*THE EFFECTS OF CLIMATE CHANGE ON THE UK ROAD TRANSPORT SYSTEM

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ABSTRACT

Within the lifetime of present and planned Highways Agency (HA) assets significant changes are expected in UK climate. The HA is required to minimise the risk climate change poses to the strategic road network and has begun a programme of research aimed at understanding the impacts of climate change and planning revisions to Standards Specifications and Operating Procedures. Priorities for further investigation were identified and more detailed investigation has been undertaken into the impact of changes in extreme temperature and precipitation.

The analysis of historical data illustrates the possibility of a small increasing trend in extreme daily maximum temperature, in some regions, although any difference in extremes is within the range of standard error. Our analysis of climate model simulations, however, highlights the possibility of much larger changes in extreme temperature during the lifetime of present and planned HA structures. Therefore, existing design standards are likely to be adequate for the present day, but revisions should be considered due to the scale of changes that are possible during the lifetime of new structures.

Our analysis of extreme precipitation illustrates that the 20% contingency presently applied may be adequate for 1 and 5 year return period storms even up to the 2080's for a high emissions scenario, but uncertainties in climate model projections should be further assessed.

1. INTRODUCTION

The Highways Agency (HA) commissioned a programme of work to establish how climate change may impact upon the technical Standards, Specifications, and Operational Procedures (SSOPs) that it currently applies.

In the autumn of 2006 the HA in conjunction with the Met Office (the national meteorological service of the UK) undertook a Scoping Study to investigate the impacts of climate change on the assets and operations of the HA [1]. The scoping study assessed HA Standards Specifications and Operating Procedures against projected changes in UK climate and identified the following list as priority areas for future investigation.

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- High priority
  - Impact of changes in extreme -
    - temperature on HA assets
    - precipitation on drainage from roads and structures.
- Medium priority
  - Impact of climate change on earthwork stability and erosion.
  - Impact of climate change on HA operations.
  - Impact of changes in mean and extreme wind climate on the design and operation of bridges.

This study follows on from the Met Office scoping study and further investigates the likely effect of changes in extreme temperature and precipitation on HA assets.

The development of HA standards has traditionally been based on historical weather data. In a time of changing climate this approach is no longer robust. New maps illustrating the projected change in extreme temperature and extreme precipitation over the lifetime of present and planned HA assets have been produced. The new maps are presented and discussed in this paper. They represent the first step in assessing the need for updating the treatment of extremes in HA SSOPs.

The HA SSOPs that relate to temperature have been broadly assessed against the new maps. Several SSOPs refer to the use of extreme precipitation information in design of drainage systems and structures. New HA guidance in HD33/06 (design guidance produced by the HA) states that rainfall intensities used to calculate the design storm must include an allowance for climate change otherwise a contingency of a 20% increase must be applied. This guidance is assessed against the new maps.

2. BACKGROUND

2.1. Calculation of extremes and analysis of changes

Extreme Value Analysis (EVA) is a statistical technique that allows the calculation of the extremes of a distribution based on a limited number of observations. A variety of different distributions can be fitted to the data being considered. The distribution fitted will depend on the data themselves; different meteorological variables have different extreme characteristics. The choice of EVA distribution for each application is described in the relevant section. The outcome of applying an EVA to, for example, daily precipitation accumulations is the quantity of rain (mm) that may fall in an event with a specified return period.

To understand the impacts of climate change on the likelihood of an extreme event occurring, the following steps are taken:

- Define the present day extreme climate by conducting an EVA using the most up to date observation based data.
- Calculate the differences in extremes in modelled climate between the present day and projected future climate.
- The skill of the climate model can be assessed through a comparison between modelled current climate and observations.

2.2. Data Sources

2.2.1. Observations

Precipitation

The National Climate Information Centre at the Met Office has generated a new gridded observed precipitation data set for the period 1958 to 2002. The daily precipitation field for the UK has been generated, with a grid resolution of 5km, by averaging the numerous rain gauge station data [2]. The observational data set has been re-gridded to have a 50km resolution to match the resolution of the climate model.

Temperature

The National Climate Information Centre at the Met Office is in the process of producing a high resolution gridded temperature dataset from observations. This dataset is expected to be available by the end of 2007 and will be ideal for application in future EVA studies. It will be 5km resolution over the whole of the UK and will include daily maximum temperature data.

In the absence of any high resolution temperature data at this time, the most suitable gridded dataset for application in this study is HadGHCND (Hadley daily Global Historical Climatology Network Dataset), which covers the period January 1946 to December 2000, and includes daily maximum temperature. A major disadvantage of this data is the spatial resolution of 2.5° latitude by 3.75° longitude, or roughly 300km by 300km at UK latitudes. This means that England and Wales are represented by only three grid-boxes, roughly corresponding to S & E England, Wales & Midlands and N England & S Scotland. However, it includes more than 50 years of daily maximum temperatures, so offers some utility for understanding the baseline extreme climate.

The HadGHCND dataset is documented in peer-reviewed literature [3] and is interpolated from a global data set of quality-controlled station observations compiled by the U.S. National Climatic Data Centre.

3. IMPACT OF CHANGES IN EXTREME PRECIPITATION ON HA ASSETS

3.1. Overview

Several HA SSOPs refer to extreme precipitation information. For example the design guide produced by the Highways Agency HD 33/06 has three drainage requirements. Firstly, the drainage must accommodate a one year storm in-bore without surcharge. Secondly, the design must be checked against a 5 year storm intensity to ensure that surcharge levels do not exceed the levels of chamber covers. Lastly, the rainfall intensities used to calculate the design storm must include an allowance for climate change otherwise a contingency of a 20% increase must be applied.

Climate model output is generally averaged over periods of 6 hours or more. However, the HA SSOPs relate to high intensity – short duration precipitation events. This study has used daily rainfall accumulations for the EVA. The results are very useful to begin to understand the nature of the changes projected in extreme precipitation into the future; however, further work is required to estimate short period rainfall changes from these daily extreme accumulations.

Within this section of the study we have:

- Performed a return period analysis, at 1-year, 5-year and 30-year return levels, for estimated daily precipitation from gridded observations.

- Performed return period analysis, at 1-year, 5-year and 30-year return levels, of daily precipitation anomalies for the 2080's from HadRM3 (Hadley Centre Regional Climate Model) climate model output, and estimates for the 2020's and 2050's.

- Investigated the seasonality of extreme daily precipitation projections.

- Related the results to HA SSOPs.

- Assessed the options for projecting changes in high intensity – short period events from climate model output and made recommendations for future research.

3.2. Changes in Extreme Precipitation

The impact of changes in extreme precipitation on the HA SSOPs has been assessed by undertaking an extreme value analysis to calculate 1-year, 5-year and 30-year return levels.

3.2.1 Extreme Precipitation from Observations

The analysis has shown that the highest Return Period Amounts in mm (RPAs) can be found in the west of the country and, as would be expected, the rarer the event, the more intense (a higher daily accumulation).

Figure 1 shows how observed annual RPAs for all three events vary across the UK. Higher RPAs in the west of the country can be explained by the predominant westerly air-flow in the UK, bringing Atlantic low pressure systems onto the western coasts. The high ground over Dartmoor, western Wales and Scotland also generates uplift and further enhances precipitation in these areas. The south westerly flow also influences precipitation around the south coast, which has generally has generally higher RPAs than central and eastern England.

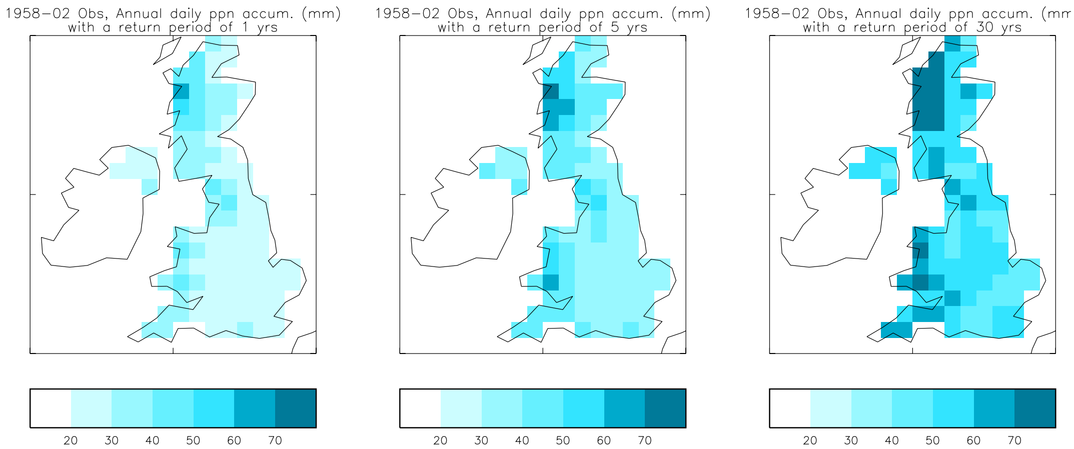

Figure 1.
Daily Precipitation Return Period Amounts (mm) for a 1, 5 and 30 year return period event (All seasons).

3.2.2. Future Projections

All the results of the future projections described below concentrate on the distribution in daily precipitation extremes across England to fit the remit of the HA.

Figure 2 (a, b and c) shows how the annual RPAs may be affected by climate change over the UK. For an event with a return period of one year, by the 2080s, the majority of the UK is predicted to experience an increase in precipitation up to 10%. The western and southern coasts experience an increase in precipitation accumulations by 10 to 20%. Only a few locations experience a reduction in the daily rainfall totals, for example in NE England.

Figure 2 also shows how the effects of climate change are predicted to increase through time (from top to bottom of figure*)* and for the two emission scenarios. The influence of these different time periods and scenarios can more clearly be seen when looking at the rarer events, such as an event that occurs every 30 years. The signal (whether positive or negative) increases in magnitude both with time into the future and with a stronger Green House Gas forcing. The 5 and 30 year return period events show a different signal to the 1 year return period. For the 1 year return event (Figure 5a) there is a general increase of up to 20% across much of the country.

For 5 and 30 year events (Figure 2b & 2c), over most of the country an increase in the daily precipitation totals is projected; however, this is not the case in the southeast of England where a reduction is apparent. The contrast is particularly visible when looking at the High Emissions scenario for the 2080s. From the SW to the NE of England there is an increase in daily precipitation by up to 40%, whereas in the SE of England there is a reduction in precipitation by up to 20%.

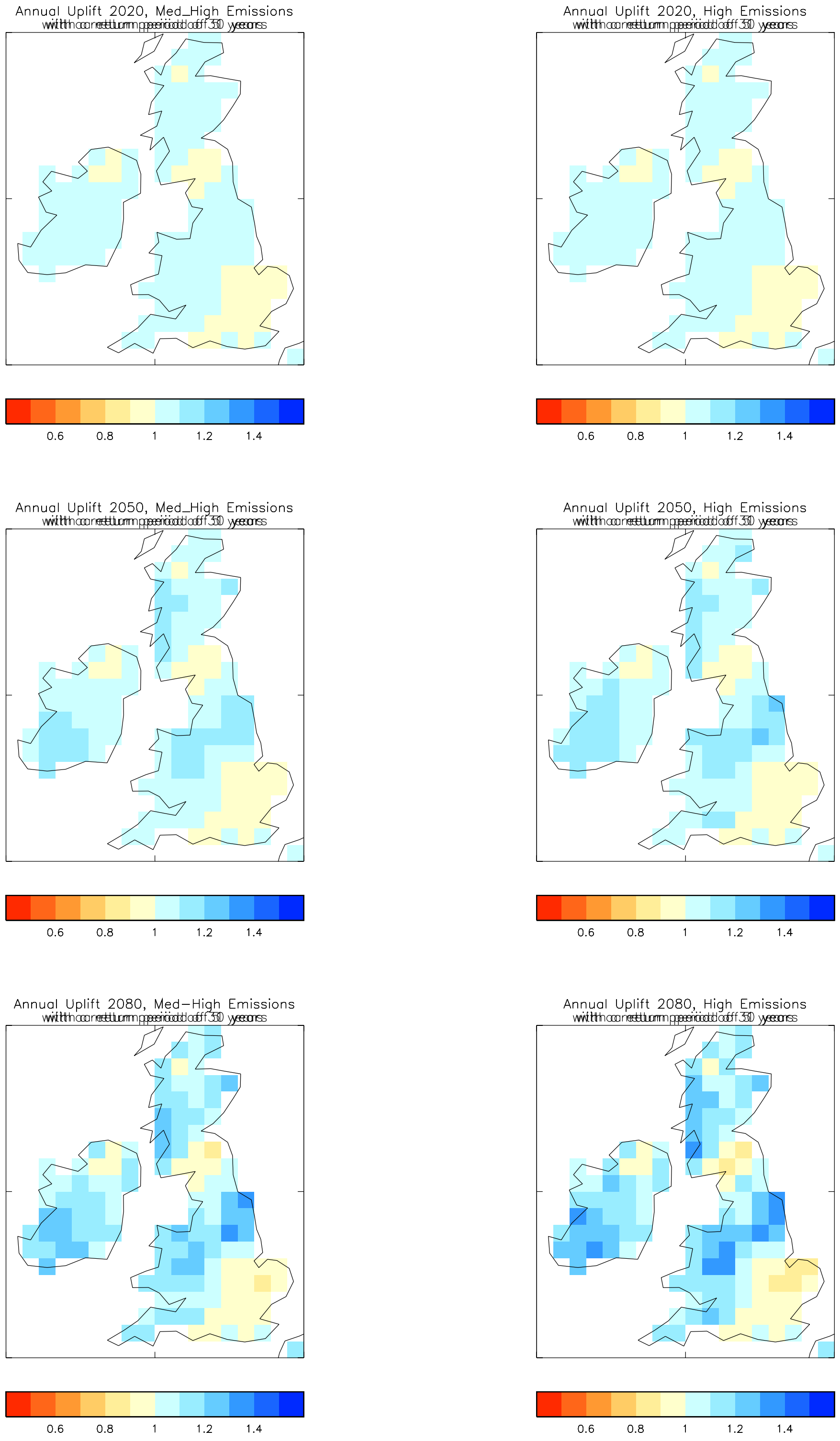

Figure 2a. Climate Change multiplication factors for daily precipitation accumulations, for a 1 year return period event. Two emission scenarios are shown, Medium-High and High, and for 3 periods, 2020s, 2050s and 2080s.

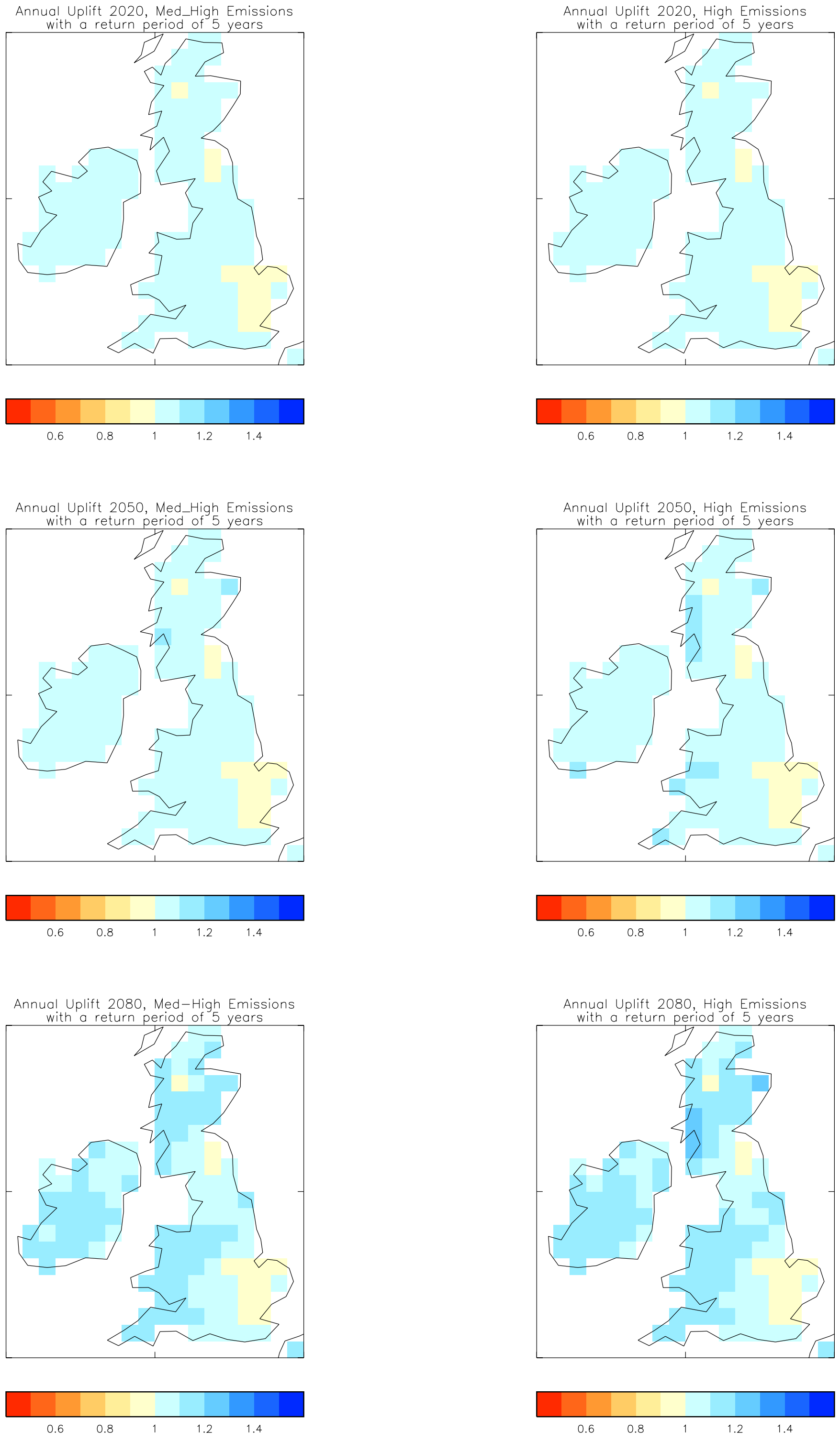

Figure 2b. Climate Change multiplication factors for daily precipitation accumulations, for a 5 year return period event. Two emission scenarios are shown, Medium-High and High, and for 3 periods, 2020s, 2050s and 2080s.

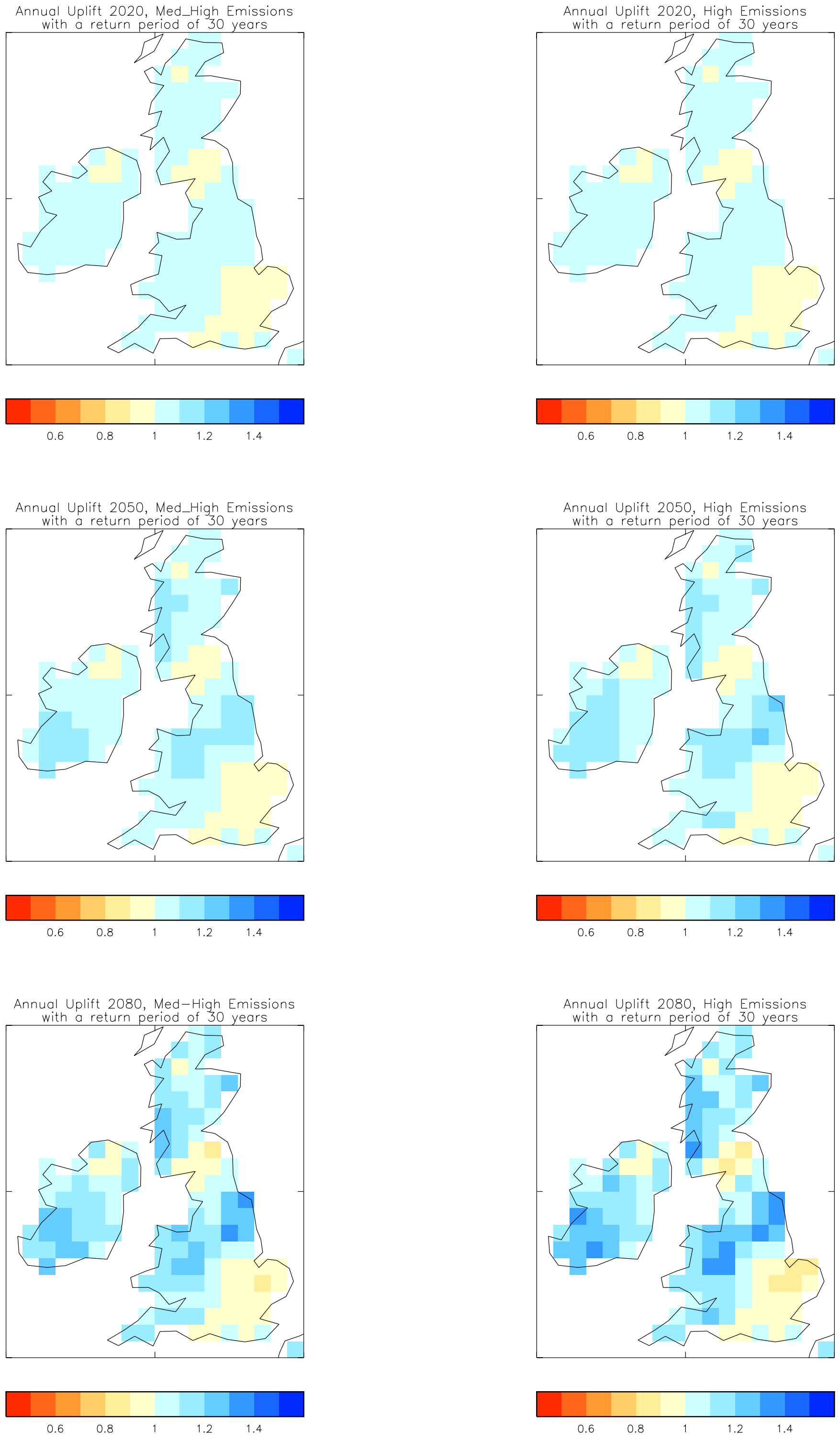

Figure 2c. Climate Change multiplication factors for daily precipitation accumulations, for a 30 year return period event. Two emission scenarios are shown, Medium-High and High, and for 3 periods, 2020s, 2050s and 2080s.

3.2.3. Impact on HA SSOPs

The HA SSOPs state that when designing drainage an allowance must be made for climate change otherwise a contingency of 20% must be applied to calculated storm intensities. Our analysis of annual extremes illustrates that the 20% contingency may be adequate for 1 and 5 year return period storms even up to the 2080's for a high emissions scenario. However, if a 30 year return period event is considered, a 20% increase is insufficient, with parts of Northern England showing up to 40% increases.

We have also undertaken a seasonal analysis of changes [14]. Based on the seasonal analysis the 20% contingency increase is insufficient, by the 2080's for autumn, spring and winter time events under the medium-high emissions scenario. In each of these seasons the extreme events are predicted in various parts of the country to increase by more than 20%. For example, in Southeast England the 1 year return period event in winter may increase by between 30 and 40% by the 2080's under the high emissions scenario.

To conclude, the 20% contingency may not be adequate, especially towards the end of this centaury, and the standards may need to be revised. The UKCIP08 scenarios of climate change, when available, will allow recommendations to be made on the nature of the revisions.

All the analysis presented here is based on daily accumulations of precipitation; however, high intensity – short period events are of key concern to the Highways Agency. Recently completed work [1,14] has highlighted the importance of understanding the impacts of climate change on short-period extreme events.

4. IMPACT OF CHANGES IN EXTREME TEMPERATURE ON HA ASSETS

4.1. Overview

Several HA SSOPs refer to the use of extreme temperature data, especially for design, examples include a design guide produced by the HA, BD37/01, and BS 5400 which are both applied in the design of structures. The new Eurocodes will supersede BS 5400 and are considered.

Within this section of the study we have:

- Investigated extreme temperature trends by performing a return period analysis of the coarse resolution (3 grid cells cover England) HadGHCND daily maximum temperature dataset, which was designed to complement earlier work undertaken by the Met Office [9].

- Performed return period analysis, at 10-year, 50-year and 120-year return levels, of daily maximum temperature anomalies for the 2080's from HadRM3 climate model output.

- Investigated the uncertainty of EVA of temperature extremes from climate model output.

4.2. Extreme Temperature Trends

The analysis in this work applied the same method as that used in a previous study [9]. Fullwood assessed 6 stations, and in this study we analysed gridded observations, but we have used the same method to maintain compatibility.

Fullwood used two separate thirty-year periods (1941-1970 and 1975-2004) from the station data and analysed them separately to see if a significant difference in extreme values was evident (perhaps illustrating a long period trend). The same approach was followed in the current work, although the source of observational data meant that the two periods (1946-1975 and 1971-2000) had to overlap slightly.

The analysis method we have used was as follows:

- An analysis system [10] developed in1996 was applied.

- The analysis system uses the Generalised Extreme Value (GEV) method of fitting extreme distributions.

- A series of daily maximum temperatures for each of the three grid-boxes was extracted, and the annual maxima were obtained for each of the thirty years.

- Extreme daily maximum temperatures with return periods of 10-years and 50-years were calculated. The two periods of gridded observations are only 30 years long, so return period estimates of greater than around 20 years are highly uncertain. We have extrapolated the analysis to include an estimate of 50-year return values (one of the focus return periods for this study), but it is inappropriate to estimate the 120-year return level.

The daily maximum temperature gridded observations represent large area averages; only three grid-boxes cover the UK. Therefore, they are not suitable for calculating absolute maximum values, but they are useful for assessing trends.

Our analysis illustrates the possibility of a small increasing trend in extreme daily maximum temperature, in two of the three grid-boxes, although any difference in extremes between the two periods is within the range of standard error.

For two of the grid-boxes (Wales & Midlands, and N England & S Scotland) the more recent climate gives higher extreme temperatures of approximately 0.5°C for both 10-year and 50-year return temperatures (although the differences are generally within the standard error range). For the S & E England box the more recent climate gives extreme temperatures which are the same as those from the 1946-75 data.

4.3. Extreme Temperature Projections of the Future

The model data (annual daily maximum temperature at each grid-box for 3, 30 year runs for each of the periods 1961-1990 and 2071-2100) was analysed to calculate return levels for 10-year 50-year and 120-year return periods. Trends may exist in modelled temperature, especially in projections made towards mid-late 21st Century; therefore an analysis method that accounted for trends was used [14].

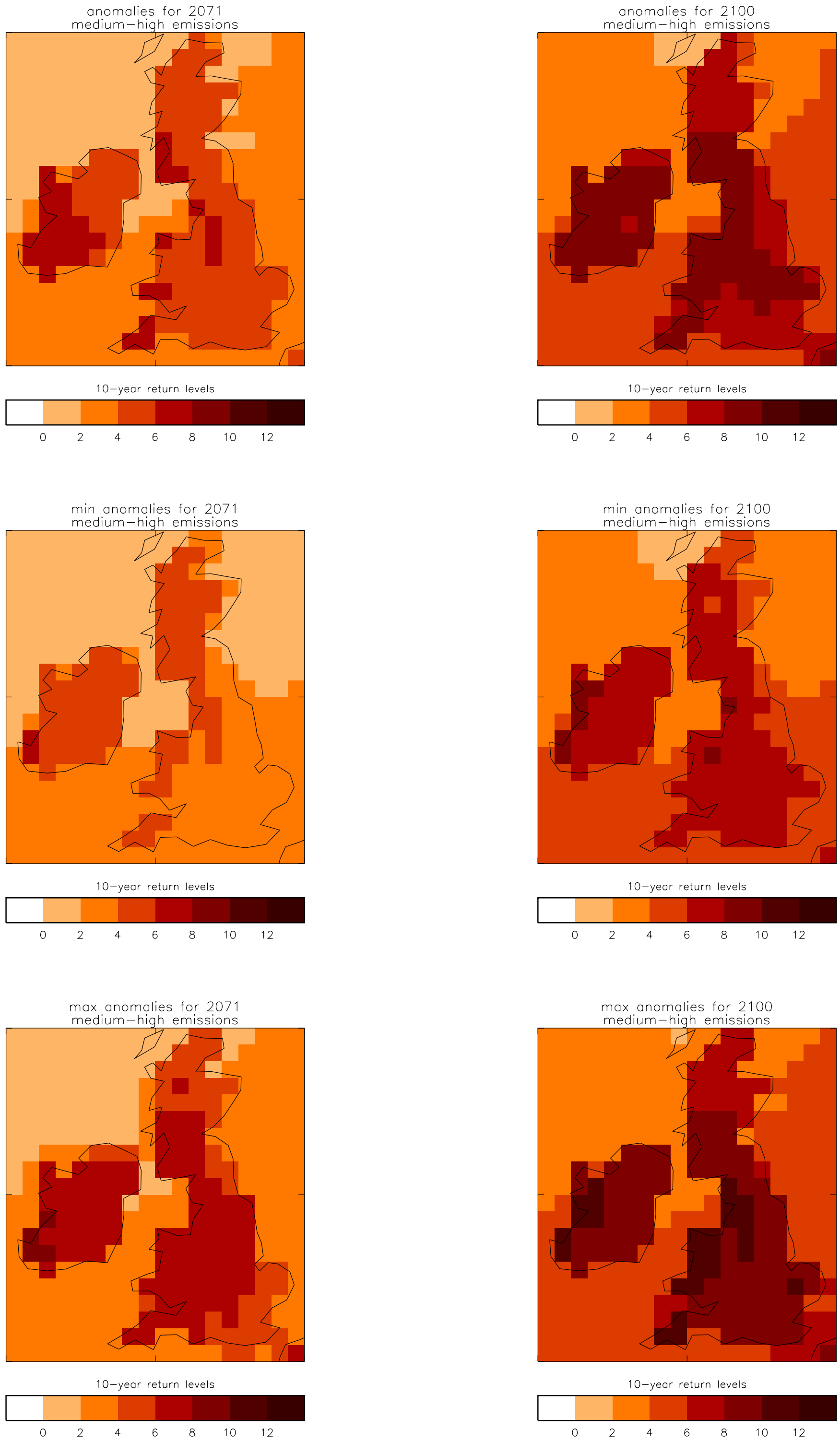

Figure 3. 10-year return daily maximum temperature anomalies (medium high emissions scenario). The left and right columns show the projected extreme climate for 2071 and 2100 respectively. The top row presents the best guess anomalies. Uncertainty in the extreme value analysis is represented by minimum anomalies (middle row) and maximum anomalies (bottom row).

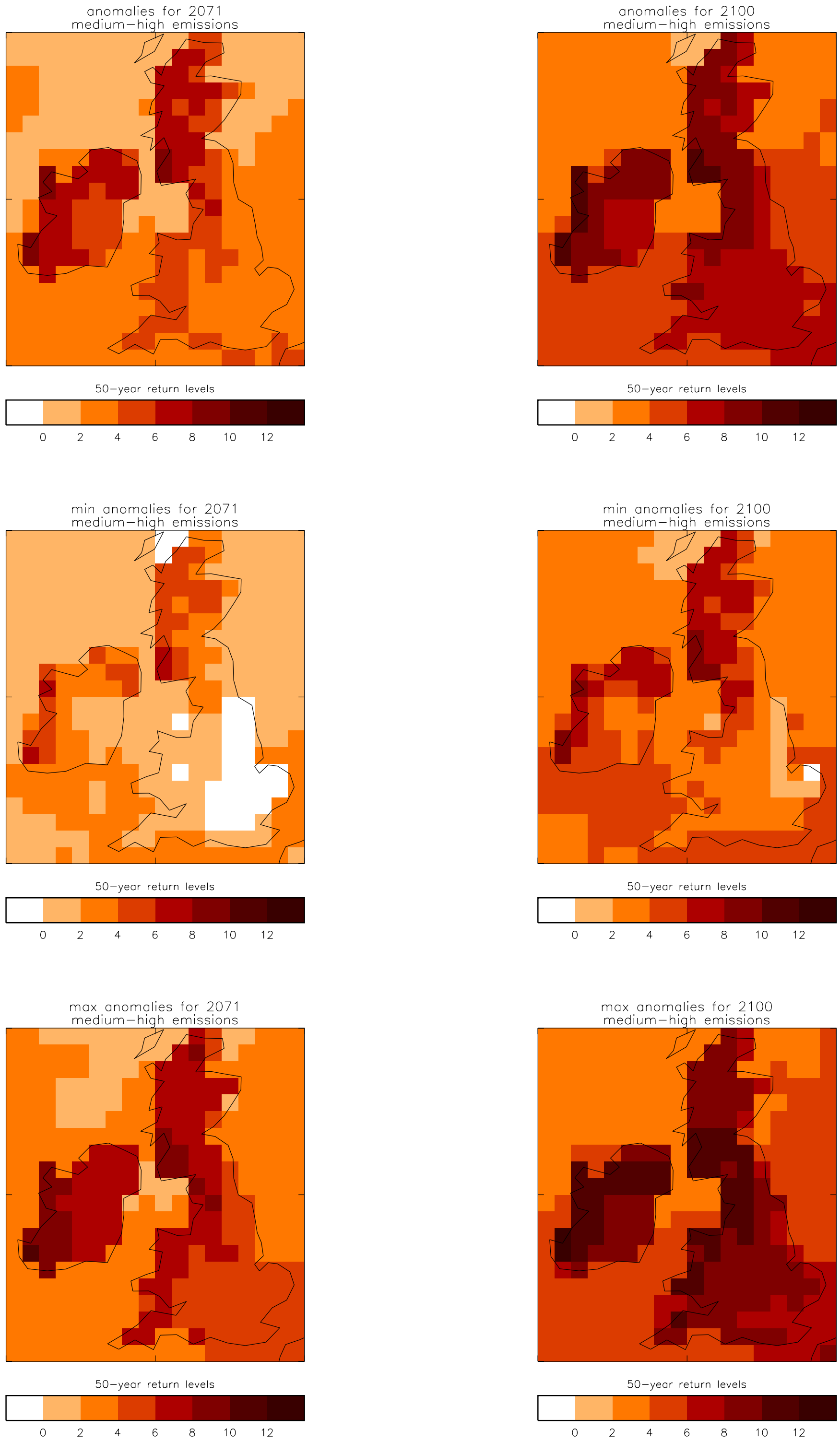

Figure 4. 50-year return daily maximum temperature anomalies (medium high emissions scenario. The left and right columns show the projected extreme climate for 2071 and 2100 respectively. The top row presents the best guess anomalies. Uncertainty in the extreme value analysis is represented by minimum anomalies (middle row) and maximum anomalies (bottom row).

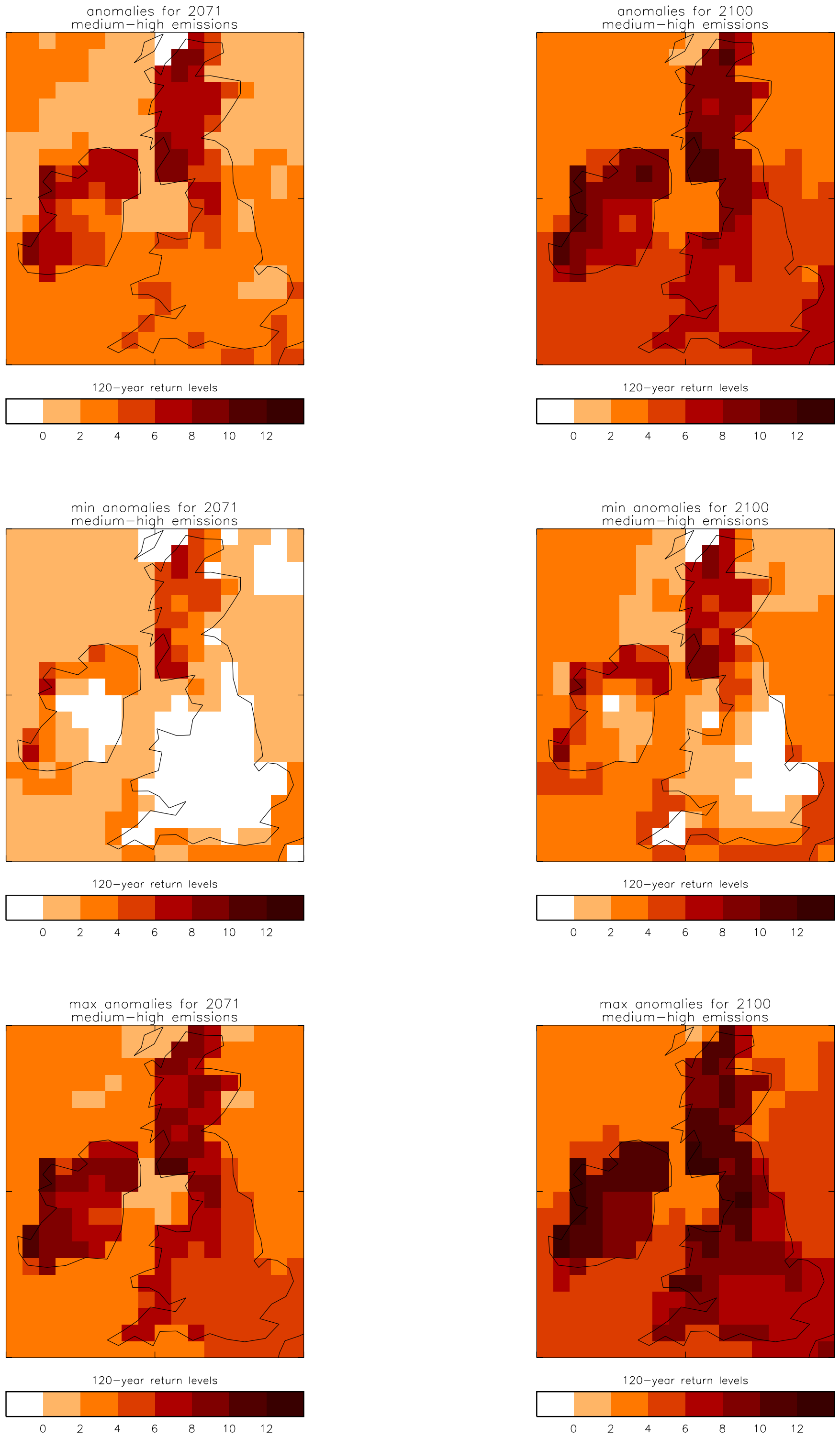

Figure 5. 120-year return daily maximum temperature anomalies (medium high emissions scenario). The left and right columns show the projected extreme climate for 2071 and 2100 respectively. The top row presents the best guess anomalies. Uncertainty in the extreme value analysis is represented by minimum anomalies (middle row) and maximum anomalies (bottom row).

Anomalies of projected changes for 2071 and 2100 compared to modelled ‘present climate’ (1961 – 1990) have been calculated.

Uncertainty has been assessed in the extreme value analysis method by calculating three extreme value estimates for each future period and return level:

- A central or 'best estimate' anomaly
- A minimum anomaly – an assessment of the smallest probable increase in extreme temperature (the difference of the best estimate future value and the upper bound at the 95% confidence level in the current climate).
- A maximum anomaly – an assessment of the largest probable increase in extreme temperature (the difference of the best estimate future value and the lower bound at the 95% confidence level in the current climate).

In figures 3 – 5 the anomalies in return levels for 10-year, 50-year and 120-year return period are represented as maps of the UK and the immediately surrounding area. Along with the best estimate of the anomalies, maps for the upper and lower limit of our estimate of the uncertainties, as derived from the model, are included for each return period.

Figures 3 – 5 illustrate that for all extreme events analysed here the best estimate maps reflect a raise in the return values of maximum temperature during this century, at all grid-points over land. There is evidence of variations in the values of the anomalies across the country, but these variations are generally spatially coherent.

The uncertainty ranges of these estimates, as a difference between the 'minimum anomalies' and 'maximum anomalies' for a given year, show an increase in uncertainty with the increase in the 'rarity' of the event. In particular, the uncertainty estimated for the 120-year return levels anomalies is large, of comparable magnitude to the value of the best estimate of the anomaly in places. This is at least in part due to the difficulties of extrapolating the theoretical results derived from a relatively short time-series (90 years of 'model data') to very long return periods (120 years). Although apparently better constrained by the 95% modelled range, the estimates of anomalies over the sea area in the domain presented in the plots should be disregarded as highly uncertain, due to the type of model used to derive these projections (where the oceans temperatures were prescribed).

4.4. Impact on HA SSOPs

Our analysis of historical data illustrates the possibility of a small increasing trend in extreme daily maximum temperature, in some regions, although any difference in extremes is within the range of standard error.

Our analysis of climate model simulations, however, highlights the possibility of much larger changes in extreme temperature during the lifetime of present and planned HA structures. For example, 50-year return daily maximum temperature may increase by 10°C in some areas of England by 2100 (best EVA estimate, medium-high emission). Under a high emissions scenario and using the maximum anomaly estimate from the EVA the increase is much greater.

In summary, existing design standards are likely to be adequate for the present day, but revisions should be considered due to the scale of changes that are possible during the lifetime of new structures.

5. UNCERTAINTIES & LIMITATIONS

The projections of only one climate model, the Hadley Centre Regional Climate Model (HadRM3); have been considered in this study. There are uncertainties in the predictions of future climate due to unknown future greenhouse gas emissions, uncertainties in the models used to simulate climate change, and because of natural variability.

The effect of different emissions scenarios is simulated by HadRM3. In this study we have assessed medium-high emissions scenario projections, and scaled the results to give estimates of high emissions forcing. The effect of natural variability is considered by analysing observed and modelled time series' that are in excess of 30 years long; however, a key limitation of this work is that the uncertainty due to climate modelling is not quantified.

Extreme values analysis, like any statistical technique, has associated uncertainty. Generally the uncertainty in the EVA result increases for estimates with greater return periods because of the finite length of the observed and modelled data series'.

The extreme temperature analysis conducted in this study includes an assessment of uncertainty (see [14] for a full description). For example, for a grid-box in central England, the 50-rear return daily maximum temperature increase is project to be 3.7°C. The range, (based on the 95% confidence level in the modelled baseline period) is an estimated increase of between 0.3 – 5.4°C.

6. POSSIBLE FUTURE RESEARCH

It is difficult to for organisations such as the HA to adapt to climate change without a quantification of all the uncertainty in the projection of climate change. Future research in this area will benefit greatly from the UKCIP08 projections of climate change. The climate projections will be created by the Met Office Hadley Centre, and access and communication will be facilitated by the UK Climate Impacts Programme (UKCIP).

The new UKCIP08 climate projections will be available for a range of emissions scenarios and will include an assessment of model uncertainty and natural variability. They will be invaluable to organisations such as the Highways Agency, as they develop adaptation strategies. For example, the work presented here has highlighted the need for updates to the SSOPs, because of changes in extreme temperature and precipitation that are possible in the future. The UKCIP08 scenarios will allow risk based decisions to be made on the scale of the revisions.

As well as direct flooding from intense precipitation events in some areas, runoff flooding from adjacent land, and flooding from rivers both affect the road network. With extreme precipitation predicted to become more intense it is important that the HA can assess how the frequency and severity of surface runoff flooding may change in the future.

Developing procedures and systems that will allow the HA to be forewarned of extreme weather will be of great benefit when adapting to climate change. With the potential for surface flooding to become more common, warning of extreme precipitation a few hours in advance could be most useful. Longer range forecasts (weekly, monthly and seasonal) could also be very useful for medium-term planning.

As highlighted in the scoping study [1], bank stability is an important issue for the HA. A landslip risk service could be developed, based on surface soil type and meteorological parameters. The impacts of climate change could also be studied. The changes in the precipitation regimes which are of particular importance to bank stability, such as 5-day cumulative precipitation totals could be investigated.

As previously described a high resolution gridded daily maximum temperature dataset covering the UK is not yet available. However, one is in production at the National Climate Information Centre at the Met Office and is expected to be available at the beginning of 2008. An analysis of 'present day' trends using this new dataset should be conducted when the data becomes available.

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