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.

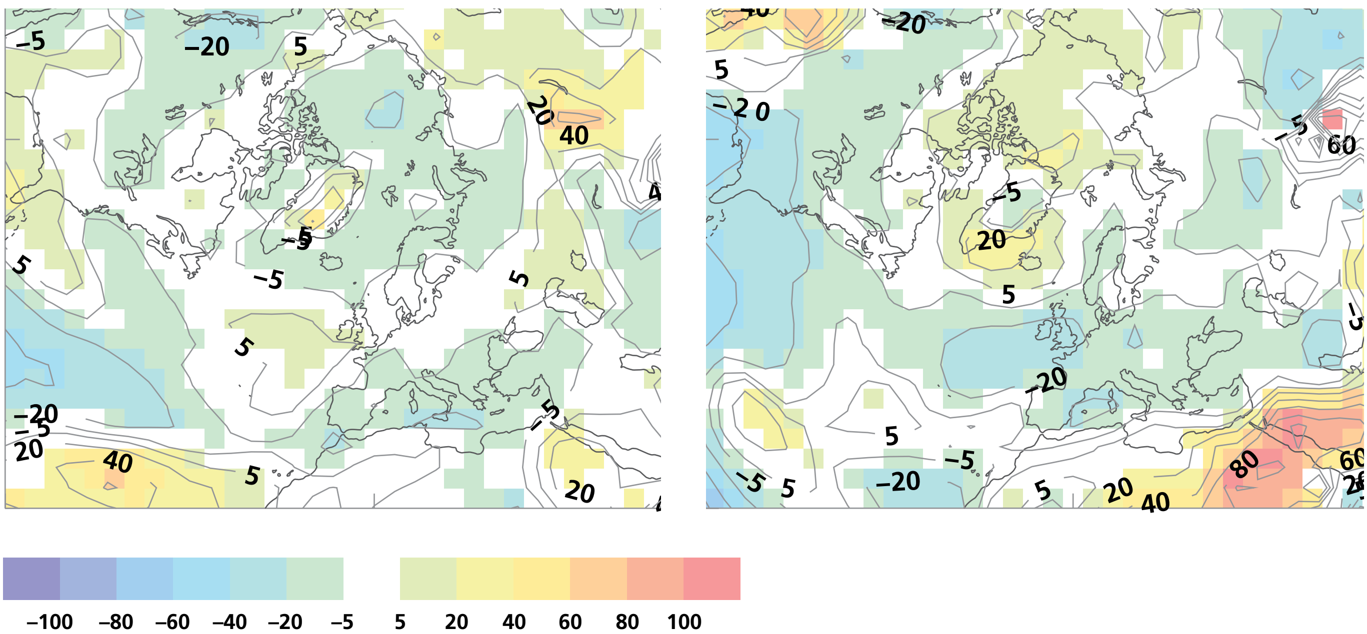
In the sections below we look at changes in storm tracks and blocking from both the 17-member Met Office GCM perturbed physics ensemble and the multi-model ensemble of other climate models.

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.



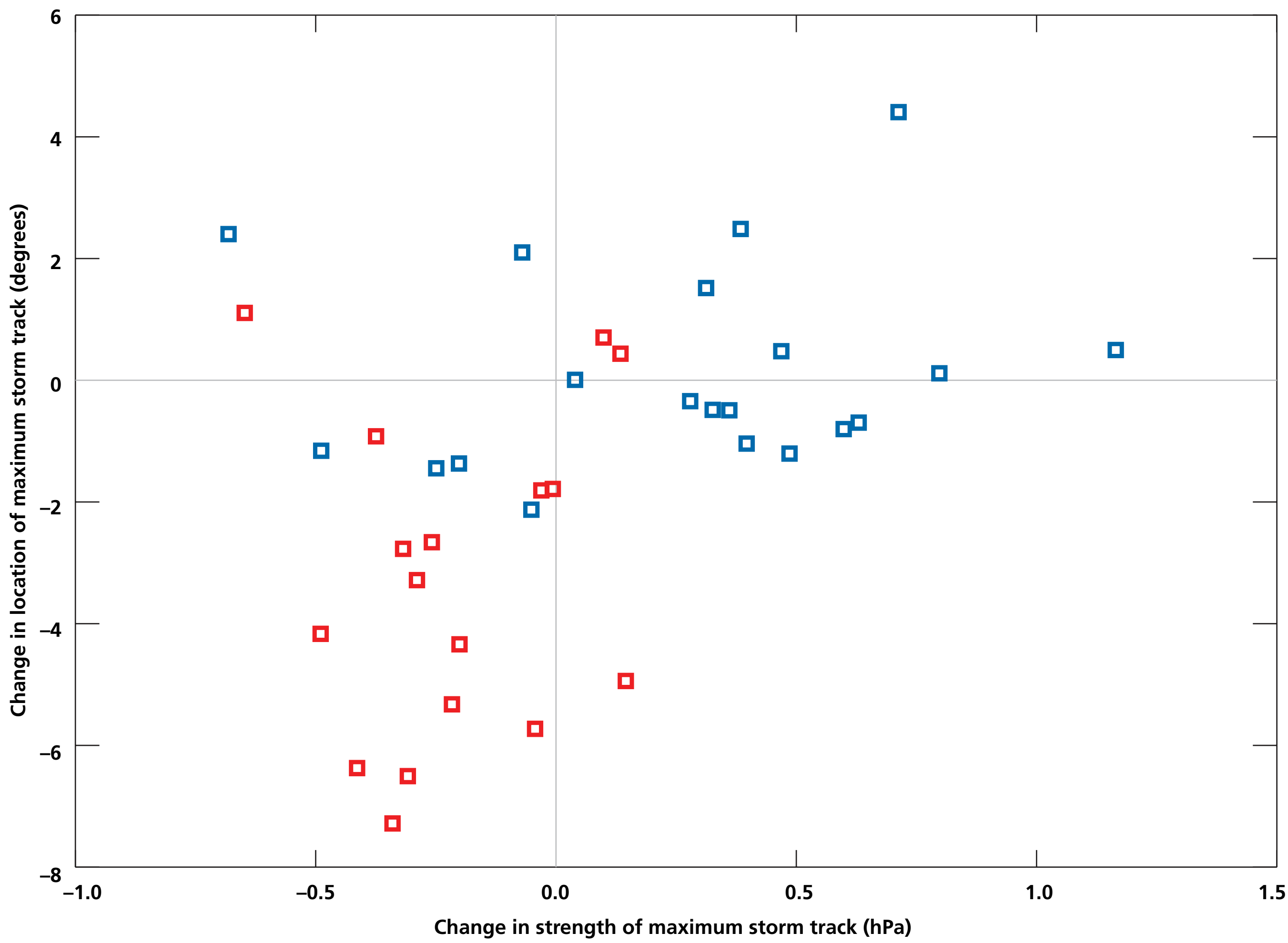
* Specifically (1) the tracking of positive 850 hPa vorticity anomalies and (2) band pass filtered (BPF) daily mean sea level pressure (MSLP).

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.



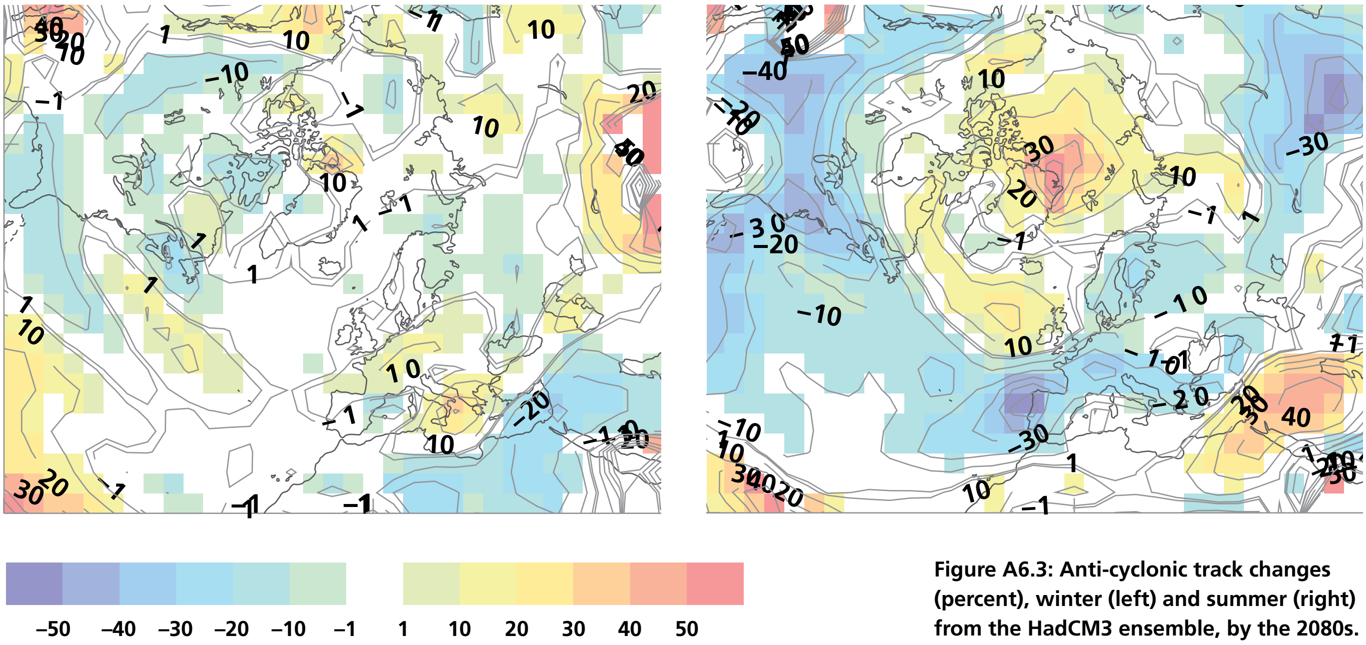


Figure A6.3: Anti-cyclonic track changes (percent), winter (left) and summer (right) from the HadCM3 ensemble, by the 2080s.

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.

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).

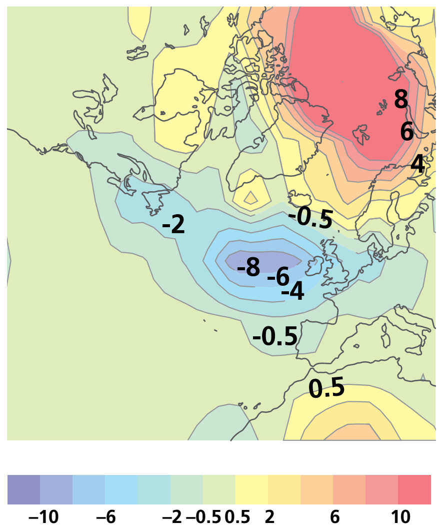


Figure A6.4: Change in number of days with blocking lasting 7 days, summer from the HadCM3 ensemble, by the 2080s.

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.

* 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.

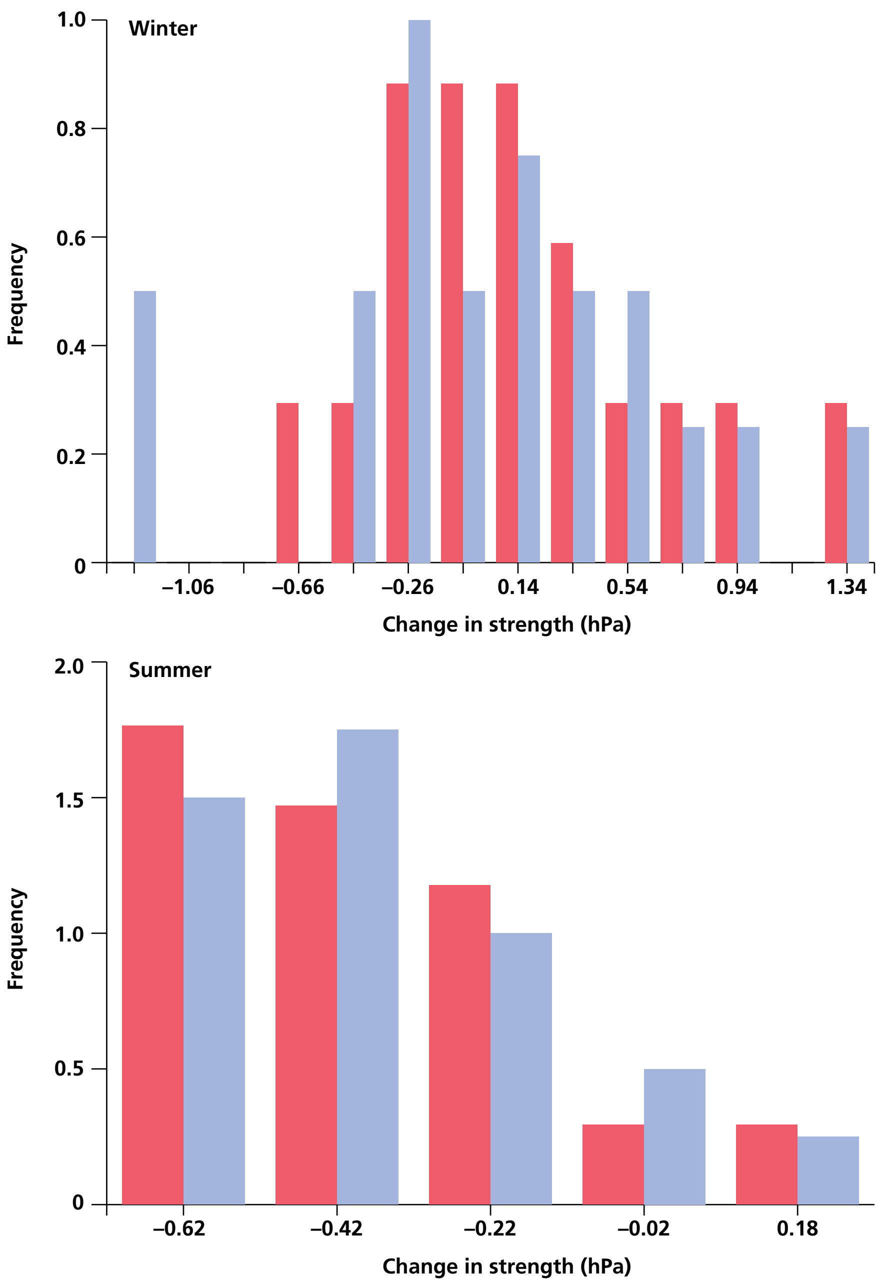


Figure A6.5: Distribution of changes in anticyclone strength for winter (top) and summer (bottom) averaged over the UK. Blue bars are from the multi-model ensemble of other climate models; red bars are from the HadCM3 perturbed physics ensemble.

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.

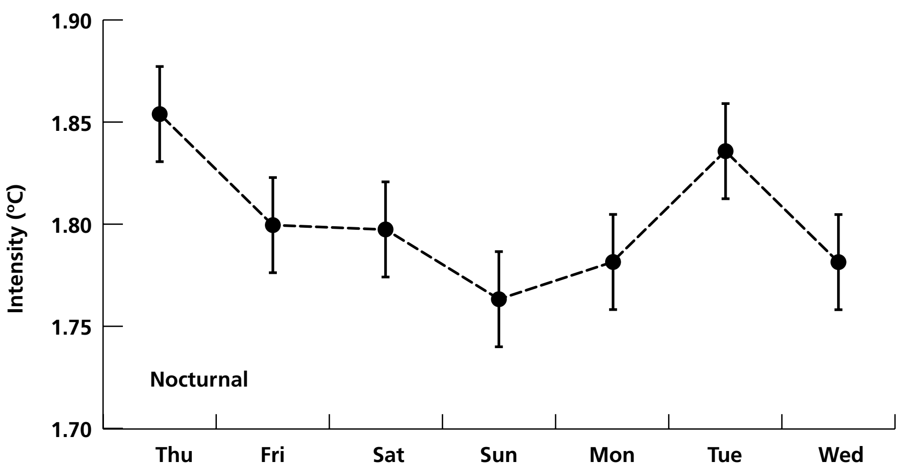

Figure A7.1: Variations in the intensity of London's nocturnal UHI by day of the week reveals a measurable HEP. Sources of artificial heat production (including space heating, air conditioning, transportation, cooking and industrial activity) would be expected to vary on a weekly basis, attaining a minimum 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

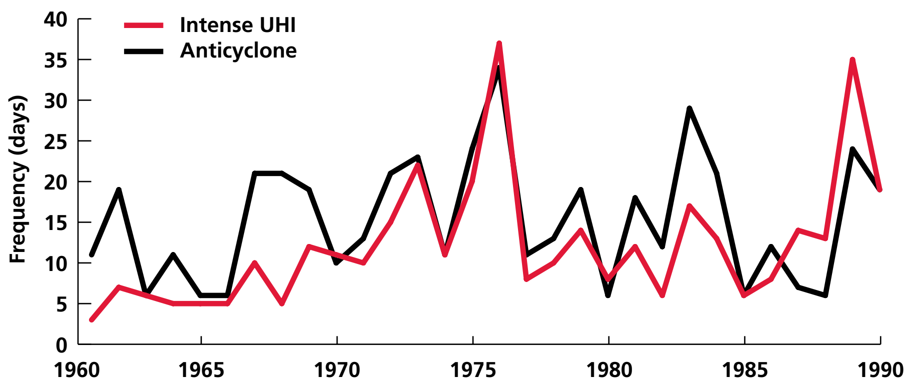

Figure A7.2: The observed frequency of intense nocturnal heat island episodes (>4°C temperature difference between urban and rural sites) and days with anticyclonic weather over London 1961–1990.

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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Department of Energy and Climate Change

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The Department of Energy and Climate Change brings together activities on climate change and energy policy and science from across Government. One of DECC's key objectives is to lead the global effort avoid dangerous climate change. To achieve this objective, it funds underpinning climate science and modelling work in the UK to provide the evidence necessary for Government to form robust policies on climate change mitigation and adaptation. The Department is the largest contributor to the Met Office Hadley Centre Integrated Climate Programme, which includes the modelling work for the UK Climate Projections.

Met Office Hadley Centre

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- Improve our understanding of climate and use this to develop better climate models.
- 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.
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