To what degree can the October/November 2000 flood events be attributed to climate change?

DEFRA FD2304 Final Report

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EXECUTIVE SUMMARY

This is the Final Report of the joint DEFRA and Environment Agency research project FD2304, ‘To what degree can the October/November 2000 flood events be attributed to climate change?’

The report presents the findings of a study, carried out by the Centre for Ecology and Hydrology (CEH) and the Met Office, to establish how unusual the flooding of October/November 2000 was, and to assess to what degree that flooding can be attributed to climate change. It is a summary that draws on, and interprets, detailed findings that are presented in an accompanying Technical Report.

Research objectives

The study was carried out by addressing the following two key questions:

- How unusual was the October/November 2000 flooding and rainfall in a historical context?
- Can the October/November 2000 floods and rainfall be linked to climate change?

Research Methods

The research combines a primary data study with analysis of climate model outputs. The main scientific elements of the study are:

- Data collation, including river flows, rainfall, groundwater levels, synoptic meteorological information and weather radar images
- Statistical analysis of frequencies of river flow extremes, rainfall extremes and associated meteorological conditions
- Statistical analysis of trends in rainfall and river flow extremes
- Analysis of climate model predictions of rainfall extremes

This Final Report includes a non-technical summary of the key scientific findings of the research. The Technical Report provides a detailed account of the analysis.

Findings of the study

There is clear evidence that the October/November 2000 floods and rainfall were unusual or unique in several ways:

- Rainfall for the September to November period (which includes the important build-up to the flooding) was the highest on record for those months.
- Rainfall for October/November 2000 was more than twice the long-term average for those two months over much of the country.
- Total river flows in five major basins (Thames, Trent, Severn, Wharfe and Dee) were greater than any time since the floods of 1947 for running totals over 10 days or more.
- For the months of October to December, the total river flows in the five major basins were the highest in a record dating back to 1940.

Viewed in a national context, the extent and duration of the flooding has few recorded parallels.

It is impossible to attribute a single ‘weather event’ to climate change by looking only at that event. In this sense, it is not possible to attribute the October/November 2000 flooding and rainfall *in themselves* to climate change.

What can be done is to ask whether there have been changes occurring in the frequency and magnitude of such events and to use climate models to see whether changes in extremes of potentially ‘flood-producing’ rainfall are predicted:

- There is evidence of increasing rainfall and river flow extremes in Britain in the last 30 to 40 years, especially for longer durations (e.g. 30 or 60 day running totals).
- Wider evidence, in the UK and globally, also shows increases in winter season heavy rainfall events.
- This evidence is consistent with *predictions* of human-induced climate change. It has not been shown that *observed* changes in precipitation can be attributed to human activity.
- The climate model used in this study provides realistic simulations of the magnitude and frequency of rainfall extremes in the recent past. It also predicts that the frequency of rainfall extremes will have increased since 1860.
- The changes predicted in extreme rainfall frequencies between 1860 and the present day are small compared to natural variability.
- The climate model also predicts further increases in extremes of rainfall accumulating over one or two month durations, as experienced in October/November 2000. Increases in the frequency of flooding can be inferred, but require further work to be quantified.

We can therefore conclude that:

- The events of October/November 2000 were extreme, but cannot in themselves be attributed to climate change. However, heavy rainfall and peak river flows of similar durations have been increasing in frequency and magnitude over the last 50 years.

- This pattern is consistent with model predictions of how human-induced climate change affects rainfall. However, it is not yet possible to say how far rainfall and flooding events such as those of October/November 2000 can be attributed to climate change, as opposed to natural variability.

CONTENTS

BACKGROUND AND PURPOSE OF THE STUDY

Following the severe floods of October/November 2000, there is a general public perception that both the occurrence and magnitude of flooding and associated extreme rainfall in the UK is increasing. There has also been speculation that the autumn 2000 floods were themselves ‘caused by’ climate change. There is therefore an urgent need to determine how unusual the flooding episode of late 2000 was, and whether or not it can be linked to climate change.

To address these issues, the Centre for Ecology and Hydrology (CEH Wallingford) and the Met Office were commissioned in December 2000 to carry out a four-month primary data and model study. The study, funded within the joint DEFRA and Environment Agency research programme, has the following overall purpose:

‘To assess whether the flooding and rainfall of October/November 2000 was inconsistent with historical records and, if so, whether the inconsistencies can be linked to climate change”

This assessment can only be provided by using past records to give a historical perspective, and by applying scientific methods of analysis to examine river flow and rainfall data. The study gathered scientific evidence, based on a number of types of data, to answer the following two key questions:

1. **How unusual was the October/November 2000 flooding and rainfall in a historical context?**

2. **Can the October/November 2000 floods and rainfall be linked to climate change?**

It is impossible to attribute a single rainfall or flood event to climate change by looking only at that event. This is because the processes that lead to such events are very complex and there is a large degree of randomness apparent in the occurrence and magnitude of extremes of rainfall, and the consequent flooding. What can be done is to look at the October/November 2000 events in the context of events of a similar nature and to assess whether there are changes in the frequency or character of such events, and if so, why these changes have happened. It is also useful to examine predictions by climate models, which incorporate possible theoretical links, to see whether changes in extremes of rainfall are predicted.

This Final Report draws on scientific data and analysis that has been described in detail in a companion Technical Report. The results are summarised in this Final Report, along with the research methods that were used to analyse the data. Technical aspects have been avoided as far as possible in the main text, but some important details are presented in separate boxes.

RESEARCH METHODS

The overall research strategy was structured around four technical objectives. These encompassed the collation of relevant data (and processing of raw data into a useable form), the assessment of the rarity of different features of the October – November 2000 period and the assessment of whether those features might be linked to climate change. The final objective, to draw conclusions from the results of the analysis, is addressed in this report.

Research objectives

The research approaches taken to address each of the technical objectives are outlined below.

Objective 1. Data collation

A first step was to identify suitable data sets for analysis. The main types of relevant data are measurements from river flow gauges, rain gauges and rainfall radar. In addition, more general meteorological data (such as atmospheric pressure, wind fields, etc.) were available for synoptic summaries, and groundwater level observations offered an additional source of catchment information. The selection and collation of data for use in formal analyses is an important prerequisite for any study such as this.

River flow gauges and rain gauges are situated throughout the UK and provide a very large amount of information on a routine basis. The quality, reliability and length of records all helped to determine the suitability of any particular gauge for this study. In view of the short, responsive nature of the study, it was necessary to operate within the logistical constraints of data availability, in particular the turn-around time for receipt of rain gauge data for the months of October and November 2000 from gauge operators.

The observational data sets used in the study were:

- Gauged river flow data from selected catchments across the country
- Rainfall measurements from the national gauge network
- Rainfall data from specific gauges with long, historical records
- Rainfall patterns derived from weather radar systems
- Synoptic meteorological observations over the British Isles
- Meteorological conditions over the North Atlantic
- Soil moisture levels
- Groundwater levels

Data were required so as to complete historical records up to the end of November 2000. The data were collated by the project team throughout December 2000 and January 2001, finishing in early February 2001. River flow gauges used in this study are operated by the Environment Agency, the Scottish Environmental Protection Agency and Rivers Agency, Northern Ireland. Gauging of flood flows is very difficult – recent data used in this study are therefore accepted as being ‘subject to revision’.

The UK maintains high hydrometric standards, but the impact of human activities on river flow regime is pervasive. For the study we chose catchments, where possible, which were largely unaffected by the most obvious artificial disturbances (e.g. major reservoirs commanding much of the catchment, or substantial diversions of flow for flood relief or, say, hydropower generation).

Objective 2. Assessment of how unusual the events were in the historical context

There are many aspects of the events of October/November 2000 that could be compared with historical records. For example, river flows and rainfall depths over sub-periods of one day, one week or one month can be considered. Also important is the coincidence and magnitude of individual flood events in different regions of the country.

The rarity of the meteorological conditions and spatial patterns of rainfall were assessed using a combination of quantitative and qualitative analysis.

Rainfall and river flows for October/November 2000 (plus antecedent conditions) were compared with historical data on a gauge, catchment, regional and national basis. Formal estimates of the return period of the peak river flows and rainfall were obtained using frequency analysis techniques (see Box 1); both at the national scale and, in more detail, at specific catchments and long term rain gauges.

It is important to note that an ‘extreme event’ (even one that breaks records) is not *necessarily* ‘unexpected’ when compared with the historical record. One analogy for this is that it is not surprising when records are sometimes broken, but it may be surprising if they are broken with increasing frequency, or by unexpectedly large margins.

Objective 3. To determine whether the events could signal a changing climate

Past rainfall and river flow data were analysed to look for changes or trends which could be consistent with a changing climate, but bearing in mind the need to try to distinguish between underlying climate change and natural variability. For rainfall extremes, the data that we examined were the largest amounts of rain falling within any period of 1-, 3-, 15-, 30- and 60-days in each year. These records were tested for trend at 28 sites across the UK. The rainfall records included 13 ‘long-record’ stations (where measurements have typically been made for the past 100 years) and 15 shorter records (with record lengths of typically just under 40 years).

BOX 1

Frequency analysis and Return Period

Frequency analysis uses robust statistical procedures to estimate the return period (or rarity) of an event. Return period can be defined generally as the average interval, in the long run, between events of a given size. An event with a return period of *T* years is generally referred to as the ‘*T*-year event’. Although a simple ranking of events gives some indication of rarity, much better estimates are provided by fitting statistical models to the data that relate the size of events to their return period. This study uses techniques set out in the Flood Estimation Handbook (IH, 1999) and a method called the ‘Tabony Table’ (Tabony, 1977).

BOX 2

Climate models

Enhanced concentrations of greenhouse gases (most notably CO_2) produce a different atmospheric radiation balance, with more outgoing longwave radiation being trapped within the atmosphere (the ‘greenhouse effect’). As this extra heat raises global air temperature it will, almost certainly, affect global climate. This changed global climate can be estimated using coupled atmosphere-ocean General Circulation Models (GCMs). These are essentially the same large numerical computer programmes that are used for weather forecasting, but run for long periods – years rather than days. These models require the largest, fastest computers, but even with these computers compromises must be made, trading off length of model run against the size of the numerical ‘mesh’ or model resolution over the globe.

Climate modelling (see Box 2) was used to assess the projected effects of climate change on UK rainfall. Currently, global climate models are run with a grid of about 300 x 300 km – a scale that is too large to model the structure of weather events. Global models, on their own, are therefore of limited use in predicting extreme rainfall events, such as the October – November 2000 events.

Statistically based ‘disaggregation schemes’ can be used to downscale GCM rainfall predictions, but a better method is to embed (or ‘nest’) a higher resolution Regional Climate Model (RCM) within the global model for particular regions and periods of interest. The RCM takes the global model prediction of the large-scale circulation and translates it into an estimate of the local weather. The RCM uses a 50 km grid.

Objective 4. To consider the findings of the project and draw conclusions

This Final Report presents an overall assessment, based on the research approaches outlined above, of the extent to which the October/November 2000 flood events can be attributed to climate change. The overall assessment draws upon the results presented in the project Technical Report.

Notes on terminology

The following terms are used in this report with particular interpretations in mind:

Event	Throughout this study, we have used analysis techniques that estimate the rarity of identifiable ‘events’ of one type or another. Estimates of rarity are based on statistical techniques that account for both the size of an event and the number of times events of a given size have been observed (see, for example, Box 1). The term ‘event’ is therefore used to describe, *inter alia*, an individual, discrete period of heavy rainfall (over three days, for example), rainfall over the entire period of a month or more, discrete peaks in river flows or sustained periods of high flows. It can also be used to describe a ‘storm’, commonly used by hydrologists to indicate a heavy rainfall event.
Return period	The average interval, in the long run, between events of a given size. Note that this is a notional long-run average, and that the actual intervals between events of a given return period can vary.

Climate change	Climate change may be a consequence of natural processes, or human action, or both. This report follows the IPCC usage in regarding ‘climate change’ as referring to a change in climate brought about by any cause. Change caused by human action is referred to as ‘human-induced’, or ‘anthropogenic’, climate change.
Natural variability	Natural variability in climate can occur at different timescales. ‘Variability’ is used in this report, depending on the context, to refer both to cyclical or quasi-cyclical changes on a time scale of decades or to the randomness of the magnitude and timing of individual weather or flooding events.

KEY SCIENTIFIC FINDINGS

The two key questions asked by this study are:

1. How unusual was the October/November 2000 flooding and rainfall in a historical context?
2. Can the October/November 2000 floods and rainfall be linked to climate change?

The scientific objectives were designed to answer these questions in as much detail as possible within the timing of the study. This section of the Final Report summarises the findings. The evidence provided by these findings is then assessed within a structured framework in the following section of the report.

How unusual was the October/November 2000 flooding and rainfall?

In addressing this question, we have examined river flows and meteorological conditions during the period, placing them in a historical context to establish the rarity of the late-2000 events. Supplementary information about groundwater and soil moisture was also taken into account. The key findings, highlighted below, are based on a combination of expert interpretation of data and formal, tested methods.

The evidence from rainfall

Analysis of synoptic weather data makes it clear that the period of October – November 2000, leading up to and including the main flood events, was dominated by persistent and repeated frontal depressions. Weather radar helped to characterise the patterns of the rainfall across the British Isles, showing broad bands of rain enclosing notable high-intensity rain cells. This explains both the widespread high rainfall accumulations and the high intensity rainfall over certain smaller areas.

It is difficult to assign exact measures of rarity from radar data because of the length of the historical records. However, the subjective view of an experienced analyst is that the existence of very broad, relatively static weather systems during October – November 2000 was very unusual for the British Isles. The weather systems experienced during the period were associated with patterns of sea-surface temperatures and air pressure over the North Atlantic. The patterns experienced over the North Atlantic during November 2000 were rare, and would be expected to occur in the long run no more often than once every 20 years, and perhaps as rarely as once every 100 years, although we cannot say whether this is influenced by human-induced climate change.

The gauged rainfall totals over Britain were high for October and November 2000, with more than 400 mm falling in parts of the South East, and more than 300 mm over Yorkshire. In places, the monthly accumulations of rainfall were as much as three times the long-term averages. The pattern of total rainfall as a percentage of the long-term average is shown in Figure 1, where it can be seen that return periods for the two-month period were in excess of 200 years (for those two months) for much of the country.

There were three main rainfall events of several days duration during the period. These events produced several extensive areas of exceptionally high rainfall, with return periods of 200 years (or more, in localised areas). A question that it has not been possible to address within the scope of this study is whether the spatial *coincidence* of these extensive, rare rainfall totals is unexpected.

Whilst rainfall during the period was not necessarily remarkable in every river catchment, the rainfall at gauges in severely affected catchments had return periods of well over 100 years. In the Uck catchment (Sussex), the total rain falling over the 30 days had an outstanding return period of approximately 650 years.

Using data from the Met Office, we can say with a high degree of confidence:

- **The weather over the British Isles during October – November 2000 was dominated by repeated frontal depressions that were associated with rare meteorological conditions over the North Atlantic.**
- **The national picture was of persistent, widespread heavy rain, rather than very strong, localised events (although these did also occur).**
- **This widespread, persistent nature of the rainfall over the whole period caused catchments to become saturated in many places, and was the root cause of the flooding.**
- **Over England and Wales, the September-December 2000 rainfall was the highest on record (i.e. in a series from 1766) for any period of four consecutive months.**
- **The September – November 2000 rainfall over England and Wales was the highest on record for those months, and the second highest on record for any period of three consecutive months.**
- **Over much of the country, rainfall for the whole October – November 2000 period was more than twice the long-term average for these months, and had a return period of more than 200 years.**
- **In contrast, the main rainfall events, which each lasted for several days and affected different regions, produced rainfall amounts with return periods of less than 50 years on the whole, but localised areas had totals with a return periods greater than 200 years.**

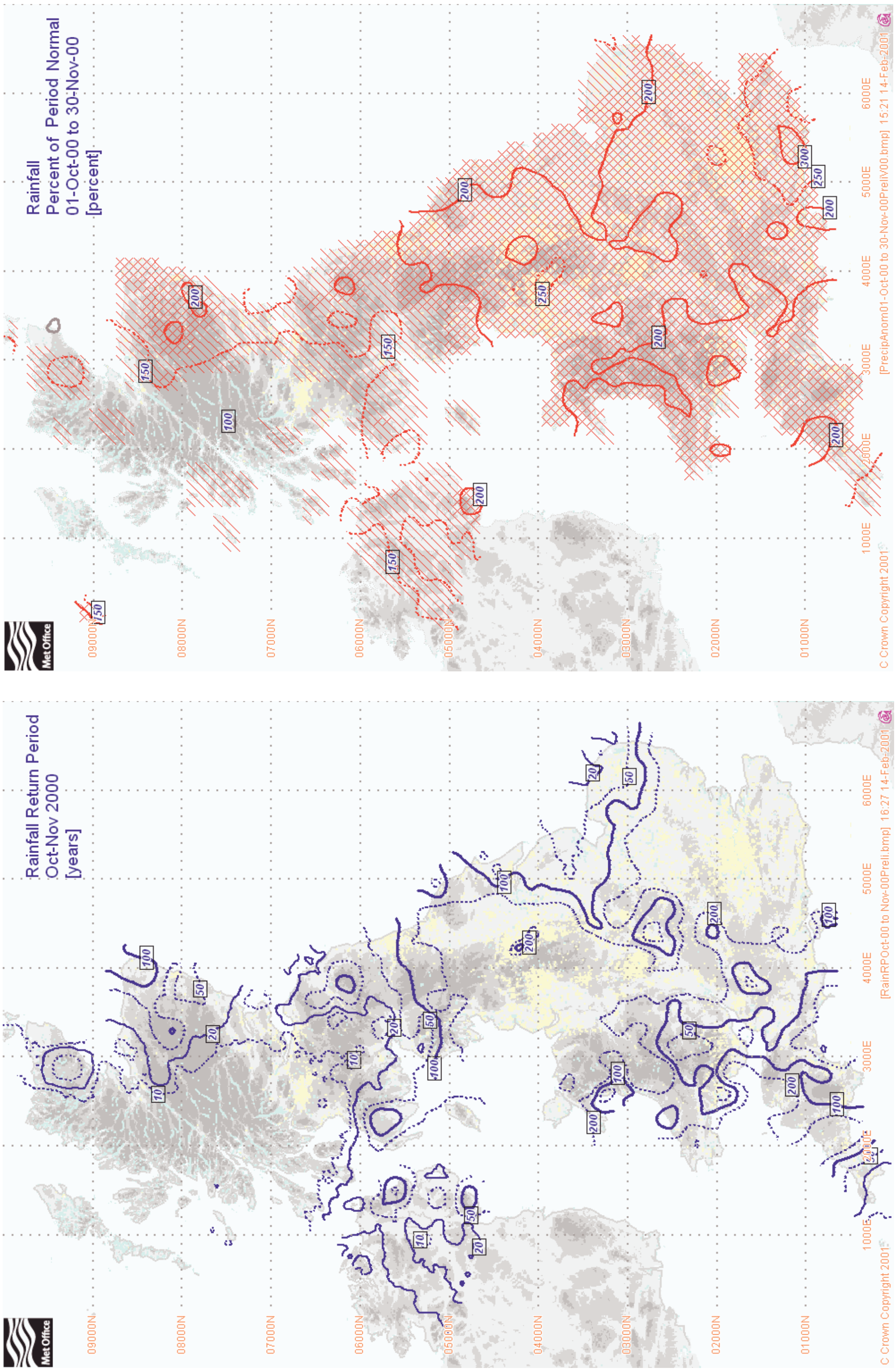

Figure 1. Accumulated October and November 2000 rainfall as a percentage of the long-term mean October and November rainfall (top), and the corresponding Return periods (bottom) Rainfall for the two months had a return period of greater than 200 years over much of the country.

The evidence from river flows and groundwater

The extent and duration of the flooding is outside the experience of most of the population of England and Wales, and, considering the rainfall, river flows and groundwater levels across the country as a whole, the events stand at the extreme of the range of recorded variability.

Figure 2 shows daily outflow estimates for England and Wales as a whole covering the 1940-2000 period. This chart is based on the combined river flows in five major basins (selected in part for having long flow records) and allows comparisons to be made with other major flood episodes over the last 60 years.

In terms of maximum flows, the flooding of March 1947 is clearly outstanding. This was a snowmelt-generated event that produced very high runoff rates over still-frozen ground. High flows were, however, maintained for a shorter time than in the late-2000 floods. Apart from 1947, the majority of prolonged and widespread flooding episodes were, like 2000, a response to sustained frontal rainfall on near-saturated ground.

Looking at the national picture provided by the combined river flows from the major basins in England and Wales, the total flows over the 90-day period of October – December 2000 were the most extreme on record. Prior to this, for individual major rivers, there have been slightly higher flows recorded during the winters of 1915, 1930 and 1937. For shorter periods of 10 days or 30 days, the events of late-2000 are out-ranked only by the 1947 snowmelt flood flows in the national frame.

In larger catchments – and those where river flows are derived largely from groundwater – high flows were sustained over exceptionally long periods, and groundwater levels were also unusually high throughout the latter part of the year 2000. On smaller, more responsive catchments, the prolonged nature of the flooding was experienced as a sequence of events in which water levels repeatedly rose above the river bank because of the passage of separate frontal weather systems.

When viewed in the historical context provided by flood information from the few very long records and from the pre-instrumented era (e.g. flood marks and anecdotal accounts), the late-2000 flooding is less remarkable (although still severe) when considered on a site-by-site basis. Flood frequency analysis was used at individual river sites to estimate return periods of the October/November 2000 peak flood flows in selected flood-affected and reference catchments. The preliminary results indicated return periods of about 100 years in affected areas. However, the most striking features of the records for major rivers in October/November 2000 were the sustained and widespread high flows.

Although river flows are difficult to measure during flood conditions, we can say with a high degree of confidence that:

- **The late-2000 floods were the most extensive across England and Wales since the snowmelt-generated flooding of March 1947.**
- **Although the flooding was especially severe in some areas (the South-East and Yorkshire, for example), it was also notable for its wide extent and prolonged duration.**
- **For five major rivers in England and Wales (Thames, Trent, Severn, Wharfe and Dee), the combined flows over the months of October – December 2000 were the most extreme for any 90-day period in a record since 1940.**

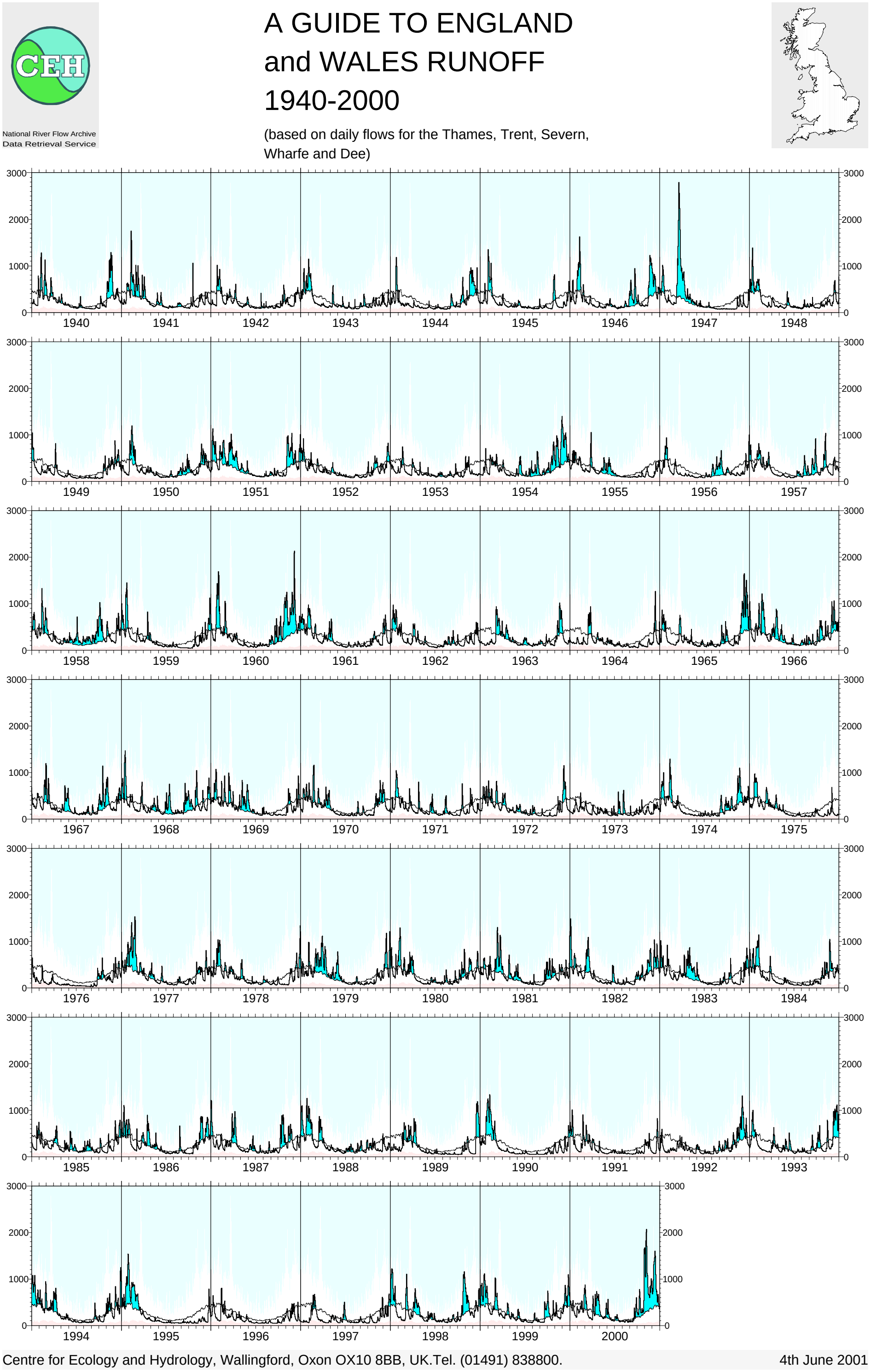

Figure 2. A guide to daily runoff from England and Wales 1940-2000. The maximum and minimum outflows for each day of the year are indicated by the light green and pink envelopes. The thick black trace illustrates the actual daily outflows; periods with flows greater than the long term mean daily outflow (shown as the thin black trace) are emphasised by the cyan shading.

Can the October/November 2000 floods and rainfall be linked to climate change?

We address this question first by using statistical methods of trend analysis to look at historical data, to see if there are any signs of changes in the occurrence of events of the type experienced in October/November 2000. We then use climate model simulations of rainfall to see if changes in the frequency of such events are predicted to have occurred already, or to occur in the future.

The evidence of trends in rainfall and river flows

If the UK climate is changing then this could cause trends in rainfall and river flows. Of particular interest in this study are changes in the *extremes*, i.e. the heaviest rainfalls and the highest flows. The statistical significance of observed changes can be evaluated by applying suitable tests for trend (Robson *et al*., 1998). We analysed annual maximum (AM) data, which are commonly used in practice to establish the rarity of rainfall or river flow extremes. We examined AM data sets that included single-day maxima, and maximum values of rainfall or river flows accumulated over longer durations.

This study asks whether flooding and rainfall extremes can be linked to climate change. It does not set out with the aim of detecting climate change *per se*. Evidence for climate change is best sought where natural variability is smaller in relation to underlying ‘signals’, for example at large scales (e.g. global or continental) and for time-averaged variables (e.g. seasonal averages or totals). Although we have used time-averaged variables (in the form of rainfall and river flow totals for periods of up to 90 days), we did not examine seasonal measures explicitly. It is worth noting a recent study (Osborn *et al*., 2000) that showed increases in the contribution to autumn/winter rainfall from the heaviest rain days (i.e. the wettest days getting even wetter) within the latter part of the 20th Century.

Records that are at least 50 years long are recommended for investigating possible effects of climate change on rainfall or river flows, although most records are actually shorter than this. Long records are needed because there is a large natural variability in the UK climate that causes cycles over periods of the order of decades. For records shorter than 50 years, natural variability may give rise to misleading but statistically significant trends: these are ‘trends’ that may disappear in the future. Thus, for records less than 50 years it is very difficult to distinguish between natural variability and anthropogenic climate change. In the following, long time series were used where possible, but short time series were also considered so as to give better spatial coverage and to include sites that lie within the most affected catchments.

Rain gauges with long historical records

The flooding of October/November 2000 was a result of prolonged rainfall. We were therefore most interested in the extremes of rain falling over durations of up to 60 days. At these longer durations, the results of tests for trends in long rainfall records (typically greater than 100 years) were rather variable, although two out of 15 sites with long records showed a statistically significant trend towards more extreme rainfall. There is a lack of spatial coherence in the long-term rainfall results and there remains a possibility that hidden data quality problems affect the results.

Rain gauges with shorter records

Looking at rainfall data available since 1961 suggested different results. For 1-day extreme rainfalls, most sites showed a slight decrease but this was statistically significant at only 1 of 15 sites. For longer duration (60-day) extreme rainfalls, there have been increases since 1961. Five out of 15 sites showed strongly significant trends with the remainder showing nonsignificant but nevertheless upward trends in the size of annual maxima. These changes could be due to climate change or to natural variability.

River flow extremes

Gauged river flow records are generally not as long as rainfall records, and there are very few flow records that date back more than 60 years (five such sites were used here). Studying flood series is important because river flows represent the accumulated effect of rainfall across catchments and through time. However, a problem with using flow records is that long records are prone to error or lack of homogeneity (accurate gauging of high flows is difficult and methods have changed over time).

Floods may be characterised in terms of the highest flow (the peak) or by the duration and volume of the flood. When examined for trends, the longest series of flow peaks (which vary between 60-118 years long, depending on the gauging station) showed mixed behaviour with no clear pattern of change.

River flow data for the last 30-50 years, however, do provide strong evidence of increases in the number of days when river flows are considered to be ‘high’, and increases in the maximum outflows over 30-day and 60-day periods.

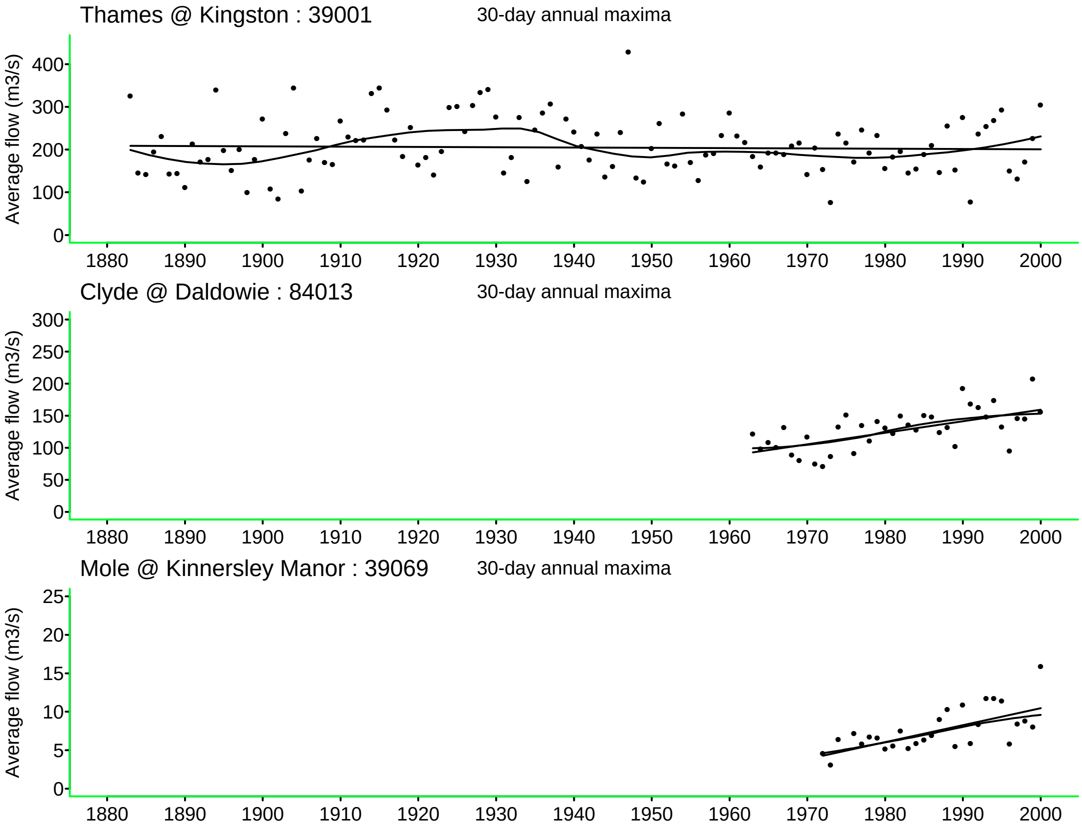

Figure 3. Straight line and ‘smoothing curve’ trends in 30-day annual maximum river flows. No trends are seen on the long series for the Thames, but significant trends are seen at both the Mole and the Clyde. Note from the Thames data that shorter-term increasing or decreasing trends occur throughout the record (as shown by the smoothing curve).

The results of a statistical analysis of trends on rainfall and river flows are that:

- **Long-term rainfall series show evidence that 1-day UK rainfall extremes have increased over the last 100 years. These, however, are not the type of rainfall extremes that are the root cause of the October/November 2000 flooding.**

- **Annual maxima for longer-duration rainfall (which was more important in late-2000) seem to have increased in magnitude over the last 40 years or so, but did not show overall change at individual gauges over the longer term.**

- **We have analysed annual maxima and cannot therefore comment on trends in autumn/winter rainfall specifically. Work by others does indicate a trend towards higher rainfall contributions from 'heavy rain days' during autumn and winter within the latter part of the 20th century (Osborn *et al*., 2000, IPCC, 2001).**

- **The longest available river flow records (60 –118 years) show no clear pattern of trend in flood peaks or in the overall volume or duration of flood flows.**

- **River flow data for the last 30-50 years show strong evidence of increases in the number of days when river flows are considered to be 'high', and increases in the maximum flows over 30-day and 60-day periods.**

- **Long river flow records indicate the changes seen over the last 30-50 years are not particularly unusual when viewed in a historical context. The UK has seen extended periods of high river flows in the past, although not within recent memory.**

- **Rainfall and river flow trends over the last 30-50 years could be caused by climate variability (i.e. they are changes that may not persist) or by 'man-made' climate change.**

The evidence from climate models

The Hadley Centre Regional Climate Model (RCM) nested within a global model has been used to predict the likely change in the frequency of extreme rainfall events caused by anthropogenic climate change. The two existing simulations broadly correspond to (1) the climate of the recent past (taken to be broadly 1960-1990), and (2) how the climate may be at the beginning of the 22nd Century. We have analysed three areas roughly corresponding to RCM grid-boxes in flood affected areas allowing direct comparison with raingauge observations available for the recent past (see Figure 4).

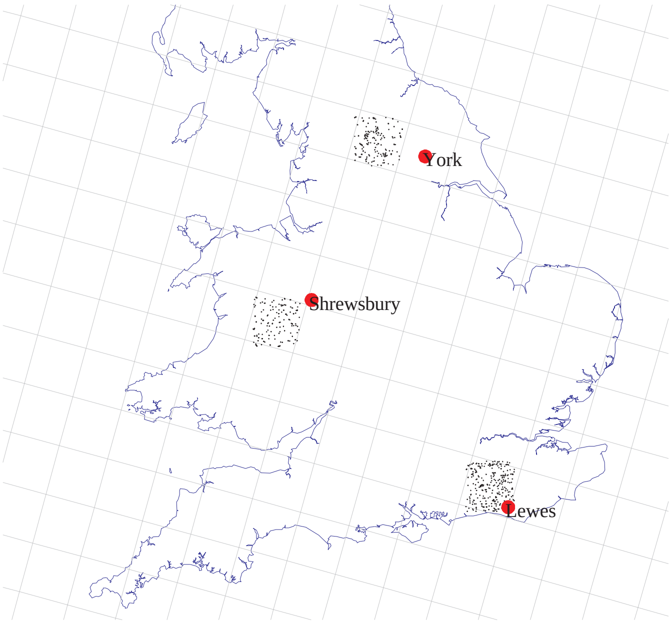

Figure 4. A map of the gridboxes of the Regional Climate Model over the UK (light grey lines). The black dots correspond to the position of the raingauges used for comparison with the RCM. The three selected gridboxes relate to the catchment areas having most influence upon the towns of Lewes, Shrewsbury and York. These towns were particularly affected during the Autumn 2000 floods.

How is the frequency of extreme rainfall events predicted to change?

The analysis in Box 3 shows good agreement between observations and the RCM simulations of the frequency of extreme events. This gives us some confidence in the RCM. However to assess the extreme events of 2000 we need an estimate of how the extreme rainfall distribution may have changed between the mid 19th Century and the present. To do this it was necessary to assume a relationship between changes in the rainfall extremes and changes in global mean temperature, and to interpolate between the two existing numerical experiments on this basis (see Box 4). It should be noted that this assumption has not been tested for extremes.

BOX 3

How well does the RCM simulate observed extremes?

This is the first use of the RCM to predict the frequency of extreme rainfall events and, as an initial step, it is important to test its ability to reproduce the statistical structure of the present conditions. This has been done by comparing the simulated frequency distribution with the observed daily rainfall amounts for 1961-1990. These data were areally averaged over the single 50 km grid squares shown in Figure 4..

For each of the three areas, a series of the Annual Maximum (AM) rainfall was calculated for the gauged rainfall data and the two RCM simulations. Series were calculated for a range of durations, from 1-day maxima up to 60-day maxima. It was the accumulated rainfall over longer durations that was outstanding in October – November 2000; results for the 30-day duration are therefore presented here. Each value in the AM series represents the maximum observed 30-day average rainfall rate (in units of mm/day) within each year. Figure 5 shows the relation between Annual Maximum rainfall and Return Period.

If both the averaged station data and the regional climate model were perfectly representing the climate during the period of record the underlying distribution curves for the data (black) and RCM prediction for the recent past (red) would be identical. Although this is not the case, they are sufficiently close to each other for us to have confidence in the ability of the model to predict extreme events of this type. The good agreement between observations and the RCM simulation of recent climate (black vs red) is an important improvement on previous work.

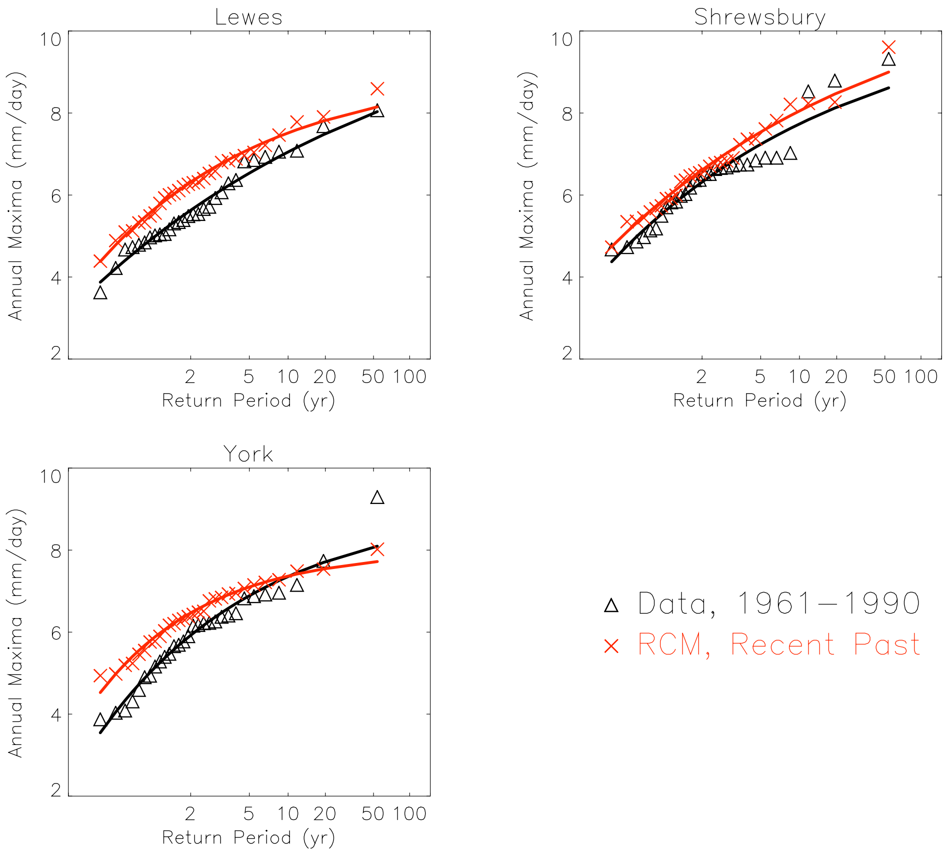

Figure 5. The relation between 30-day duration Annual Maximum (AM) rainfall and Return Period. The plots are for the RCM grid squares near to Lewes, Shrewsbury and York. At each site, data are plotted corresponding to measurements, for 1961-1990 (black triangles) and the RCM simulation representative of recent climate (red stars). Also plotted as smooth curves are the fitted distributions.

BOX 4

Interpolation of the extreme rainfall distribution

There is growing evidence from climate models that changes in many mean climatological variables occur in proportion to the predicted changes in the global mean temperature. It was assumed that this also applies to the extreme rainfall distributions. Global mean temperatures from the Hadley Centre GCM indicate an increase from 1860 to 1975 of 0.8°C, from 1860 to 2000 of 1.3°C and from 1860 to 2100 of 4.3°C. Using these values, it is possible to estimate (from the two existing RCM simulations) the percentage change in extreme rainfall distribution for periods where there is currently no RCM simulation. Such percentage changes are then applied to the observed rainfall data for 1961-1990 in order to construct 'best estimates' of extreme rainfall distributions for chosen periods centred on 1860 and 2000.

Percentage changes from the 1975 RCM simulation (for each return period) were added/subtracted to the 1961-1990 data, providing new estimates of the extreme rainfall distributions for 1860 and 2000 based upon both the data and changes predicted by the RCM.

The interpolation method described in Box 4 allows for predictions to be made of the extreme rainfall distributions for the mid 19th century and for the present climate. Also shown are predictions for a possible future climate for 2090 based upon likely future greenhouse gas emissions. The results are presented in Figure 6.

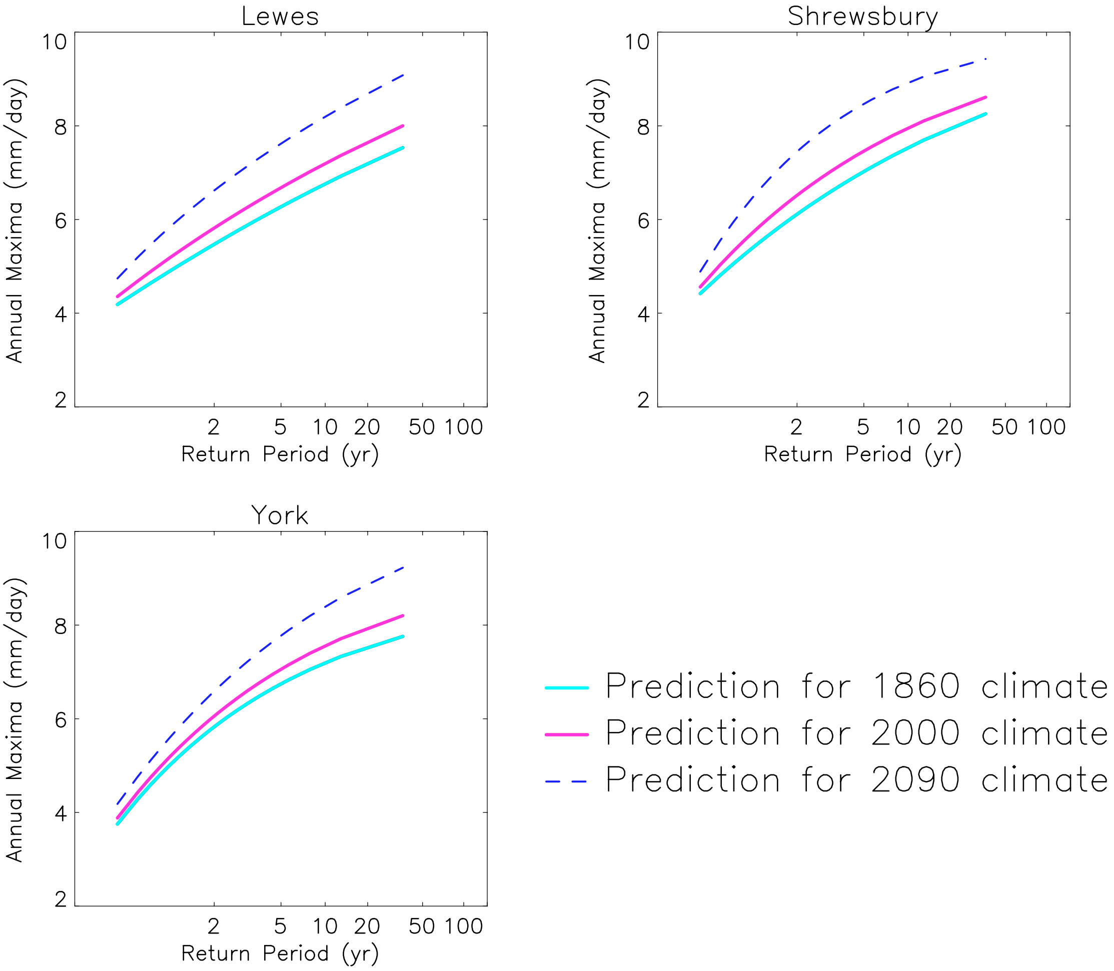

Figure 6. Extreme value distributions as predicted for 1860, 2000 and a potential future climate centred upon 2090.

Based on the 50 km grid boxes, the graphs in Figure 6 can be interpreted as saying that extreme rainfall events over 30-day durations are predicted to have become increasingly common (i.e. a reduction in return period). The precise degree of increase is uncertain as our analysis has been based on a pair of simulations made by one particular regional climate model, driven by one global climate model for one future emissions scenario. However, the concensus emerging from many GCMs and a range of emissions scenarios on future increases in precipitation over high northern latitudes (Giorgi *et al*., 2001) suggests that this may be representative of future climate conditions.

Based on a comparison of the Hadley Centre Regional Climate Model and observed rainfall data averaged over 50 km x 50 km grid squares we can say that:

- **We are confident that the Regional Climate Model (RCM) provides good simulations of rainfall extremes under current climatic conditions.**

- **The RCM predicts that extreme rainfall events of the type experienced in late-2000 should already have become more common (i.e. reduced return period) as a result of human-induced climate change.**

- **Further increases in heavy rainfall frequency are predicted to continue into the future as greenhouse gas concentrations in the atmosphere continue to increase. (This prediction is based on one set of climate model outputs for one future emissions scenario.)**

ASSESSMENT OF THE EVIDENCE

The key statements in the previous section of this report provide a varied body of evidence to be assessed. A basic framework for carrying out this assessment is to express the key questions as propositions (i.e. (1) the October – November 2000 events were unusual; (2) they are linked to climate change) and then judge the evidence for and against these propositions. The main strands of evidence are summarised, and are judged in terms of:

- The degree to which the evidence supports the belief that the proposition is true.
- The degree to which the evidence supports the belief that the proposition is false
- The strength of the evidence for or against the proposition
- The degree of confidence in the evidence itself

We present the key evidence for and against each proposition, and indicate in parentheses the strength of the evidence (i.e. its relevance to the question being asked) and the scientific confidence we have in the evidence (i.e. an indication of the reliability of data, analysis or models).

Where possible, the degree of confidence is based on quantitative tests, but this is not always possible or desirable. We therefore interpret measures of confidence subjectively, based on scientific experience, in terms of ‘high’, ‘moderate’ or ‘low’. As an example, consider a hypothesis of increases in flood frequency: An upwards trend in 50 years of quality-controlled river flow data that was significant at the 99% level would be strong, high-confidence evidence in favour of the hypothesis. The same trend in 20 years of data would be moderate or weak evidence, with high confidence. A significant trend in long but poor-quality data would be strong evidence, but with low confidence.

Proposition 1: ‘The October/November 2000 flooding and rainfall was unusual in the historical context’

Evidence for Proposition 1

1. Taking the combined flows in five major basins as a measure of rivers in England and Wales, total river flows over the period from October to December 2000 were the highest in a record dating back to 1940. For a 30-day period to November 2000, only the snowmelt-dominated flood flows of 1947 were greater – and this was a shorter ‘event’ producing very high runoff rates over frozen ground. The repeated and/or prolonged flooding of winter 2000 was without recorded precedent on many rivers. (**Strong** evidence. **High** confidence).

2. Very brisk seasonal recovery of groundwater levels has been a feature of several recent winters but none compares with the magnitude and rapidity of the 2000 recovery (which began from a relatively high base). For example, the Chilgrove borehole in West Sussex began overflowing earlier in the year than at any time in a 165-year record. The extent and duration of groundwater flooding is without modern parallel. (**Strong** evidence. **High** confidence).

3. Over much of the country, rainfall for October – November 2000 was more than double the long-term average for these months. (**Strong** evidence. **High** confidence).

4. The main rainfall events, which each lasted for several days and affected different regions, produced rainfall amounts with return periods generally of less than 100 years at individual gauges, but some gauges had totals with a rarity of once in 200 years or more. (**Moderate** evidence. **High** confidence).

5. Meteorological observations over the North Atlantic indicate that the conditions during October/November 2000 might be expected on average once in 20 to 100 years. (**Moderate** evidence. **Moderate** confidence – methods for assessing rarity of these conditions are not well established).

6. Weather radar data indicate that certain aspects of the rainfall patterns over the British Isles were very unusual. (**Weak** evidence – only one example found. **Moderate** confidence – limited record lengths and subjective analysis only).

Evidence against Proposition 1

1. Although still notable, flood peak and rainfall return periods for *individual locations* were generally not so outstandingly high, in the sense of there being at least a 50:50 chance of such events happening within the period of gauged records. (**Moderate** evidence. **High** confidence).

2. Weather radar indicate that most rainfall patterns were typical of passage of frontal depressions. (**Moderate** evidence – but not addressing the repeated occurrence of such patterns during the period. **Moderate** confidence).

Proposition 2: 'The October/November 2000 floods and rainfall can be linked to climate change.'

Although the meteorological conditions associated with the heavy rainfall of late 2000 were assessed to be rare, no evidence has been found that these events could only have happened 'because of climate change'. Indeed, given the variable and chaotic nature of weather systems, it is impossible for a climate change 'signal' to be detected in an individual flooding and heavy rainfall episode. Any such effect is more likely to be apparent in the frequency of extremes of rainfall and river flows, or in changes in the magnitude of extremes. The following evidence concentrates therefore on possible statistical links between events of the type experienced in late 2000.

Evidence for Proposition 2

1. Climate modelling predicts that a reduction in the return period of rainfall extremes of the type experienced in late-2000 (i.e. over long durations of say 30 or 60 days) should have already happened since 1860. (**Strong** evidence. **Moderate** confidence – depends on the reliability of climate models).

2. There is evidence from the last 30 or 40 years for increases in the magnitude of rainfall extremes, especially for longer durations. (This evidence is categorised as **moderate** because although taken alone it could be attributed to natural variability, it is consistent with the wider evidence of increases in winter heavy rainfall events. Confidence in the evidence, however, is **high**.)

3. There is similar evidence of increases in the largest annual 30- and 60-day river flows over the last 30 to 40 years, and in the number of days each year when flows are high. (Again, this evidence has to be categorised as **weak** because, in itself, it could be attributed to natural variability and might be affected by land use or gauging changes. Confidence is **high** however.)

4. Recent events have extended the range of recorded river flows and groundwater levels. (**Weak** evidence – this could be natural variability. **Moderate** confidence – only a limited analysis has been possible at this time.)

Evidence against Proposition 2

1. There is an absence of trend in extremes of river flows in catchments with long records. (**Strong** evidence. However, confidence is **low** because of the difficulty of high-flow gauging and the possible effects of factors such as land use change, changes in gauging methods and operation of flood defences.)

2. There is an absence of significant trends in annual maximum data from longer-term rain gauge records. (**Moderate** evidence – this analysis does not consider seasonality. **Low** confidence – only a few gauges with long records are available.)

3. When viewed in a historical context, the extreme rainfall and river flows of late 2000 are rare, but do not appear to be inconsistent with recorded variability at individual locations. (**Moderate** evidence – difficult to distinguish natural variability from climate change. **Moderate** confidence – based on ranking and time series plots.)

Summing up the evidence

The evidence for and against the two propositions is summarised in Table 1 below. The structured assessment could, in principle, be extended to give numerical estimates of the degree to which each item of evidence supports or refutes a proposition. However, such quantitative procedures can give a misleading impression of objectivity. We believe that it is more useful and informative to adopt qualitative measures of the strength and confidence of the evidence in this context.

Table 1. Structured assessment of the scientific evidence. ('Mod.' = moderate.)

Proposition *H* =	**Evidence**	**Support for *H* = true**	**Support for *H* = false**	**Strength of the evidence**	**Confidence in the evidence**
'The October - November 2000 flooding and rainfall was unusual in the historical context'	River flows (national scale)	✓		Strong	High
	River flows (localised)		✓	Mod.	High
	Groundwater (regional)	✓		Strong	High
	Rainfall (national, whole period)	✓		Strong	High
	Rainfall (regional, main events)	✓		Mod.	High
	Rainfall (radar patterns)	✓		Weak	Mod.
	Rainfall (radar patterns)		✓	Mod.	Mod.
	Rainfall (localised)		✓	Mod.	High
	Synoptic situation	✓		Mod.	Mod.
'The October - November 2000 floods and rainfall can be linked to climate change.'	Climate model simulations	✓		Strong	Mod.
	Trends in river flows (1960-)	✓		Weak	High
	Trends in rainfall (1960-)	✓		Mod.	High
	Ranges of river flows	✓		Weak	Mod.
	Ranges of groundwater levels	✓		Weak	Mod.
	Trend (river flows, long records)		✓	Strong	Low
	Trend (rainfall, long records)		✓	Strong	Mod.
	Historical range of extremes		✓	Mod.	Mod.

Conclusions to be drawn from the evidence are as follow:

1. It is clear that the flooding episode in Britain during October/November 2000 was highly unusual, particularly in respect of the extent, duration and persistent nature of the heavy rainfall and consequent flooding. The total rainfall over the whole period was extreme; rainfall for September to November was the highest on record for those three months. The

October – November 2000 rainfall was more then twice the average for those months, and had a return period of greater than 200 years, over much of Britain.

In rivers, it was the repeated and widespread occurrence of flood flows that was particularly unusual. Combined data for major basins showed the highest or second-highest (depending on the measure chosen) river flows in England and Wales in a record from 1940, and the highest since 1947.

2. The root cause of the flooding was a succession of frontal weather systems that crossed the British Isles during the period. These brought widespread rain with radar images clearly showing embedded cells of very heavy rainfall. The extent and slow moving nature of the rainfall shown on radar images for particular dates was judged to be unusual, but it is difficult to be more precise than this about the rarity of patterns seen in radar images.

3. The weather of the period was associated with strong patterns of pressure and sea surface temperatures over the North Atlantic. Quantitative analysis indicates that these strong gradients have return periods in the range of approximately 20 to 100 years. Although some aspects of the meteorological conditions leading up to and during the flooding were rather unusual, it is not possible to link these conditions directly to climate change.

4. We have therefore also considered possible evidence of statistical links between climate change and heavy rainfall/flooding events, especially those of the type experienced in late 2000 (i.e. extremes over durations of say 30 or 60 days). Short-term records (i.e. dating from roughly 1960 onwards) of annual maximum rainfall and river flows show some evidence of systematic increases in the magnitude of extreme events of the type experienced in late-2000.

   On the other hand, long-term annual maximum data on rainfall and river flow extremes do not reveal trends over the longer periods of record (roughly 100 years or more). These longer records do show considerable variability, raising questions over whether the more recent trends are simply a sign of natural climatic variability, as opposed to on-going climate change.

   Apparent short-term (approximately 20-40 year) trends in gauged rainfall and river flows are found throughout long records. It is therefore difficult to distinguish underlying changes from background variability. This is particularly so when we have only a limited amount of data to look at. Whilst increases in temperature at the continental scale over the last three decades have been attributed to human-induced climate change, possible links to regional scale weather patterns or to flood frequency are not conclusively known.

   What can be said is that the data on annual maximum river flows and rainfall are consistent with predictions of increasing magnitudes or frequencies of extremes. These data are not sufficient to prove that trends over the last 30-50 years are either natural variability or climate change (and, if the latter, whether this is human-induced or not). The annual maximum data are also not inconsistent with observations of greater contributions to winter rainfall from ‘heavy rain days’ since the 1960s, a finding that is in line with predictions of human-induced climate change. Indeed, it is a limitation of the current short study that *seasonal* measures of extremes could not be examined as well as *annual* maxima.

5. The synthetic rainfall extremes generated using the Regional Climate Model (RCM) incorporate a degree of variability as found in natural data. RCM simulations of rainfall extremes for the recent past have been compared with observed rainfall data, giving us a

degree of confidence in the climate model outputs. We have therefore used the RCM to model likely changes in rainfall extremes between 1860 and the year 2000. The climate modelling indicates that increases in the frequency of rainfall extremes should have happened, if the model and interpolation scheme are reliable.

6. Given that there is some degree of confidence on the predictions of the climate models, how can the results be reconciled? The answer lies in the balance between *variability* and *underlying change*.

   The recent trends in rainfall and river flows could be attributed to anthropogenic climate change, or to natural variability. Theoretical links between climate change and changes in rainfall (and hence river flows) are complex and difficult to demonstrate conclusively. However, it has been found (Stott and Tett, 1998; Stott *et al*., 2000) that human-induced forcing has dominated the increases in *temperature* at the continental scale over the last three decades of the 20th Century.

   There is also considerable year-to-year random variability in rainfall (and river flow) extremes. This, coupled with a high degree of spatial variability in rainfall, means that estimates of the frequency of extreme events may not have changed significantly in individual gauged records, even if there has been some, as yet relatively small, underlying change.

7. The Regional Climate Model has also been used to predict the statistical distribution of rainfall extremes for the year 2090. These predictions have been based on a scenario for greenhouse gas emissions of 1% compound increases per year from 1990 to 2100. Under this scenario, the RCM predicts future increases in the frequency and magnitude of rainfall extremes, including extremes over 30- and 60-day durations.

   Clearly, if extreme rainfall events become more common, it is to be expected that flooding will also become more common. It is more difficult to say just how much effect any increase in the frequency of rainfall extremes will have on flooding. This is because the effect of rainfall on river flows can be a complex process, governed by the local patterns and timing of rainfall. Whilst these factors are more important for shorter flood events than for long-duration events of the type experienced in October/November 2000, we would still not expect an exact one-to-one relationship between changes in the frequency of extreme rainfalls and the resulting changes in flood frequency. The form of the relationship can only be determined using hydrological modelling.

CONCLUSIONS

The conclusions of the four-month study FD2304, carried out by CEH Wallingford and the Met Office for DEFRA, are:

1. The floods of October/November 2000 were unusual, particularly in extent and duration: Over five major basins in England and Wales, total river flows for October – December were the highest over 90 days in a record since 1940.

2. The floods were caused by heavy rainfall from repeated frontal depressions passing over the British Isles. Over much of Britain, October/November rainfall was at least twice the long-term average for these months, with return periods of greater than 200 years. Autumn (September – November) England and Wales rainfall was the highest on record.

3. Some of the meteorological features of October/November 2000 were unusual. It is not possible to demonstrate a direct link with climate change in view of the complexity of the climate system and the randomness apparent in the occurrence of individual ‘weather events’.

4. There is evidence of increasing rainfall and river flow extremes in Britain in the last 30 to 40 years, especially for longer durations (e.g. 30 or 60 day running totals). Wider evidence, in the UK and globally, also shows increases in winter season heavy rainfall events. This evidence is consistent with *predictions* of human-induced climate change. It has not been shown that *observed* changes in precipitation can be attributed to human activity.

5. The Regional Climate Model used in this study provides realistic simulations of the magnitude and frequency of rainfall extremes in the recent past. It also predicts that the frequency of rainfall extremes will have increased since 1860.

6. The changes predicted in extreme rainfall frequencies between 1860 and the present day are small compared to natural variability. We would not therefore expect detect such changes in frequency easily in recorded data, even if they are occurring. (However, see Conclusion 4).

7. The Regional Climate Model predicts further increases in extremes of rainfall accumulating over one or two month durations, as experienced in October/November 2000. Increases in the frequency of *flooding* can be inferred, but require further work to be quantified.

We can therefore conclude that:

- **The events of October/November 2000 were extreme, but cannot *in themselves* be attributed to climate change. However, heavy rainfall and peak river flows of similar durations have been increasing in frequency and magnitude over the last 50 years.**

- **This pattern is consistent with model predictions of how human-induced climate change affects rainfall. However, it is not yet possible to say how far events such as those of October/November 2000 can be attributed to climate change as opposed to natural variability.**

RECOMMENDATIONS FOR FUTURE RESEARCH

Summary of priorities

We recommend the following agenda as the highest priority:

1) improve global and regional model capability to predict future extremes of local rainfall
2) enhance and develop rainfall and flood flow data resources
3) advance methodologies for flood risk analysis
4) link hydrological and climate models to estimate catchment flood risk in a changed climate.

These are expanded below.

1) Strengthening the climate modelling capability

The extent to which the October/November 2000 floods were due to climate change cannot be answered by observational data alone, but only in conjunction with climate model simulations. Changes in rainfall characteristics can also only be assessed by using climate models. Yet even the best current climate models do not simulate well the climatology of the fronts and depressions which lead to heavy rainfall - this is reflected in substantial uncertainty in predictions of changes in rainfall over the UK.

a) Better estimates of rainfall will come from global climate models with a greater resolution (around 100km) than those in use today (about 3-400km), but to take full advantage of higher resolution also requires improving the representation of critical processes, for example clouds and rainfall. We recommend that the high resolution global model, currently under construction, be enhanced in this way as soon as possible.

b) In parallel with this, we recommend the development of regional models at even higher resolution (10-25km) than those used in this report. These, when embedded in the global model, will take account of the effect on rainfall of features such as hills and coasts.

c) Flooding at some locations in 2000 arose from a combination of high river levels (due to heavy rainfall) and high estuary levels (due to elevated sea level). Sea levels will increase in future due to climate change, and we recommend that research is carried out to better estimate sea level rise at a regional scale.

d) We recommend research to quantify the uncertainty of predictions (e.g. in extreme rainfall) in a statistically rigorous way which enables their use in risk analyses. This could be done using a large number of climate models to generate a distribution of possible outcomes.

e) The major constraint in a better attribution of recent heavy rainfall events to climate change is the huge natural variability of climate. We recommend increased research into quantifying and understanding natural climate variability (e.g. the North Atlantic Oscillation).

2) Enhancing and developing data resources for flood analysis

a) High resolution, high quality, climate data for the UK are essential for the monitoring and analysis of extremes of climate, the validation of climate models, and applications to impacts studies. Because of the high natural variability of UK climate, we recommend the analysis of as many rainfall station data as possible, back as far as possible in time. This will require digitisation and quality control. Rainfall data should be gridded, as this will allow the analysis of extremes at any point or over any area.

b) This study has identified the need for a comprehensive analysis of radar data dating back to 1988 to look at spatial variability of rainfall on a national scale. We recommend that the October/November 2000 rainfall should be placed in the context of these 13 years and compared with the Easter 1998 floods, those of 1993, 1994 and other significant events.

c) Many high flow records include ‘artificial’ influences, for example due to land-use change or changes in measurement techniques. This, allied to the difficulty in extrapolating from trends in rainfall to trends in floods, underlines the importance of capitalising on index river flow series. The establishment of ‘benchmark’ catchments is an important means of strengthening the national capability to identify and interpret trends in flood magnitude, frequency and seasonality. A need for such an improved capability has been identified in a review of national policy objectives for hydrometric networks (Anon. 1999). We recommend extending the programme of the National River Flow Archive (maintained by CEH Wallingford) to incorporate the necessary additional flood information.

3) Improving methodology for flood risk analysis

a) The spatial coincidence of flooding in many parts of the country was a notable feature of October/November 2000. Whilst methods for estimating the expected frequency of flooding in specific locations are well-established, the techniques available for estimating the frequency of spatial patterns of flood are not well-developed. We recommend developing analytical techniques for assessing flood risk over large areas that will allow us to quantify the risk of different regions of the country experiencing severe flooding at the same time.

b) Methods for estimating the frequency of floods generally assume that past records contain no underlying trend in the size or frequency of extremes. Given that we have climate model predictions of increases in the frequency of rainfall extremes, we recommend the development of analytical techniques for assessing and presenting flood risk under changing conditions. This would help both in analysing past data for evidence of climate change, and in understanding and summarising the predictions of models of future rainfall and flood extremes (see below).

c) We recommend that the methods used to calculate return periods of rainfall events for n-month rainfall totals (the Met Office Tabony Table) should also be improved to produce a methodology that provides return period estimates for such extreme events as those in 2000.

4) Improved estimates of future flood risk by driving hydrological models with the Regional Climate Model.

The current analysis was restricted by the limited number of existing model simulations and is best regarded as a pilot study. An important result is that the Regional Climate Model (RCM) used in this study predicts reductions in extreme rainfall return periods in a greenhouse gas enriched atmosphere. We recommend a study specifically designed to derive the most accurate estimates of the changes in return period of extreme hydrological events to be expected under future climate conditions. This will closely link the RCM with catchment hydrological modelling to provide flood risk estimates of benefit to catchment flood management in a changed climate.

The research path should be as follows:

a) Establish how well combining the RCM with hydrological models predicts actual river flow in the UK, by nesting the RCM within the European Centre for Medium-Range Weather

Forecasting (ECMWF) reanalysis data rather than the GCM predictions of large scale weather. The ECMWF archive gives a close approximation to the actual, observed weather patterns. Where possible, the RCM and catchment models should be improved or adjusted to give the best representation of observed river flow.

b) Remove the need for interpolation by making a set of RCM (time slice) runs for greenhouse concentrations representing 1860, 1975, 2000, and at several points up to the expected level in 2100. Ensemble integrations are required to improve extreme statistics.

c) Complete the analysis for the whole country (rather than just the three squares analysed here), linking the modelled rainfall data directly to catchment models of river flow (as in (a)).

d) Extended the analysis to cover droughts and low flows as well as high rainfalls and floods. Although current emphasis is understandably on floods, the prospect of more severe summer droughts has serious implications for water resource management.

e) Identify and understand the underlying changes to the physical processes driving predicted changes in extreme hydrological events.

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Detailed discussion of the methods and results summarised in this report may be found in the project FD2304 Technical Report to DEFRA.

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