MOC, through the Faroe Bank Channel (and farther downstream e.g. Bossenkool *et al*. 2007) has decreased by approximately 20% compared to 1950 estimates (Hansen *et al.* 2001), more recent observations (Østerhus *et al.* 2008) call such a trend in to question. Recent large scale freshening of the high latitude North Atlantic, including deep water flowing through the Faroe Bank Channel, has also been the subject of much research (e.g. Dickson *et al.* 2002) but neither the mechanisms of the freshening, nor a clear link with MOC changes, have been established.

In addition to the Faroe Bank Channel, deep returning water also flows through the Denmark Strait, between Greenland and Iceland. Observations within (Macrander *et al.* 2005) and just south (Dickson *et al.* 2008) of the strait do reveal a weakening of the through flow between 1999 and 2003, but this is likely a feature of the natural year-to-year variability, rather than part of any longer-term trend. Deep water from both the Faroe Bank Channel and the Denmark Strait combines south of Greenland to form the Deep Western Boundary Current which is the primary return leg of the MOC south of ~55°N. Measurements of this unified current are also sparse, although comparison of what data is presently available (representing 1993–1995 and 1999–2001, respectively) reveals little change in transport (Schott, 2004).

Knowledge of whether or not the strength of the MOC is changing with time has been hampered to date by the lack of continuous, robust measurements. Since the last UKCIP02 report, however, considerable effort has been made to collate

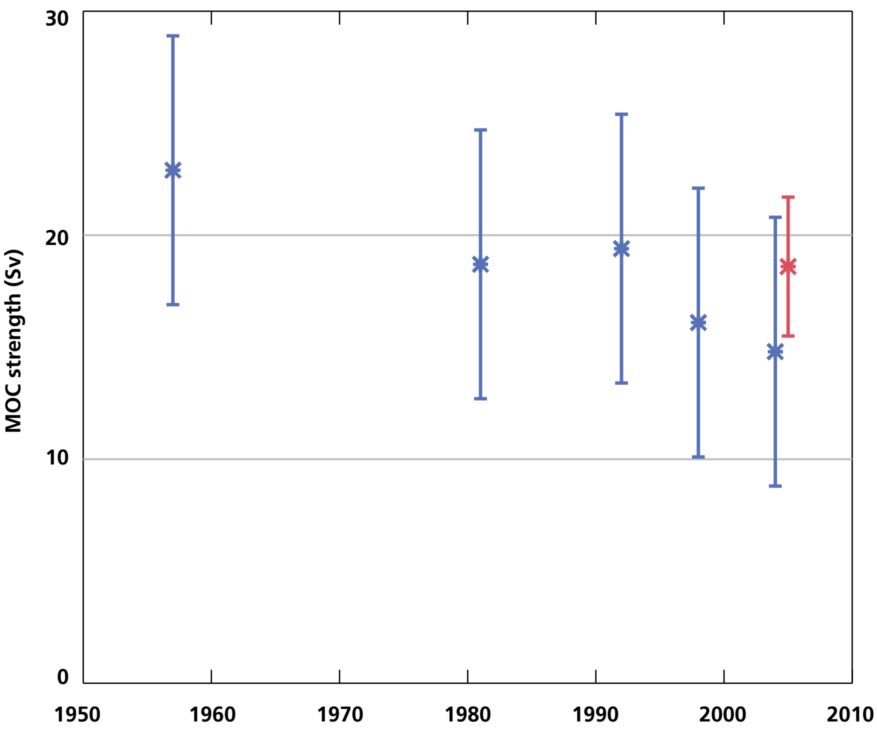


Figure A5.2: Estimates of observed Atlantic MOC strength (asterisks), and associated errors (bars), at ~26°N between 1957 and 2005. Blue denotes calculations incorporating ship-based observations of the free ocean (Bryden *et al.* 2005) whilst the final, red, point incorporates the first year's (April 2004–April 2005) continuous observations from the RAPID mooring array deployed in 2004. The quantity shown is transport in the top 1000 m of the ocean, with positive values indicating northward flow. Units are Sverdrups (1 Sv = 1 million cubic metres of water transported per second).

and analyse existing observations, for example via the ASOF* initiative, and a substantial UK-led monitoring programme, RAPID, has commenced, involving the installation of permanent moorings at a number of locations within the Atlantic Ocean (see http://www.nerc.ac.uk/research/programmes/rapid/). Initial results (Cunningham *et al.* 2007; Kanzow *et al.* 2007) have confirmed the ability of this system of moorings to monitor the MOC to a high degree of accuracy. As the time series accrues to a statistically meaningful length scientists will be able to comment with more certainty on whether any long term change is underway.

A5.3 Projections of future changes in the Atlantic circulation

Recent projections, using a new generation of climate models, support the assessment presented in UKCIP02 and suggest that the MOC will weaken gradually in response to increasing greenhouse gases. The models examined in the IPCC AR4, excluding those with a poor simulation of the present day MOC, suggest reductions of between 0 and 50% in the MOC by 2100, under the SRES A1B (UKCP09 Medium) emissions scenario. An ensemble of HadCM3-based coupled models, similar to the one used to generate the UKCP09 probabilistic projections, shows a slightly narrower range of weakening under an idealised scenario of CO_2 increase (Figure A5.3). The effects of the gradually weakening MOC on UK climate are included in the UKCP09 climate projections.

No comprehensive climate model, when forced with one of the SRES emissions scenarios, produces a complete or abrupt MOC shutdown in the 21st century,

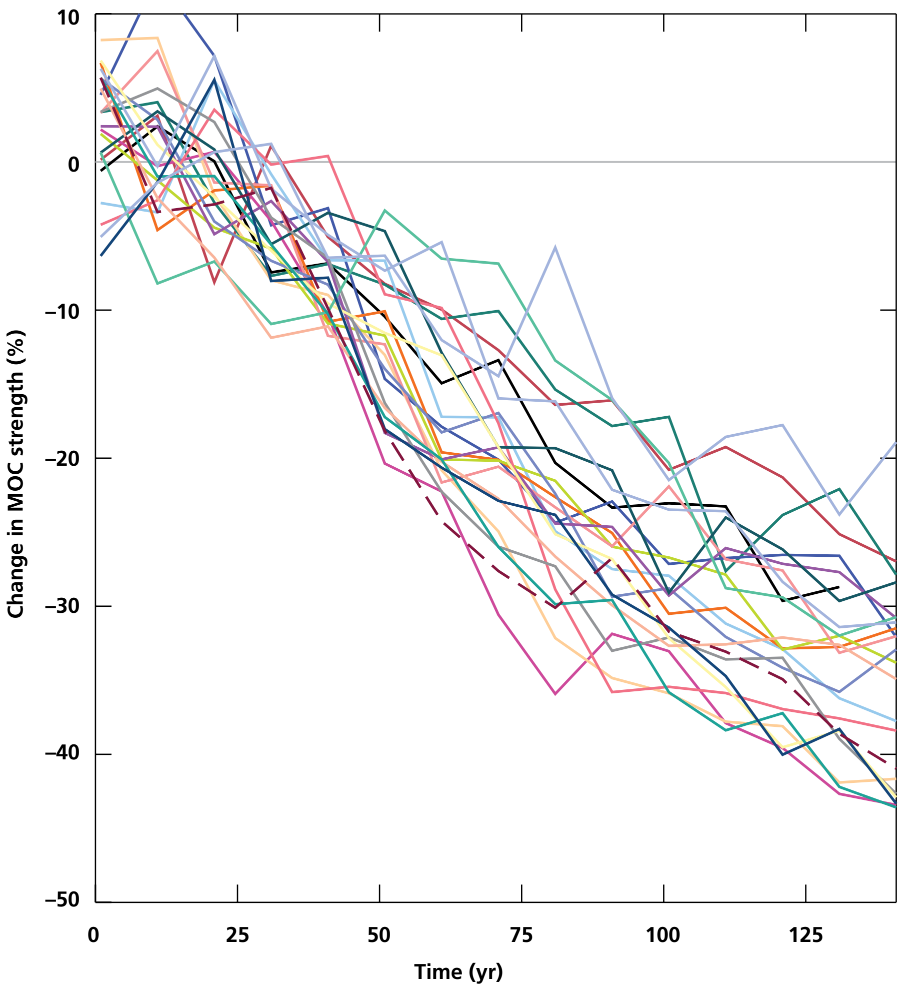


Figure A5.3: Model simulations of the change in MOC strength under an idealised 1%-per-annum increase of CO_2 concentrations. Twenty-two simulations are shown, from a HadCM3-based perturbed physics ensemble similar to the one used to generate the UKCP09 projections. MOC change is expressed as a percentage of its value in the corresponding control run. (Courtesy M. Vellinga.)

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* Arctic-Subarctic Ocean Fluxes http://asof.npolar.no

consistent with the models shown in Figure A5.3. However models in general do not allow for the possibility of increased fresh water supply due to rapid ice flow from the Greenland ice sheet, which has been observed in recent years; such extra fresh water could result in further MOC weakening. The simulations of rapid MOC changes that have been seen generally come from less complex climate models; such models are computationally cheaper and so the range of possible behaviours can be explored more fully than with the comprehensive climate models used in UKCP09, but, being simpler, the models may omit key processes affecting the stability of the MOC.

Assessing the evidence overall, the IPCC AR4 concludes that it is very likely (>90% chance) that the MOC will weaken gradually over the 21st century in response to increasing greenhouse gases, but very unlikely (<10% chance) that an abrupt MOC change will occur in that time. Longer term changes cannot be assessed with confidence at this stage.

The effects of any rapid MOC changes (beyond the expected gradual weakening seen in most climate model simulations) would be superimposed on any man-made global climate change that had already taken place. Some of the MOC effects, for example any cooling over the UK, would oppose those due to man. Others, however, would reinforce the global man-made signal — for example additional summer drying, and sea level rise reinforcing that due to thermal expansion.

The figures derived from hypothetical MOC shutdown experiments such as those discussed above show that an MOC shutdown, while very unlikely, could produce climatic effects as large as, or larger than, the effects of increasing greenhouse gases. Thus research to improve our understanding of the probability of such events, and to improve the prospects for early warning, continues to be a priority. Recent developments in both models and observations have improved our fundamental understanding of what controls the MOC, and in time this can be expected to narrow the uncertainty over the future of the MOC.

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Annex 6: Future changes in storms and anticyclones affecting the UK

A6.1 Introduction

Simon Brown, Met Office Hadley Centre

It has not been possible to produce probabilistic projections of changes in frequency, strength and location of future storms and anticyclones (often called *blocking* events) — collectively known as synoptic-scale (that is, weather system) variability. This is due to the reasons discussed in Chapter 3, Section 3.3, namely that large differences are found between projections from the Met Office perturbed physics ensemble and those from a multi-model ensemble of alternative climate models (see Figure A6.2). This implies that attempts to construct probabilistic projections would be too dominated by the contribution arising from structural model errors (see Section 3.2.8) to be considered robust. Furthermore, the required storm tracking statistics from other models are not available in any case, thus precluding the use of the UKCP09 methodology (described in Chapter 3) to produce PDFs for this metric. However, storms and blocking events are explicitly modelled in climate models, and the impacts of such synoptic-scale variability and potential changes are considered in the production of PDFs of mean and extreme climate shown elsewhere in this report. Each of the models used in the ensembles which underlie the PDFs, both the perturbed physics and the multi-model, simulate storms and blocking and their integrated impact on those mean and extreme conditions. In addition, the PDFs are constrained by the large-scale observed fields of climate which are partly determined by synoptic-scale variability. In short, the effects of synoptic-scale variability, including potential changes, are taken into account.

Useful information can be gleaned from examination of the present day and future synoptic-scale variability simulated by the Met Office ensemble of 17 HadCM3 experiments (described in Chapter 3, Section 3.2.4) and a multi-model ensemble consisting of 20 alternative coupled models, all using the same SRES A1B (UKCP09 Medium) emissions. Preliminary analysis of these ensembles suggests that the simulated future changes in storms, and their impact on mean climate conditions, are rather modest. Subtle shifts in the position of the North Atlantic storm track are possible, but are inconsistent between different models and different model variants. The frequency and strength of storms remain relatively unchanged in the future simulations, as does the frequency and strength of blocking events. It must be borne in mind, however, that these two ensembles sample a smaller range of uncertainty than do the UKCP09 projections. The IPCC AR4 assessment concluded that the majority of current climate models show a poleward shift of the storm tracks, with some indication of fewer, but deeper, depressions. This can only be concluded when looking at the hemispheric scale;

the UK is very much smaller than this scale and any climate change signal is swamped by natural variability and sampling uncertainty resulting in a lack of any robust signal of changes for the UK.

It is clear from an examination of the model output that, as in the case of previous studies, (e.g. Carnell and Senior, 2002) the main drivers of regional climate change in the UK are thermodynamic in nature, that is, arising directly from the additional man-made greenhouse heating. These processes are sampled by both the HadCM3 perturbed physics ensemble and the multi-model ensemble and constrained by the observational data used in generating the PDFs. Changes in climate that may be attributed to changes in synoptic-scale variability are a relatively small component. That is not to say however that, as models improve in the future that the role of changes in storms and blocking events might become more important. There is a possibility that such non-linear climate change could occur, but based on the current level of understanding and the current ability of climate models, there is no evidence for this.

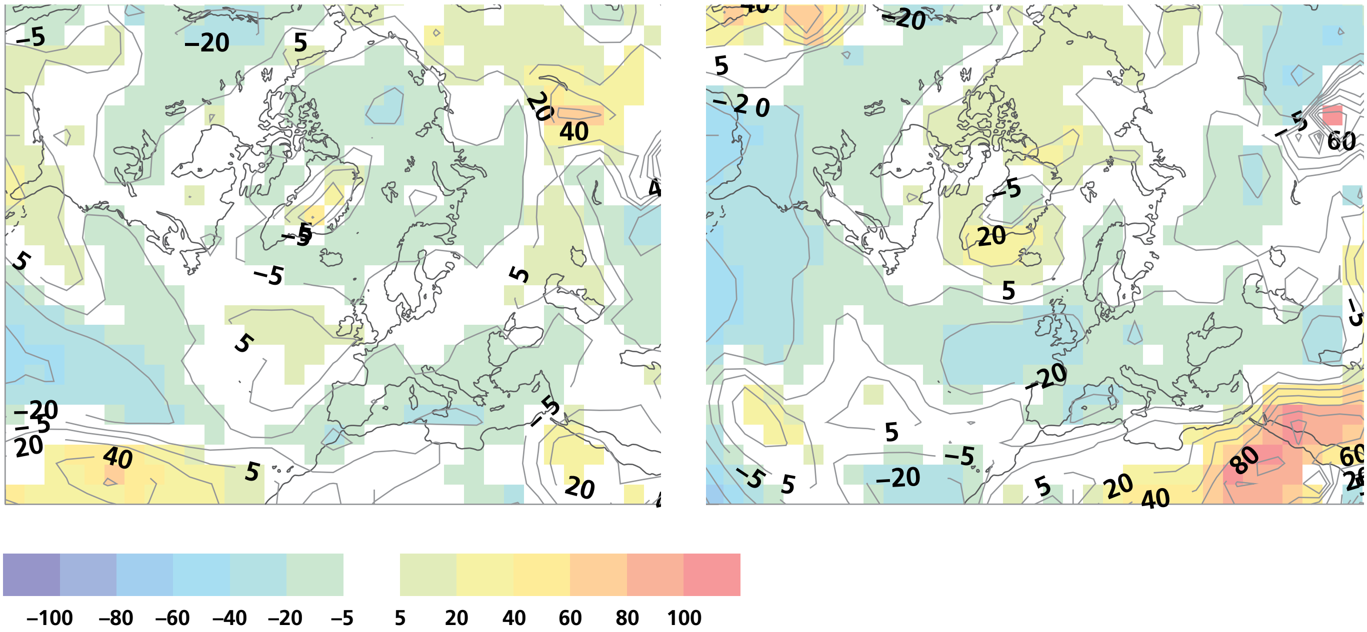
In the sections below we look at changes in storm tracks and blocking from both the 17-member Met Office GCM perturbed physics ensemble and the multi-model ensemble of other climate models.

A6.2 Future changes in mid-latitude depressions

Characteristics of mid-latitude North Atlantic depressions are assessed using two metrics* based on patterns of atmospheric pressure at the surface or at a height of about 2 km (away from the disturbing influence of the ground). As was found from validating the storm climatology of the models (see Annex 3), the different metrics can give a different picture for future changes, although to a lesser degree.

Considering the first metric applied to the 17-member Met Office GCM projections, for most of the UK the storm tracking results suggest little change (<5%) by the 2080s in the number of storms that occur in all seasons except summer where

Figure A6.1: Changes in storm track density (% change) for winter (left) and summer (right) from the HadCM3 ensemble.



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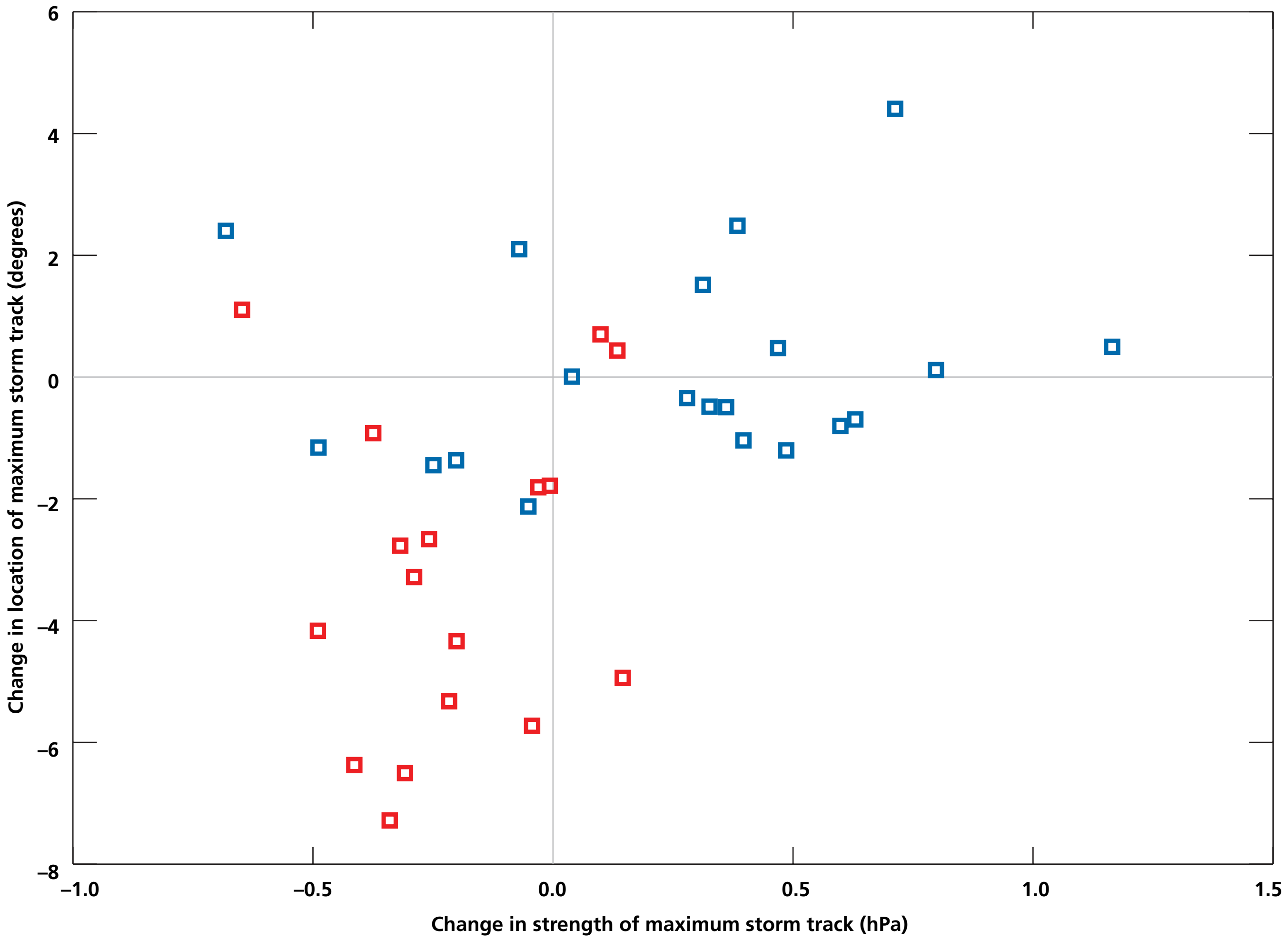
* Specifically (1) the tracking of positive 850 hPa vorticity anomalies and (2) band pass filtered (BPF) daily mean sea level pressure (MSLP).

the ensemble mean shows a reduction of ~20% (Figure A6.1). There is also a suggestion that the south east may see modest reductions in spring and autumn (not shown).

The second metric (not shown here) also suggests little change in winter, spring and autumn, and a reduction in summer. Figure A6.2 shows changes, derived from the second metric, from (1961–1990) to the 2080s under the Medium Emissions scenario, in the location and strength of the storm track over the UK in winter, from both the HadCM3 17-member perturbed physics ensemble and a multi-model ensemble of 20 other climate models. Taking changes between periods removes the climatological biases in the storm track locations from each ensemble member, allowing assessment of the general tendency of the models. The HadCM3 ensemble shows relatively small, and generally negative, changes in the strength of storms, and most of them show a southerly shift in the storm track, up to 7° of latitude. On the other hand, projections from the multi-model ensemble of other climate models for this metric suggests relatively little shift in the storm track but a wider range of, generally positive, changes in strength.

It should be recalled from Annex 3, Figure A3.6, that current positions and strengths of the modelled storm track do not always agree well with observations, and this should be taken into account when assessing the credibility of their future projections. The HadCM3 ensemble shows a better agreement in present day location than most other climate models, and a reasonable agreement in strength.

Figure A6.2: Change in location (degrees latitude) and strength (hPa) of maximum storm track over the UK for winter. The red squares are from the 17-member HadCM3 perturbed physics ensemble; the blue squares are from an ensemble of other international climate models.



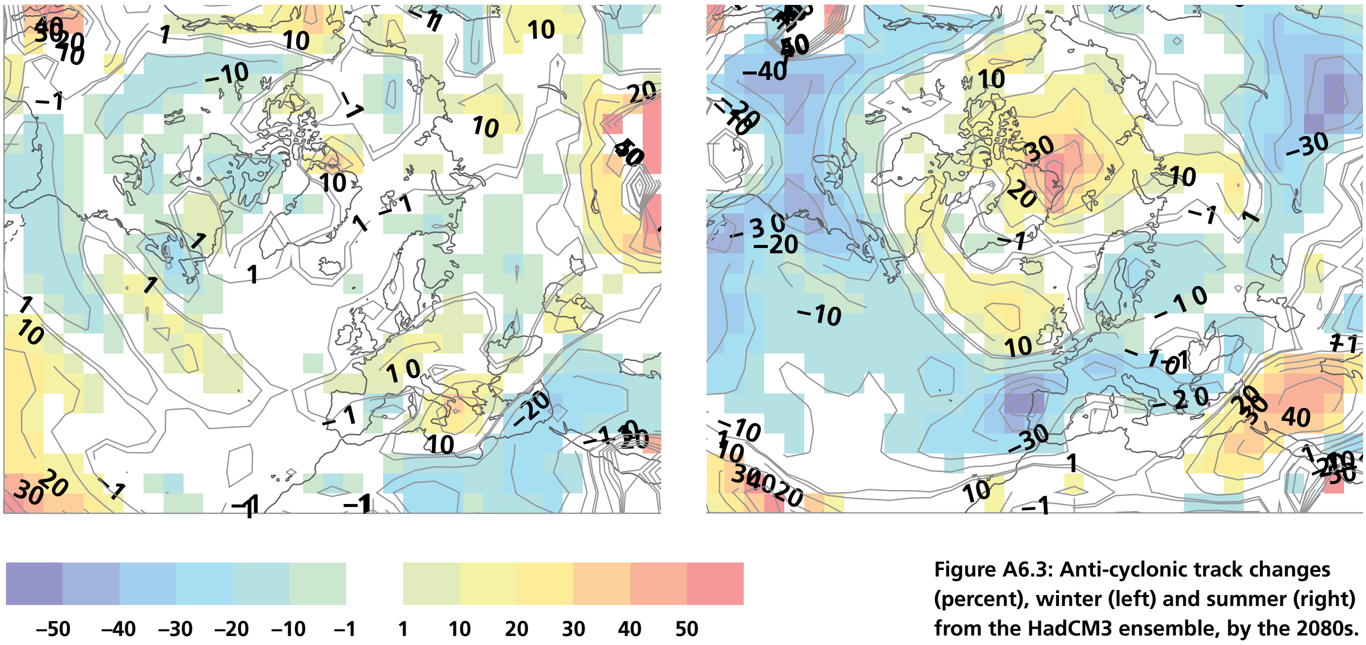


Figure A6.3: Anti-cyclonic track changes (percent), winter (left) and summer (right) from the HadCM3 ensemble, by the 2080s.

A6.3 Future changes in blocking

The strength of anticyclones over the UK, and their duration, are important influences on runs of hot days and high air pollution levels. We diagnose changes in anticyclonic blocking characteristics using three different metrics,* again involving pressure patterns at the surface and higher in the atmosphere. The projected future changes in these three metrics is diverse.

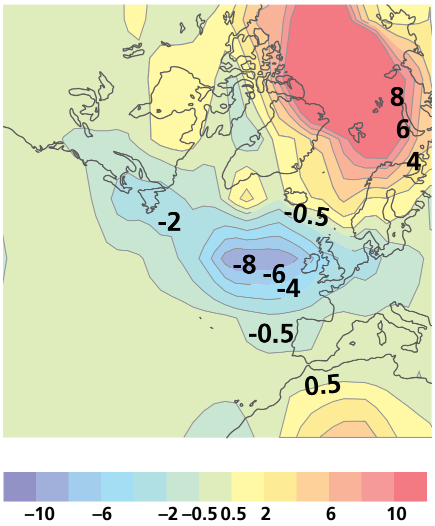


Figure A6.4: Change in number of days with blocking lasting 7 days, summer from the HadCM3 ensemble, by the 2080s.

Using the first metric, analysis of the 17-member HadCM3 ensemble suggests there will be 10–20% fewer anti-cyclones over the continent and southern England in summer and similar increases over the northern Atlantic possibly affecting northern UK (Figure A6.3). For winter there is little change.

Using the second metric, an index corresponding to 7-day blocking events in summer, again using the HadCM3 ensemble, shows a centre of decrease west of Ireland affecting the whole of the UK (Figure A6.4).

Changes determined by the third metric, from the filtered analysis of surface pressure, for both the perturbed physics ensemble of HadCM3 and the ensemble of other climate models, are shown in Figure A6.5. For the UK as a whole reductions in anticyclones** in summer (Figure A6.5, bottom) are projected by both ensembles. This is also seen in autumn, with smaller reductions in spring (neither shown). No clear agreement on change in winter is seen, from either the HadCM3 or the alternative model ensembles (Figure A6.5, top).

As these three metrics represent different aspects of the climate system it is perhaps not surprising that the future changes are not that similar, implying that it is difficult to characterise future changes with a single diagnostic but that metrics specific to each impact are required.

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* These are (1) tracking negative 850 hPa vorticity anomalies, (2) persistent 500 hPa height anomalies (PA) lasting 7 days and (3) low pass filtered (LPF) daily mean MSLP.

** Note that this metric, although dominated by changes in anticyclones, could also be influenced by other slow-moving weather systems.

A6.4 Summary

There is no consistent signal of change in either storms or blocking near the UK in either the ensemble of Met Office models or the ensemble of alternative models. Such changes as are seen are relatively modest, and the potential for substantial changes appears to be small.

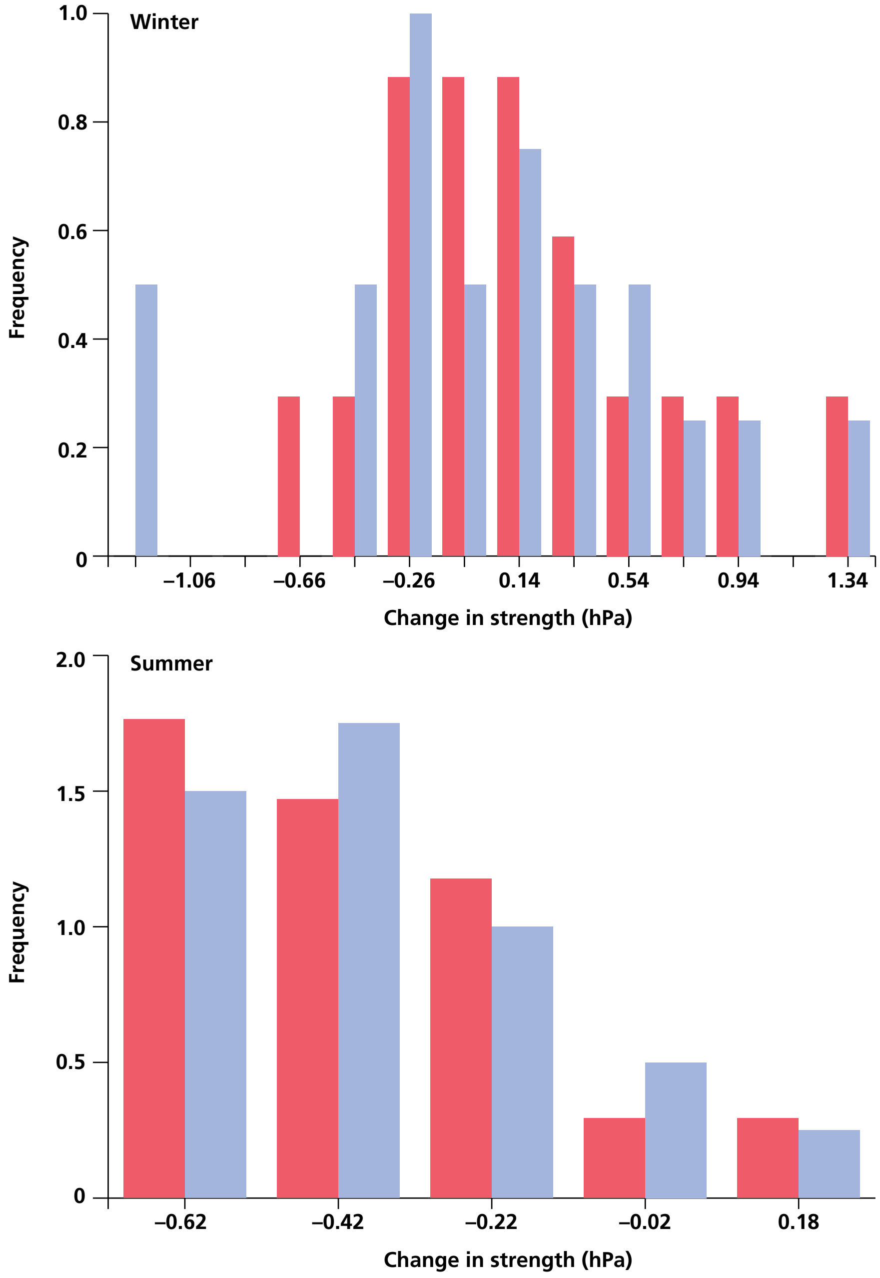

Figure A6.5: Distribution of changes in anticyclone strength for winter (top) and summer (bottom) averaged over the UK. Blue bars are from the multi-model ensemble of other climate models; red bars are from the HadCM3 perturbed physics ensemble.

A6.5 Reference

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Annex 7: Urban heat island effects

A7.1 Causes of the Urban Heat Island and observations

Rob Wilby, University of Loughborough, Richard Betts and Mark McCarthy, Met Office Hadley Centre

There is growing recognition that the populations, infrastructure, and ecology of built environments are potentially vulnerable to climate change (Wilby, 2007). However, built-up areas also exert significant influences on their local climates, with an *Urban Heat Island* (UHI) being observed in many cities. This is due partly to the influence of the urbanised landscape on the surface energy budget and local meteorology, and partly from sources of heat arising from human activities (*Human Energy Production*, HEP). The nature of the land surface is a key factor influencing the sensitivity of near-surface climates to increasing greenhouse gas concentrations, so the responses of urban climates may be different to those of non-urban climates. Urban areas generally feature a less porous surface than non-urban areas, promoting the removal of precipitation via surface runoff and channelling away through drains, instead of water soaking into the soil. There is also a limitation on evaporation of soil moisture due to built-over surfaces. Both of these limit the evaporation of moisture which is a key factor in the local climate response to warming. Furthermore, the large heat capacity of the built environment causes heat to be stored during the day and released gradually overnight, increasing night-time temperatures in comparison with non-urban area.

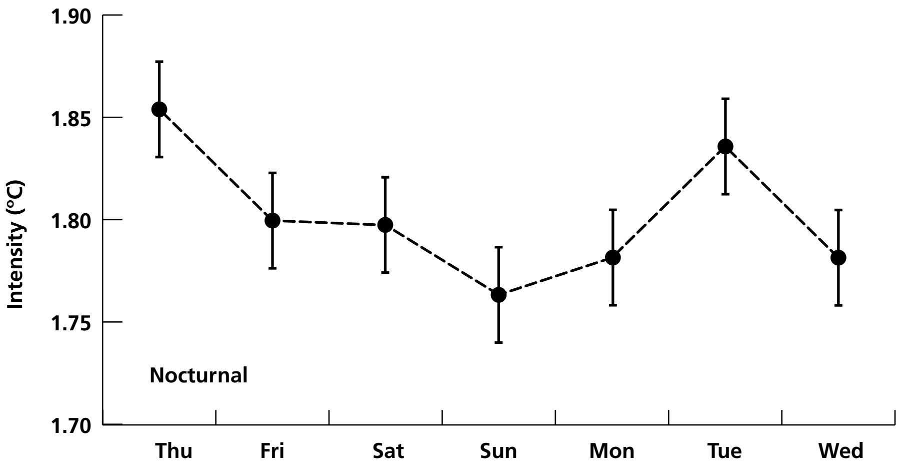

Figure A7.1: Variations in the intensity of London's nocturnal UHI by day of the week reveals a measurable HEP. Sources of artificial heat production (including space heating, air conditioning, transportation, cooking and industrial activity) would be expected to vary on a weekly basis, attaining a minimum at weekends. Assuming that weather patterns are the same regardless of the day of the week, the temperature difference between urban and rural areas should, therefore, be a minimum on Sundays — this is indeed the case. The weekly component amounts to ~0.1°C variation compared with an average nocturnal UHI of 1.8°C throughout the year. Source: Wilby (2003a).

Moreover, increases in anthropogenic heat sources may exert an additional direct forcing of local climates (Figure A7.1). The global total HEP heat flux is estimated as 0.03 Wm^{-2} (Nakićenović *et al*. 1998); although this is a very small influence at the global scale, it may be important for local climate changes in cities (Crutzen, 2004; Forster *et al*. 2007). The annual average HEP over Greater London is estimated from energy use statistics as 11 Wm^{-2}, rising to 57 Wm^{-2} in Westminster, and exceeds 100 Wm^{-2} in some specific areas (Greater London Authority, 2006). (This compares with an annual average net shortwave solar heat flux of ~100 Wm^{-2} over southern England, although this may be up to ~300 Wm^{-2} in July.) Temperature measurements taken at an inner city (St. James Park) and suburban site (Wisley in Surrey) suggest that London's nocturnal UHI has intensified by approximately 0.5°C since the 1960s (Wilby, 2003a), partly as a consequence of HEP, increased urbanization, and changing frequency of weather patterns.

A7.2 Future changes in the Urban Heat Island

The regional climate model used in UKCP09 include a scheme which represents the land surface within each 25 km gridbox as a uniform surface, with physical properties determined by parameter values representing the *average* character of the different land surface types within that gridbox (Cox *et al*. 1999). However, the surface types are defined using a land-surface dataset at a 1° x 1° latitude–longitude resolution (Wilson and Henderson-Sellers, 1985). At this resolution there is no contribution from urban surface types, so the Met Office RCM does not include any influence of the urban surface on climate. Furthermore, the RCM does not include heat storage during the day and heat release at night by buildings, or HEP as a term in the surface energy balance. Thus the UKCP09 projections will not take into account changes to any of the factors, outlined in Section A7.1, which could change the intensity of the UHI. If none of these factors were to change, or changes were not significant, then the UHI would not change, and it would be reasonable to add UKCP09 projections of temperature change to an observed baseline urban climate to obtain an urban climate of the future.

In applications of the UKCP09 model output, some account of urban effects could be taken by using statistical downscaling techniques calibrated against data which included urban influences. Previous work has shown that the intensity of the UHI is stronger under the low wind speeds, high sunshine, and low humidity conditions typically associated with stagnant high pressure situations (Wilby, 2003b; McGregor *et al*. 2006). For example, Figure A7.2 shows the strong correlation between the occurrence of anticyclonic weather over Eastern England in summer and the frequency of intense UHI episodes. Assuming

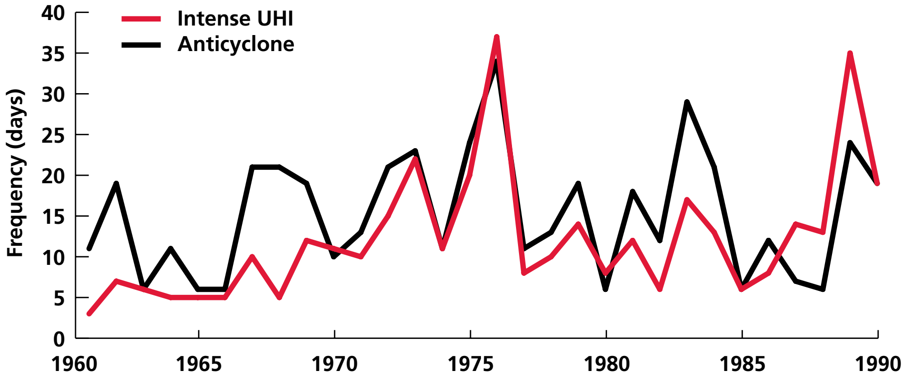

Figure A7.2: The observed frequency of intense nocturnal heat island episodes (>4°C temperature difference between urban and rural sites) and days with anticyclonic weather over London 1961–1990.

that these downscaling relationships hold under future climate conditions, any changes in circulation during the summer (see Annex 6) would have the potential to intensify UHI by a further 0.5°C by the 2020s (Wilby, 2008). Although there are subtle differences in UHI projections downscaled from different GCMs, all point to continued intensification of London's nocturnal UHI and a greater frequency of intense heat island episodes in summer (see Wilby, 2008). These changes are set against a background of more persistent and intense heatwaves over much of Europe and the USA signalled by other studies (e.g., Meehl and Tebaldi, 2004).

Betts and Best (2004) showed that if the HEP remains unchanged over time, statistical downscaling could be viable. However, if the HEP changes in the future, as is possible under different population and energy consumption patterns, statistical downscaling calibrated against the present-day may no longer be valid. For example, Betts and Best (2004) showed that tripling the HEP from 20 Wm^{-2} (similar to that of the inner London boroughs) to 60 Wm^{-2} (the Westminster value) significantly altered the average UHI and increased the frequency of extreme UHI events. Even if the HEP is unchanged, statistical downscaling would have to be performed using predictors drawn from the suite of reliable variables in UKCP09 (including air temperatures, precipitation, relative and specific humidity, cloud cover, short-wave radiation and mean sea level pressure). Low confidence in important predictors such as wind speed, and in joint probabilities with other variables, mean that outputs from UKCP09 are unlikely to support conventional statistical downscaling models based on these data. However, probability distributions of changes in predictors such as mean sea level pressure could be used to perturb baseline pressure data and hence estimate sensitivity of simple indices of the UHI (like the frequency of intense heat island episodes shown in Figure A7.2) to changes in atmospheric circulation alone.

Further development of the HadRM3 regional climate model used in UKCP09 is underway to incorporate an updated land surface scheme which simulates separate surface energy balances for the different land surface types, including urban, within a gridbox. This should allow a more realistic representation of the surface temperature and humidity over each land surface type, including a more realistic response to climate warming. A heat capacity term allows for diurnal heat storage and release over the urban land surface, and an additional HEP term allows for the inclusion of this as an input. All these features have been shown to improve the representation of temperature in urban areas in the model, and should facilitate a more realistic representation of the change in urban temperatures over time in response to changes in urban character and extent.

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- Monitor climate variability and change at global and national scales, and use models to attribute recent changes to specific factors such as human activity.
- Quantify and reduce uncertainty in projections of climate change, particularly at a local scale and of extremes, and use this information to inform adaptation strategies.
- Define and assess the risk of dangerous climate change, whether gradual, abrupt or irreversible.
- Assess scientific aspects of options for mitigating climate change and its impacts.
- To advise government, business, the media and other stakeholders.

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ISBN 978-1-906360-02-3