

A climate change report card for water

Working Technical Paper

10. Future flood – magnitude and frequency

Professor Robert L. Wilby

Department of Geography, Loughborough University, LE11 3TU, UK

EXECUTIVE SUMMARY

This Report Card provides an appraisal of the evidence for potential changes in flood magnitude and frequency based on climate model results. The majority of climate model experiments point to increased flood hazard for the UK linked to more extreme precipitation events and greater winter rainfall totals by the 2080s. One study claims that past greenhouse gas emissions (the 'human fingerprint') have already increased the risk of major flooding events like autumn 2000.

Observed records show variability in flooding from one decade to the next but convincing long-term trends are harder to discern. Most studies are based on relatively short periods of data (often beginning in the 1960s) and predisposed to an upward trend by the extreme flooding outliers in year 2000 (and now 2012) associated with anomalously warm conditions in the North Atlantic. Sustained trends are also conspicuously absent in reconstructed flood indices (see below). However, it may be too soon to expect a clear signal of greenhouse gas forced change to have appeared in UK flood records. Understanding the drivers of North Atlantic storminess remains a very active research area.

An objective weather classification was used to reconstruct the atmospheric constituent of fluvial flooding in England, Scotland and Wales since the 1880s. Flood rich episodes were identified in the periods 1908-1934, 1977-1988 and from 1998 onwards. Five weather types account for 68% of flood occurrence, and just three types are associated with the most widespread winter floods. Nevertheless, these flood-generating weather types generally show no sustained changes in frequency, persistence, relative contribution, or rain-bearing properties since the 1930s.

So how might climate model, measured and reconstructed flood records be reconciled? First, recent studies point to gross model errors in the representation of the global hydrological cycle and rainfall-generating processes. Second, model experiments do not incorporate important factors such as the historical role of aerosols which are known to influence regional climates. Third, climate models have been calibrated in ways that do not reveal the true extent of uncertainty in future climate projections. Fourth, even if perfect models were available, the climate change signal is not expected to be detectable (given large variability in extreme precipitation metrics) for many decades.

Given the above points, it is more fruitful to evaluate future flood risk from first principles. The Clausius-Clapeyron constant predicts an increase in the moisture-holding capacity of the atmosphere of approximately 7% for each degree Celsius temperature rise. Therefore, at the global level, projected warming is expected to increase the likelihood of extreme precipitation events. However, the regional response will depend on important dynamical controls such as changes in storm track position and persistence relative to local orographic uplift of moist air streams. Working out how greenhouse gases and other drivers might influence these aspects of climate is also the subject of on-going research.

On the basis of the evidence examined in this Report Card the conclusion is:

FUTURE FLOOD RISK – LOW/MEDIUM CONFIDENCE - RISING

1. Introduction

Links between climate change and flooding attract considerable research interest in the UK. Contrary to trend analyses based on historical river flows – which suggest no long-term change in flooding (Hannaford and Marsh, 2008) – most studies involving climate models report increased risk of flooding under a changed climate (Wilby et al., 2008; Kay and Jones, 2012; Ramsbottom et al., 2012). The latter typically apply one of two approaches: 1) infer future flooding from changes in extreme precipitation (pluvial risks); or 2) downscale climate scenarios to river basins for continuous river flow simulation and/or frequency estimation (fluvial risks).

Pluvial studies generally report greater increases to multi-day precipitation totals, and proportionately greater changes to extreme- than light- or single-day events. The accepted explanation (according to the Clausius-Clapeyron equation) is that a warmer atmosphere holds and precipitates greater volumes of moisture.

Fluvial studies show mixed results as a consequence of complex interactions between regional climate change signatures and local variations in catchment properties. Until relatively recently most fluvial flood risk assessments were based on a small number of catchments so generalizing to other sites was problematic. However, the *Foresight Flood and Coastal Defence Project* (Evans, 2004), *Defra's Regionalised Impacts of Climate Change on Flood Flows* (Reynard et al., 2009; Prudhomme et al., 2010 a; b), the UK's first *Climate Change Risk Assessment – Floods Sector Report* (Ramsbottom et al., 2012), and *Climate change – is the UK preparing for flooding and water scarcity?* (ASC, 2012) have shaped national perspectives on flooding under climate change.

This report card begins with a long-term view of flooding reconstructed from atmospheric weather patterns for hydrometric regions in England, Scotland and Wales. Section 3 introduces the most significant uncertainties affecting regional climate change scenarios and hence outlooks for flood risk in the UK. A summary of expected changes in pluvial and fluvial flooding is also provided. Section 4 takes a deeper look at the accuracy of climate predictions by exploring some of the underlying assumptions of the modelling. Section 5 then considers the extent to which changes in future flood risk might be detectable given large inter-annual and multi-decadal variations in peak flows. Section 6 approaches the issue of flooding from a process-based perspective in order to envisage the kinds of weather that deliver extreme floods. The final section sums up the evidence reviewed.

2. Reconstructing fluvial flood risk for Britain

Trends in observed river flows are described by Report Card 3. However, Wilby and Quinn (2013) specifically examine the influence of atmospheric weather patterns on long (>50 year) Annual Maximum (AMAX) and peak over threshold (POT) flood records held in the HiFlows-UK archive. Flood peaks recorded at 114 stations were stratified using an objective classification of daily Lamb Weather Types (LWTs) (Lamb, 1972; Jenkinson and Collison, 1977; Jones and Kelly, 1982; Jones et al., 2013). The analysis determines which LWTs are relatively flood-rich and which are flood-poor. By combining weights for flood occurrence (Figure 1) with the annual frequency of LWTs (Figure 2) it was then possible to reconstruct time series of regional/national flood occurrence from 1871 to 2011 (Figure 3). The study also investigated the extent to which the rain-bearing properties and persistence of the most important LWTs have varied since 1931 using the daily England and Wales, and Scotland Precipitation series (Alexander and Jones, 2001) (Figure 4).

Figure 1 shows the relative loadings (weights) on POT for concurrent LWT, by hydrometric region and for Great Britain as a whole. Similar profiles emerge for AMAX (not shown). On average, all pure and hybrid cyclonic (C-type) weather patterns are flood-rich (i.e., have loadings greater than one); conversely, on average all concurrent pure and hybrid anticyclonic (A-type) weather patterns are flood-poor. Directional weather types show mixed behaviour: those from the northeast (NE), east (E), southwest (SW) and west (W) tend to be flood-rich; those from the southeast (SE), south (S), northwest (NW) and north (N) tend to be flood-poor. Across Britain as a whole, five weather types accounted for ~68% of recorded POT during the period 1961-2000. In order of importance these LWTs were the C (30%), SW (14%), W (12%), CSW (7%) and CW (5%) types.

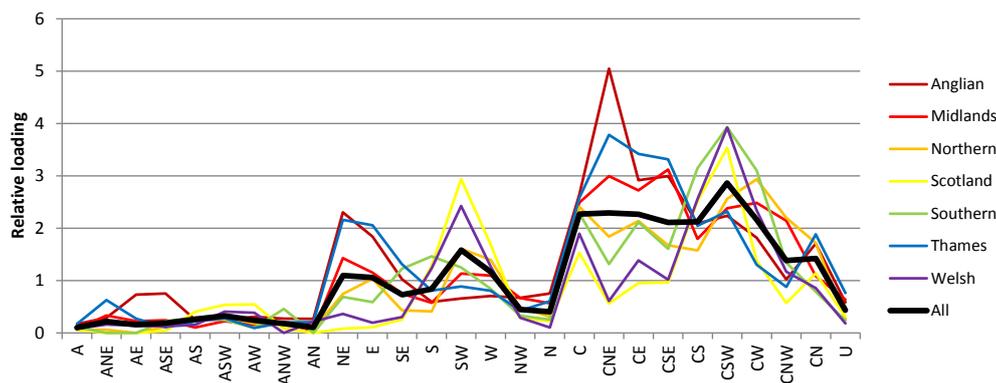


Figure 1 Ratios of observed to expected frequencies of Peaks Over Threshold (POT) flood frequencies by hydrometric region and Lamb Weather Type for the period 1961-2000. The Lamb (1972) catalogue is classification of daily atmospheric flow across the British Isles with seven main categories of synoptic pattern. These are the anticyclonic (A), easterly (E), southerly (S), westerly (W), northwesterly (NW), northerly (N) and cyclonic (C) types. Remaining days are classified into 19 hybrid combinations of the main types, such as the cyclonic westerly (CW) or cyclonic northeasterly (CNE) types.

Some notable regional variations emerge in the flood loadings (Figures 1). For example, C-types generally have loadings much greater than one (except CNE, CE, and CSE in Scotland and Wales; and CNW in Midlands, Scotland and Southern regions). The W-types (SW, W) have mixed loadings (greater than one in Scotland and Wales, and Southern England [MSLP data], but less than one elsewhere). The subtleties of the LWT loading profile also depend on the sites in the hydrometric network, choice of flood index, LWT catalogue, and sample period (Wilby and Quinn, 2013).

The top 10 floods (in terms of simultaneous recordings of AMF) all occurred in the winter half year and were generated by weather patterns with a C-, W- or S- component. The most extensive AMF in the record (14 December 1960) affected 34% of active stations in the network (under a CW-type). For comparison, the widespread summer flash flooding of 20/21 July 2007 generated AMFs at 14% of the stations (again under a C-type). The greatest proportion of stations to be affected by an A-type pattern occurred on 6 August 1981 when about 10% returned their AMF on that day. Hence, the prevailing LWT conditions not only the likelihood of a flood occurring and the associated magnitude, but also the spatial extent of the event (i.e., joint occurrence at multiple sites).

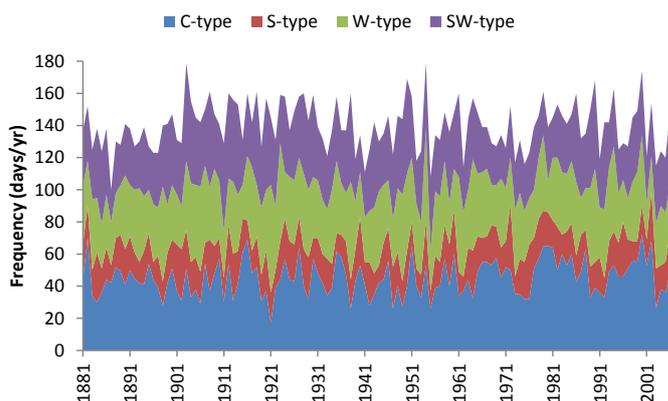


Figure 2 Annual frequencies and combined counts of the four Lamb Weather Types that

generate most widespread flooding in Britain.

Overall, the LWT catalogue suggests a slight decline in annual anticyclonic- and westerly-weather, and rise in cyclonic patterns, but none of these trends is statistically significant. However, there has been a weak but statistically significant increase in the annual frequency of the pure cyclonic type since 1881 (Figure 2). The annual frequency of the C, S, W and SW types combined shows considerable inter-annual and multi-decadal variability (see also Figure 4, below).

Figure 3 shows mean daily precipitation totals for England and Wales (left) and Scotland (right) under the three main LWT groups, for the winter half-year. C-type series show increased wetness between the 1970s and 2000s consistent with a strengthening positive phase of the North Atlantic Oscillation (NAO) (Wilby et al., 1997). Similarly, A-types became significantly wetter over the same period ($p < 0.001$). There is a slight tendency for wetter W-types in England and Wales whereas yields in Scotland exhibit multi-decadal variability. Trends for average rainfall yields are less consistent in summer (not shown). The most noteworthy patterns are a significant ($p < 0.001$) rise in wetness for the A-type in Scotland, and step- reduction in C-type yields also for Scotland after the 1970s. Furthermore, the A-type group exhibits a statistically significant trend ($p < 0.001$) of decreasing persistence which translates into fewer blocking episodes and shorter dry-spells.

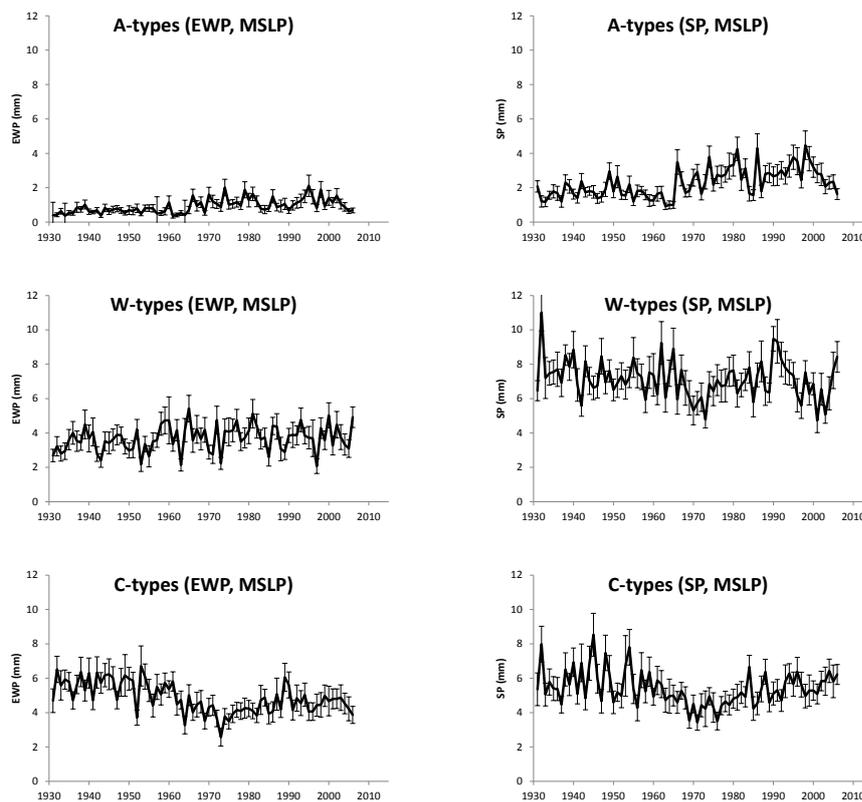
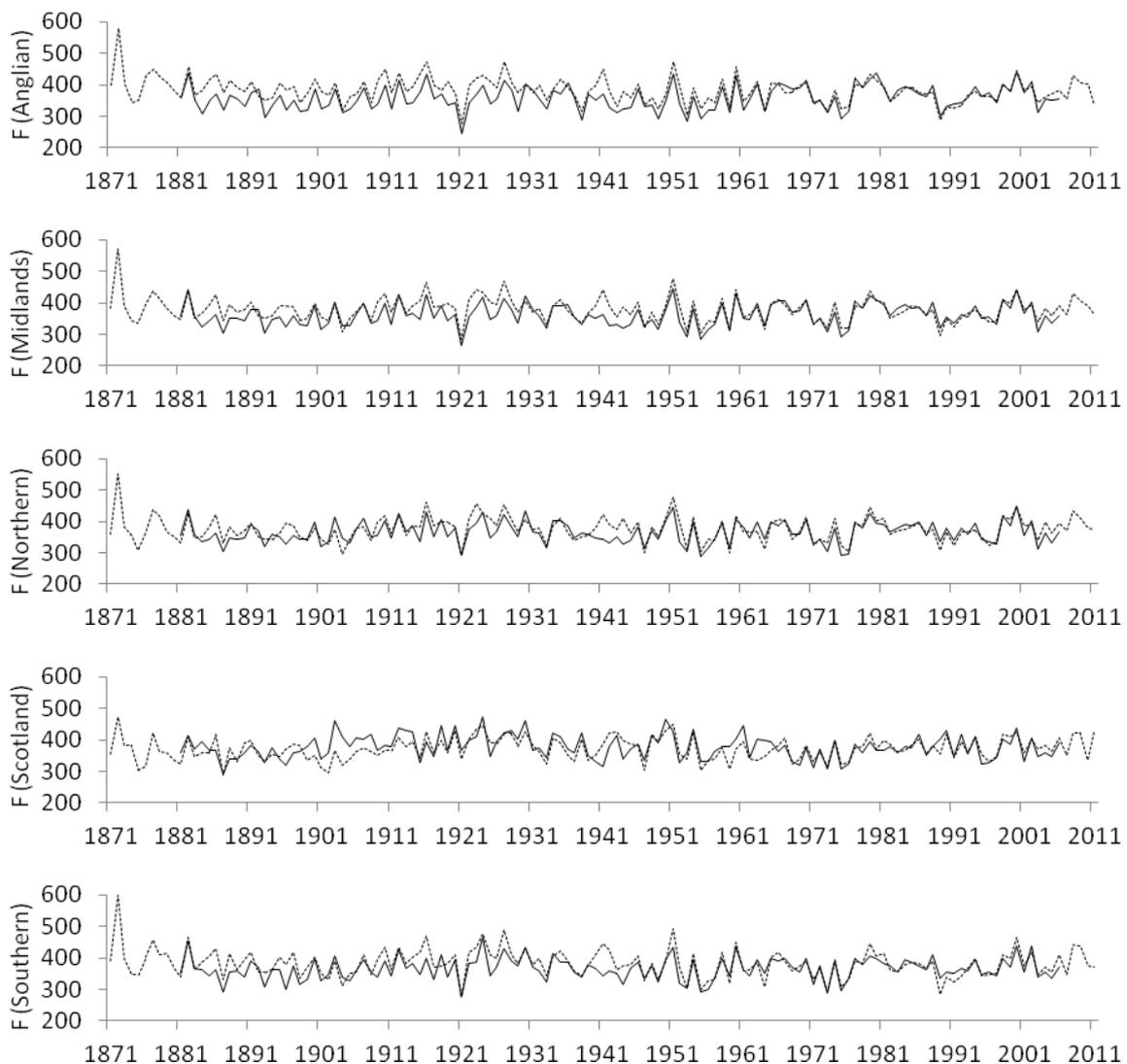


Figure 3 Annual daily mean precipitation amounts across England and Wales (left column) and Scotland (right

column) for the three main LWT groups. Error bars show the standard error of the estimate.

When the annual frequencies of these important LWTs (and all the others) are multiplied against their respective loadings in Figure 1, the aggregate gives an index of flood occurrence (Figure 4). The British flood index shows no long-term trend but is above long-term average (i.e., flood-rich) during the periods (i) 1908-1934; (ii) 1977-1988; and (iii) from 1998-onwards (Figure 4). Year 2000 returned the largest average index ($F=445$) using the Lamb (1972) catalogue. These flood rich episodes are qualitatively consistent with earlier work based on England and Wales annual maximum monthly rainfall totals and average numbers of POT events each year (Robson, 2002). Furthermore, notable winter floods such as 1872, 1916, 1928, 1951 and 2000 are detected by the index, as are major low flow episodes in 1890-1910, 1921, 1959, 1976 and the 1990s (Marsh et al., 2007).



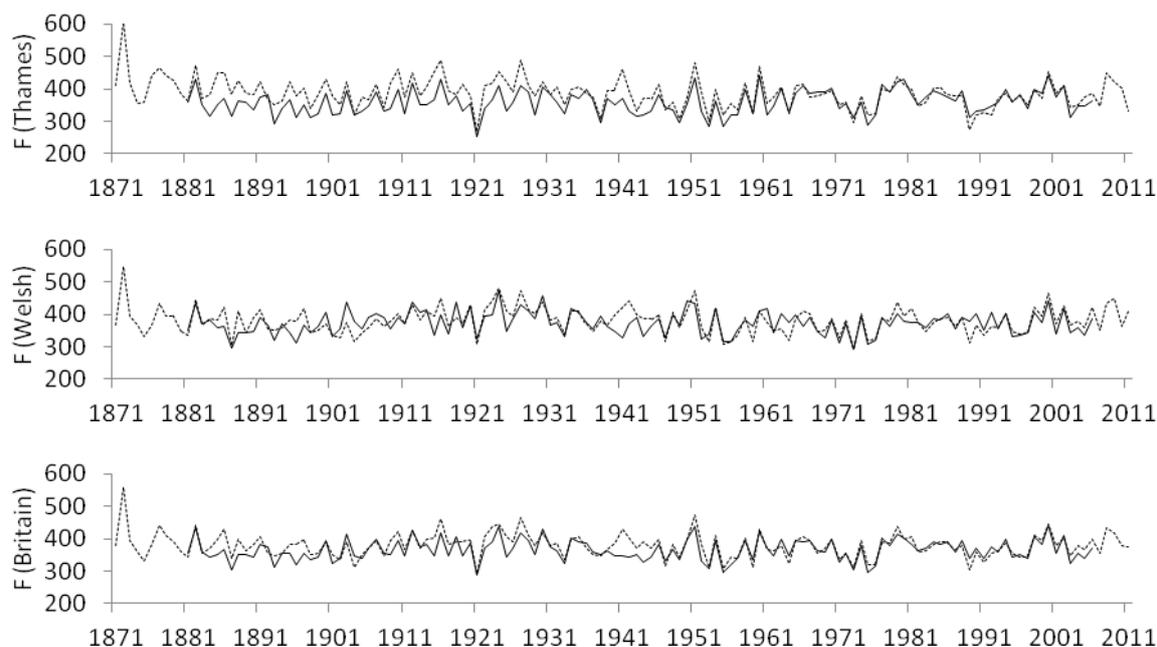


Figure 4 Annual flood frequency index by region derived from observed (solid) and re-analysis (dashed) LWT catalogues.

3. Climate model scenarios of UK flooding

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) is the premier synthesis of information on global climate change science, impacts and adaptation. The IPCC-AR4 report provides a synthesis of the state of scientific knowledge up to the year 2007 but will be superseded by the Fifth Assessment Report in 2014. These reports and other regional assessments provide high-level statements about climate-related changes in pluvial and fluvial flooding and research priorities (see Box 1).

Box 1 Summary of *Climate: Observations, Projections and Impacts Report for the UK*. Adapted from: Met Office <http://www.metoffice.gov.uk/media/pdf/t/r/UK.pdf>

Precipitation and pluvial flooding

- Rainfall extremes are generally projected to increase, particularly during winter.
- Changes during summer are more uncertain.
- Recent research on precipitation extremes over the UK has focused upon understanding and quantifying uncertainties, and on the detection and attribution of climate change.

Fluvial flooding

- Several European-scale and national-scale assessments suggest increased flood risk with climate change in the UK.
- Simulations from the AVOID programme support this. For the UK as a whole, the projections show a much greater tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario.
- National-scale studies have also shown that the UK exhibits a high degree of spatial variability in the sensitivity of rivers to changes in climate, and projections of changes in flood hazard show large uncertainty, which is mainly due to climate modelling uncertainty.
- Further work is needed to better account for the influence of natural variability and the uncertainties related to climate scenarios.

Total uncertainty in global precipitation and temperature projections is conventionally divided into natural (internal) climate variability, climate model (structure and parameter) uncertainty, and radiative forcing (scenario) uncertainty (Figure 5). Depending on region, natural climate variability

contributes 50–90% of total uncertainty over the next decade and remains the dominant source of uncertainty for 30 years (Hawkins and Sutton, 2010).

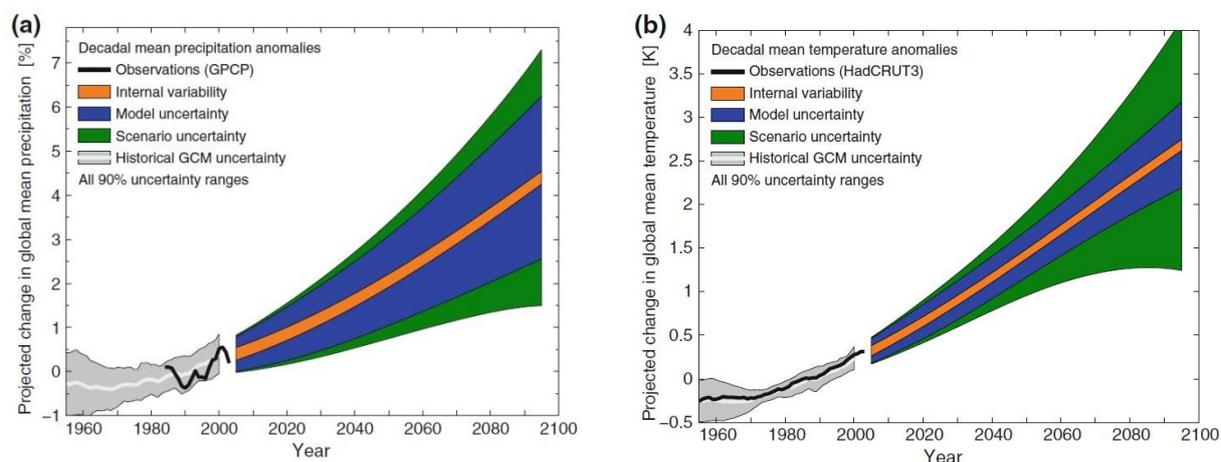


Figure 5 The total uncertainty in CMIP3 global mean, decadal mean projections for the 21st century, separated into three components: internal variability (orange), model uncertainty (blue) and scenario uncertainty (green). The grey regions show the uncertainty in the 20th century integrations of the same GCMs, with the mean in white. The black lines show an estimate of the observed historical changes. (a) Precipitation, with observations from GPCP v2.1. (b) Temperature, with observations from HadCRUT3. All anomalies are calculated relative to the 1971–2000 mean, except for the precipitation observations, for which a 1979–2000 mean is used. Source: Hawkins and Sutton (2010)

Climate model uncertainty dominates over intermediate time horizons, whereas emissions scenario uncertainty increases with time and is greatest by end of century. However, because of missing feedbacks and forcings the “total” uncertainty is likely to be under-estimated. Furthermore, it has been shown that the effective sample size of the CMIP3 multi-model ensemble is probably only five to ten independent models (Jun et al, 2008). A more diverse set of process representations, parameterizations and initial conditions would be expected to inflate the uncertainty still further.

Changes in climate at regional scales are of greater interest to decision-makers. Modelling groups such as the UK Met Office Hadley Centre provide summaries of national weather statistics, past climate trends, predictions of future climate and associated impacts. These help convey the level of uncertainty spanned by climate model ensembles such as multiple runs of HadRM3H (Ekström et al., 2005; Kay et al., 2006), EU PRUDENCE (Fowler and Ekström, 2009) or UKCP09 (Murphy et al., 2009). For example, by the 2080s projected changes in precipitation on the wettest day of winter could lie between -10% and +50% in southern England by the 2080s (Figure 6). Summer heavy rainfall changes are even more uncertain: these lie in the range -50% to +30% in the same region. However, a projected shift in the timing of peak extreme rainfall from late summer to autumn in the east of the UK could imply higher risk of flooding (Schindler et al., 2012).

Uncertainty is further inflated by downscaling and hydrological modelling of rivers flows at the river catchment scale (e.g., Cameron et al., 2000; Cameron, 2006; Harding et al., 2012; Wilby and Harris, 2006). For example, the AVOID programme estimated that UK flood risk could change by -20% to +70% by the 2030s, and one projection gives an increase as high as +360% by 2100 (Figure 7). The UK Climate Change Risk Assessment (CCRA) projects that annual flood damages from tidal and river flooding could increase by between 70% and 400% by the 2080s (Ramsbottom et al., 2012). However, these figures do not reflect changes in population or property numbers, nor take account of existing flood risk management measures.

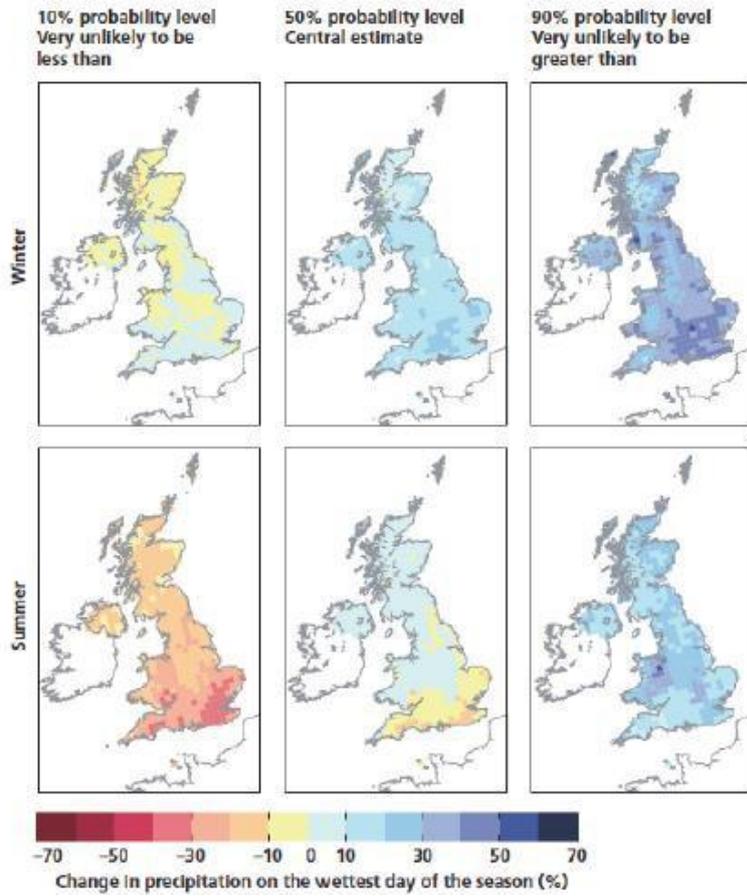


Figure 6 UKCP09 changes in precipitation on the wettest day of the winter (top) and of the summer (bottom) at the 10, 50, and 90% likelihood levels for the 2080s under a medium emissions scenario.

Source: Murphy et al. (2009).

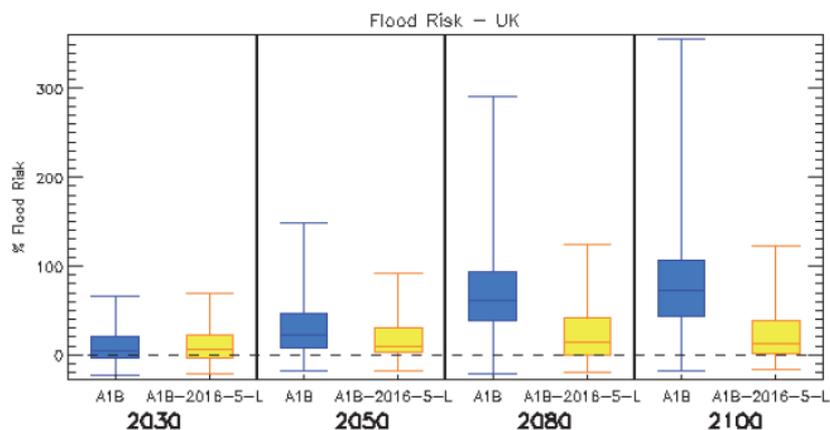


Figure 7 Box and whisker plots for the percentage change in average annual flood risk within the UK, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), at four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).

Source: Warren et al. (2010).

One of the most exhaustive analyses of flooding linked to climate change was undertaken as part of a broader initiative to review climate change ‘safety factors’ for new flood defences (Prudhomme et al., 2010a; b). The revised advice for flood management in England requires that a sensitivity analysis be performed across the range of change (in extreme rainfall, flood flows, etc) that might occur over the lifetime of the plan (EA, 2011). A central climate change factor is used for investment appraisals with the upper and lower bounds used to test the extent to which options are robust. In practice, the uncertainty in peak flows can be very large. For example, in Eastern England (Anglian region) the lower, central, and upper change factors for river flood flows are -10%, +15% and +40% respectively by the 2050s, and -5%, +25% and +70% by the 2080s.

The change factors were based on large ensembles of hydrological model simulations for over 150 catchments, with precipitation and temperature inputs perturbed over plausible ranges to sample the large uncertainty in future climate. Figure 8 shows the trade-off between the fractions of model runs that could be accommodated (vertical axis) and given climate change safety factor (horizontal axis). For example, a 50% safety margin on 20-year flood heights would be sufficient to manage climate risk in the majority of UK catchments to the 2080s. Similarly, Fowler and Wilby (2010) assessed the robustness of safety margins to projected changes in extreme precipitation and concluded that in some regions the standard of protection may be too low.

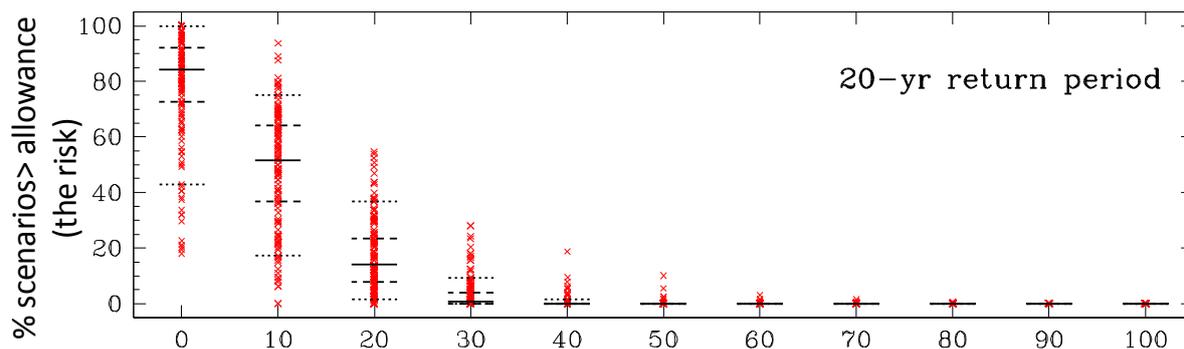


Figure 8 Percentage of model runs exceeding a given 20-year flood safety margin (%) based on 155 UK catchments and 16 AR4 GCMs (2080s, A1B emissions scenario). Each cross for a given allowance shows the results for one catchment. The 50th, 30th and 70th, and 10th and 90th percentiles (solid, dashed and dotted lines respectively) are shown for each ensemble. Source: Prudhomme et al. (2010a; b).

4. Deeper examination of climate model accuracy

The above studies convey the large uncertainty in projections of pluvial and fluvial flood risk. Even so, the true uncertainty could be even greater given recognised limitations of climate models and regional downscaling techniques (Pielke and Wilby, 2012). The following assessment of climate model capabilities is drawn from a recent appraisal by the World Bank of their utility for water policy, operational and policy decisions (Wilby, 2012). Others have also considered the extent to which climate models are ready for 'prime time' applications in water engineering design and planning (Kundzewicz and Stakhiv, 2010) or could be used in smarter ways (Brown and Wilby, 2012).

Randall et al (2007: 601) assert that *confidence in climate models comes from their physical basis, and their skill in representing observed climate and past climate changes*. Others show how important terms in the Earth's energy budget can be constrained using measurements of surface temperature, ocean heat content and satellite observations of radiative fluxes (e.g., Murphy et al., 2009). Advocates of climate models are confident that further investment in multi-national super-computing resources, unified seasonal-to-decadal approaches and finer resolution models will ultimately deliver improved regional climate change 'prediction' (Feser et al., 2011; Hurrell et al., 2009; Reichler and Kim, 2008; Shukla et al., 2010).

Such optimism is based on steady improvements in weather forecasting skill over the last 30 years and climate modelling over the past decade due, in part, to higher-resolution regional models and experience gained from the Japanese Earth Simulator. Some operational forecasting models now run at 1.5 km resolution – a scale at which important features affecting precipitation can be resolved. Hence, the best global 5-day forecasts now have accuracies comparable to that of a 2-day forecast, 25-years ago (Shukla et al., 2010). Although still in their infancy, experiments with multi-model ensembles can hindcast global mean temperature trends when initialised with observed sea surface temperatures, and forced by greenhouse gas concentrations plus aerosol distributions (e.g., van Oldenborgh et al., 2012). However, there is less skill in predicting variations around the trend after the first year because of the erratic effects of volcanic aerosols and the El Niño-Southern Oscillation (ENSO).

Others are less convinced of the power of climate models to provide sufficiently accurate predictions for adaptation decisions because of the following major caveats:

Assumption 1: Skill at simulating present climate demonstrates future skill. This premise is often implicit rather than explicit yet is open to question. Knutti (2008) shows that climate models replicate 20th century global mean temperatures because of compensating effects amongst dependent

parameters involving radiative forcing (aerosols) and climate sensitivity. Since some models do not incorporate aerosols, model agreement with observations is explained by ‘tuning’ and may be partly spurious. This is because different sets of model parameters can produce identical simulations in the calibration period, but very different results when applied out of sample (a behaviour termed “equifinality” by hydrologists [Beven, 2006]). In other words, climate models simulate observed patterns of warming for different reasons (Crook and Forster, 2011). Other major sources of uncertainty due to historic aerosol forcing, clouds, snow and ice, and carbon cycle feedbacks, and abrupt, non-linear changes all mean that present skill is not necessarily a reliable basis for assuming future skill (Rial et al., 2004).

In other words, ability to simulate global mean surface temperatures trends is not a severe test of climate model quality, and is not a *reliable guide to out-of-sample accuracy* (Katzav, 2011: 195), especially for hydrological variables relevant to infrastructure planning. In fact, gross biases are known to exist in many climate models. For example, Liepert and Previdi (2012) show that 13 out of the 18 climate models used in Climate Model Intercomparison Project 3 (CMIP3) generate more global annual mean precipitation than evaporation – termed ‘ghost’ precipitation (the blue bars in Figure 9). Clearly mass is not being conserved in these experiments, bringing into question their wider credibility for hydrological cycle applications. Climate models are also known to produce precipitation more often and more lightly than is observed (Stephens et al., 2010), or to exaggerate the role of soil moisture feedbacks in convection schemes (Taylor et al., 2012).

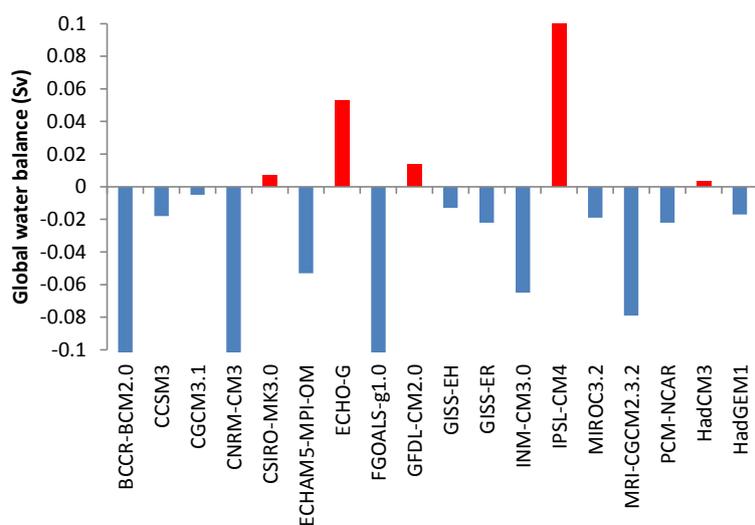


Figure 9 Global annual mean residual of the atmospheric water balance ($E - P - dw/dt$) for CMIP3 climate models. One Sverdrup (Sv) is $10^6 \text{ m}^3 \text{ s}^{-1}$ or $31,600 \text{ km}^3 \text{ yr}^{-1}$. Note that four climate models have residuals $> 0.1 \text{ Sv}$. For comparison, observed atmospheric moisture transport from ocean to land is estimated to be 1.2 Sv . Data from: Liepert and Previdi (2012)

Assumption 2: Consensus amongst models boosts confidence in their predictions. This contention requires that each model is an independent representation of the climate system and thereby contributing additional useful information (Pirtle et al., 2010). In practice, climate models share structural features such as the same fundamental equations for conservation of momentum,

parameters, sub-grid schemes, or modules representing the land surface. A degree of similarity is expected, not least because of the common physics included in models.

Climate model ‘ensembles of opportunity’ are, therefore, unlikely to be truly independent so the effective number of models in the sample is actually much smaller. This suggests that there is a risk of double counting and undue confidence whenever models produce similar patterns of climate change (Knutti, 2010; Masson and Knutti, 2011). Conversely, when applied outside of the calibration period, impact studies based on just a handful of climate scenarios can produce divergent results for the reasons noted above (see Harding et al., 2012).

Assumption 3: Model projections include all known regional climate forcings. It is widely accepted that uncertainty due to poorly understood or resolved climate processes will be reduced through further research (into cloud physics, for example). However, uncertainties arising from the intrinsic randomness of the climate system are irreducible (Curry and Webster, 2011) as are the unknowable decisions taken by future generations that will affect demographic and economic change, and ultimately greenhouse gas emissions. Other, first-order climate forcings beyond carbon dioxide, (e.g., aerosol effects on clouds, black carbon deposition, reactive nitrogen, and changes in land use/land cover) are seldom included in climate model simulations yet are known to be significant on multi-decadal time-scales (Pielke et al., 2009). Hence, climate model experiments that omit these important drivers of regional climate change do not qualify as ‘predictions’.

In summary, the above factors complicate the task of reconciling observed flood records and climate model predictions. Apparent discrepancies between the two can be explained by the combined effects of brevity of observations, climate (and hydrological) model uncertainties, natural multi-decadal variability, and incomplete understanding of the drivers of storminess in the UK.

5. Detectability of trends in flood indicators

Even if model predictions could be produced would changes in floods be detectable at the scale of the UK, or for individual river basins? This depends on several factors (Fowler and Wilby, 2010):

1. *The choice of flood indicator.* This might be monthly, seasonal, annual, rainfall/river flow, maxima, *N*-day rainfall totals, proportional contributions, counts of peaks over threshold flows, point or area average data, individual records, pooled, or gridded data.
2. *The period of record.* This matters because when longer precipitation and river flow records are analysed trends found in shorter series can fade away (see for example Murphy et al., 2013). This can be due to the influence of outliers (at the start or the end of the record), or simply a result of multi-decadal climate variability.
3. *The power of statistical tests to detect change.* Widely used methods include (logistic) linear regression, “change point” tests, and the nonparametric Spearman rank correlation and Mann-Kendall tests. Detectability of trends in extreme events can be improved by regional pooling of data.
4. *Confounding factors.* Gradual or sudden changes in hydrometeorological records can arise from changes in site, instrumentation, observing or recording practices, site characteristics, or sampling regime. Discharge records may also be affected by land-use changes, urbanization, river regulation, water abstraction and effluent returns, or peak flows by-passing gauging structures.

The number of years of precipitation or river flow record needed to detect a statistically significant trend depends on the strength of the trend; the amount of variance about the trend; the probability of erroneous detection (type 1 error); and the probability of missing a real trend (type 2 error). Preliminary estimates using data for river basins in the United States and UK suggest that statistically

robust, climate-driven trends in seasonal runoff are unlikely to be seen until the second half of the 21st century (Ziegler et al., 2005; Wilby, 2006). Fowler and Wilby (2012) found that the earliest detection times for extreme multi-day precipitation events could be in SW England (Figure 10, SWE).

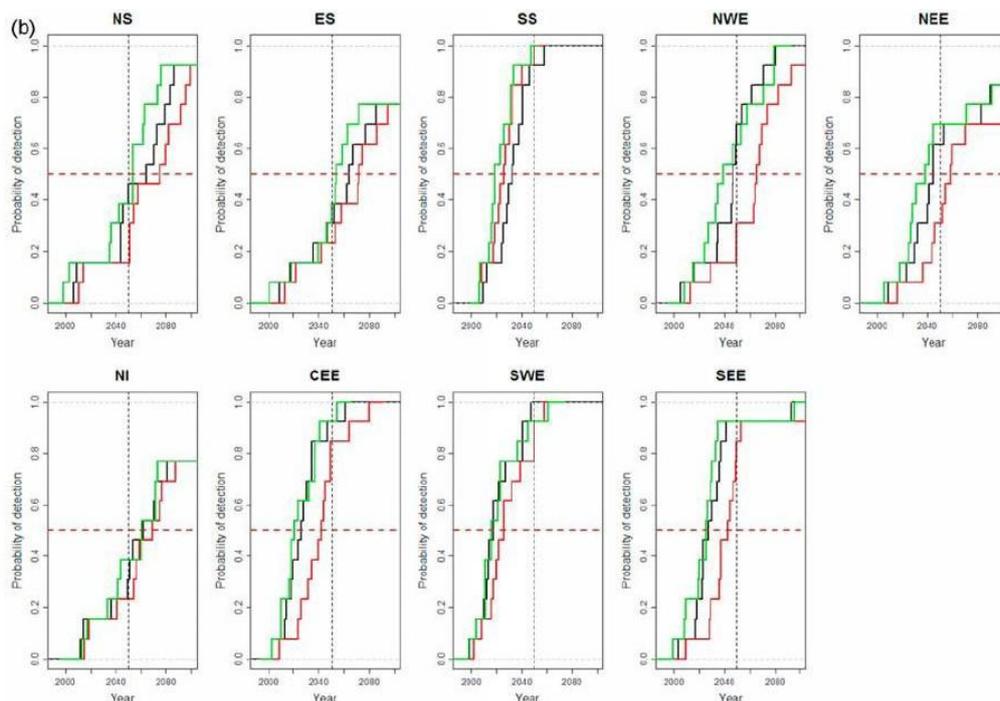


Figure 10 Detection years for significant change ($p = 0.05$) in the estimated 10 day winter precipitation totals with 10 year return period by region. Data used to estimate natural variability: observed 1958–2002 (black lines), RCM 1961–1990 (green lines), and observed 1961–1990 (red lines). Source: Fowler and Wilby (2010)

Others believe that detection and attribution of extreme flooding is already feasible at the scale of England and Wales (Kay et al., 2011). For example, climate model experiments performed by Pall et al, 2011) suggest that simulations with greenhouse gas forcing (Figure 11, blue dots) lift the flood frequency curve above those without (Figure 11, coloured dots). However, credibility of this form of analysis hinges on the realism of both the climate model projections and modelled impacts. In this example, confidence is reduced by the unrealistically high frequency (1 year in 10) of the autumn 2000 event in the runoff simulations (Figure 11, horizontal line). Regardless of concerns about climate threats, some experts are calling for more scientific rigour when attributing trends in flood behaviour (Merz et al., 2012).

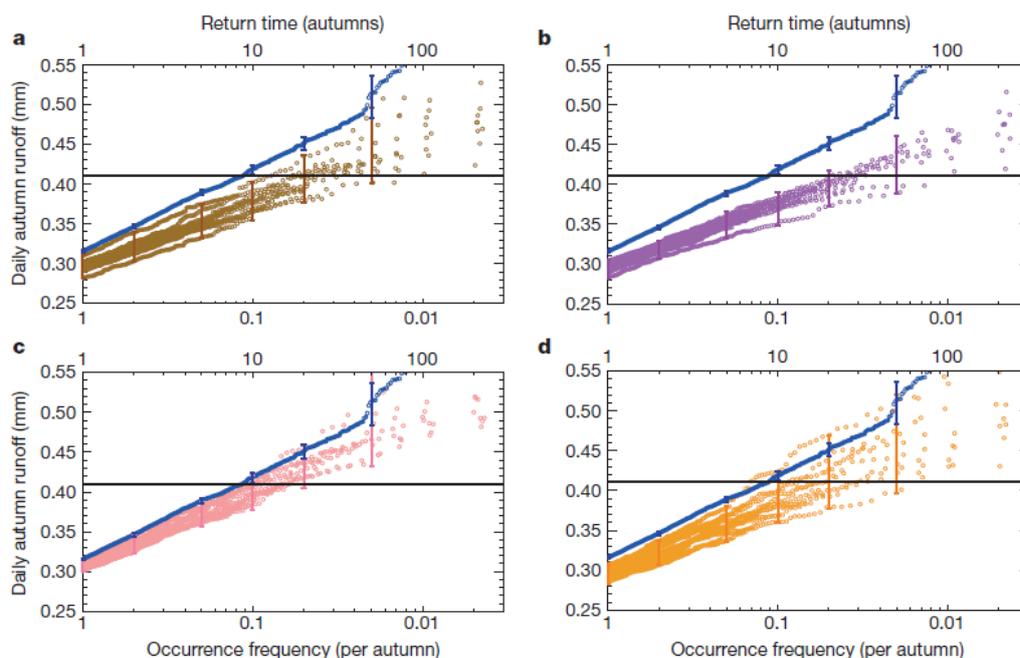


Figure 11 Change in frequency of daily river runoff for England and Wales in autumn 2000 with (blue dots) and without greenhouse gas emissions (coloured dots, four different climate models). Source: Pall et al. (2011)

6. Process-based flood studies

The Clausius-Clapeyron constant predicts an increase in the moisture-holding capacity of the atmosphere of approximately 7 % for each degree Celsius warming. This is widely believed to be a robust response of the hydrological cycle to global warming (Groisman et al., 2005; Held and Soden, 2006; O’Gorman and Schneider, 2009). Nonetheless, satellite (Allan and Soden, 2008) and rain gauge records (Lenderink and van Meijgaard, 2008) indicate that the observed increase in daily extreme precipitation may be larger than expected by climate models, implying that projections of future changes in precipitation extremes in response to global warming could be underestimated (Fowler and Wilby, 2010). Over the next decade or so, an anticipated cool downturn in the North Atlantic, could favour a return to less anomalously wet (summer) conditions across northwest Europe (Keenlyside et al., 2008; Sutton and Dong, 2012).

Recent research shows that major winter flood events in the UK are associated with atmospheric rivers – narrow bands of concentrated moisture flux between the sub-tropical Atlantic and Western Europe (Lavers et al., 2011). For example, Figure 12 shows plumes of moisture advection along an SW-NE axis on the days of the 10 largest winter flood events in the River Eden. The effect of these moisture streams is most pronounced when there is orographic uplift and/or a pattern of airflow that persists for several days.

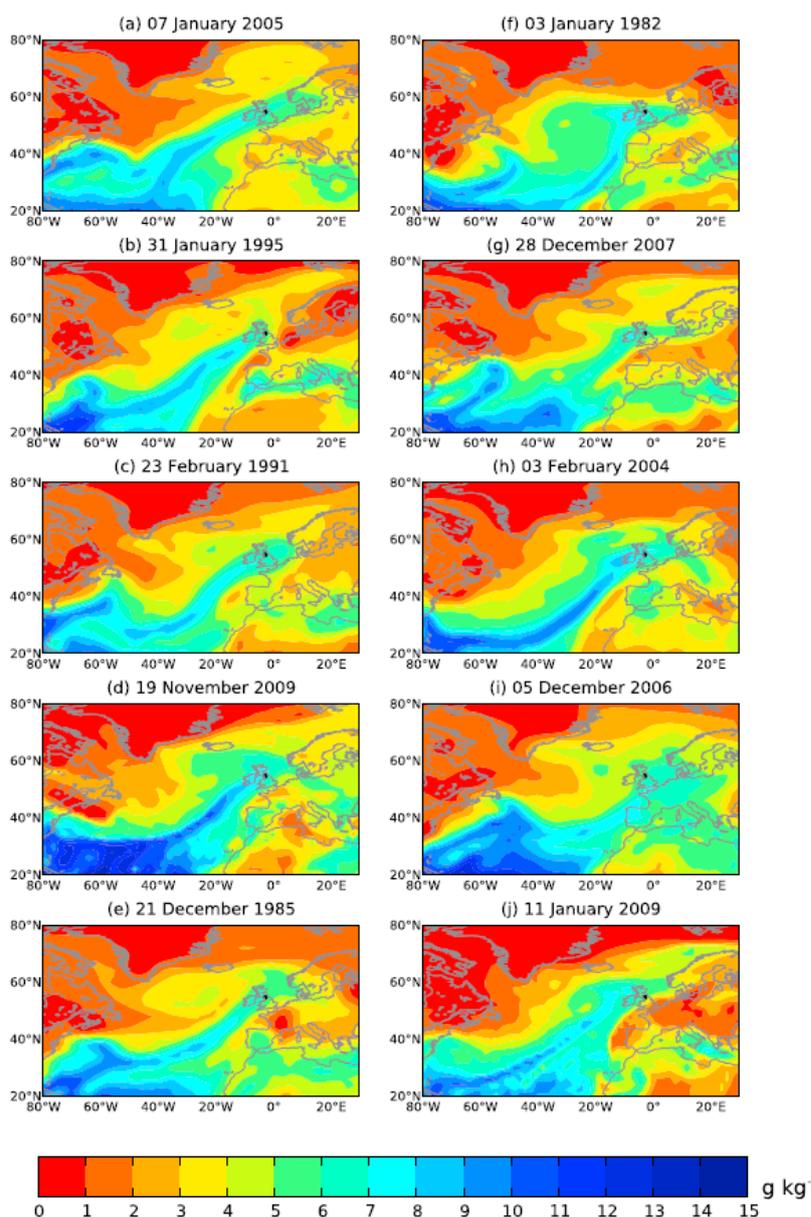


Figure 12 The 900 hPa specific humidity fields at 0600 UTC for the top 10 winter flood events on the River Eden at Temple Sowerby. Source: Lavers et al. (2011)

As noted before, the top 10 most widespread floods in Britain since 1961 were all associated with winter C, W and S types, and in the most extreme case affected up to 30% of all recording stations. However, it is recognised that a flood index at this scale could conceal coherent, regional trends in high-flows (Hannaford and Marsh, 2008). This is certainly one of the limitations of the Lamb classifications: very different weather conditions can prevail across Britain under the same LWT (Sweeney and O’Hare, 1992).

This is evident in the relative loadings attached to each LWT in each hydrometric region (Figure 1), and by regional variations in flood index behaviour through time (Figure 4). For instance, W-types are known to deliver greater rainfall over upland regions than any other type (Sweeney and O’Hare, 1992) and continue to attract most attention in studies of heavy rainfall and flooding (Pattison and Lane, 2012; Burt and Ferranti, 2012; Macdonald et al., 2010). A case can, therefore, be made for more intensive monitoring and reporting of precipitation changes, upland maritime locations (e.g., Barker et al., 2004; Malby et al., 2007; Macdonald et al., 2010).

7. Summing up

Based on the reviewed scientific evidence, the following conclusions are reached about climate change and fluvial flood hazards in the UK:

1. Long-term rainfall and river flow records exhibit rising trends between the 1960s and 1990s in western and northern regions, driven by a persistent positive phase in the North Atlantic Oscillation (NAO) over the same period. Storminess and the contribution made by heavy precipitation events to winter rainfall have increased for the same reason. When longer (>50 year) hydrometric records are examined there is little sign of these trends, suggesting that they are most likely an artefact of multi-decadal variability. However, it should be kept in mind that it may be too soon to expect a clear signal of greenhouse gas forced change to have appeared in UK flood records (see point 3 below).
2. Reconstructed indices of flood occurrence since the 1880s show no long-term trend in the frequency of events inferred from atmospheric circulation patterns. The handful of weather types most commonly linked to flooding show no changes in frequency, persistence or rain-bearing properties since the 1930s. However, there is an emergent trend towards less persistent anticyclonic weather, and more intense rainfalls in this type. Conversely, cyclonic weather patterns show a marked reduction in rainfall intensities over the period 1930 to 1970.
3. A small number of climate detection studies expect anthropogenic climate change signals to emerge first in multi-day precipitation records for upland, maritime-influenced catchments. In these locations there is a relatively strong ratio of climate signal to noise (i.e., inter-annual variability). Even so, detection of model-informed changes in rainfall is not expected for at least a decade in the best case.
4. One climate attribution study claims that an anthropogenic climate change signal may already be discerned through increased likelihood of widespread flooding. However, these findings are contingent upon the confidence placed in the regional climate change scenarios (with and without greenhouse gases) and calibre of the flood estimation.
5. The vast majority of global and regional climate modelling studies point to increased future flood risk for the UK by the 2080s. Nonetheless, probabilistic projections such as UKCP09 do show a small proportion of runs with reduced rainfall intensities in winter and summer. Greater research effort is now being focused on improving understanding of the physical reasons behind these contrasting outcomes.
6. Confidence in climate model projections is tempered by errors in global water balance terms, the multi-dimensionality of parameter sets fit to past global mean temperatures, and imperfect representation of precipitation generation mechanisms. Important boundary forces such as land-surface feedbacks and historical changes in aerosols are seldom included. Hence, the present generation of model results are best regarded as sensitivity experiments rather than predictions.
7. Despite these limitations there is strong empirical evidence for greater precipitation intensities linked to higher atmospheric temperatures and water vapour content. Recent research further highlights the importance of atmospheric rivers in generating the most extreme winter floods in the UK. Even if the specific humidity increases over the Atlantic, the future significance of these moisture fluxes will be strongly determined by the position and persistence of storm tracks over this region. Both of these factors are highly uncertain and an area of active research.

Taking all the above into account, it is concluded with LOW TO MEDIUM CONFIDENCE that FLUVIAL FLOOD RISK WILL INCREASE under a changed climate against a back-drop of multi-decadal variability. However, given the uncertainties attached to climate model projections, low regret strategies such as monitoring and detection systems for sentinel locations, with improved forecasting in floodplains and urban drainage systems, are prudent ways of applying climate science to the issue.

Acknowledgements

Thanks to Professor Rowan Sutton for constructive remarks on the headline messages of this review.

References

- Adaptation Sub-Committee (ASC), 2011. *Adapting to climate change in the UK: Measuring progress*. Adaptation Sub-Committee Progress Report 2011.
- Adaptation Sub-Committee (ASC, 2012). *Climate change – is the UK preparing for flooding and water scarcity?* Adaptation Sub-Committee Progress Report 2012.
- Alexander, L.V. and Jones, P.D. 2001. Updated precipitation series for the U.K. and discussion of recent extremes. *Atmospheric Science Letters*, doi: 10.1006/asle.2001.0025.
- Allan, R. P. and Soden, B. J. 2008. Atmospheric warming and the amplification of precipitation extremes. *Science*, **321**, 1481-1484.
- Barker, P.A., Wilby, R.L. and Borrows, J. 2004. A 200-year precipitation index for the central English Lake District. *Hydrological Sciences Journal*, **49**, 769-785.
- Beven, K.J. 2006. A manifesto for the equifinality thesis. *Journal of Hydrology*, **320**, 18-36.
- Brown, C. and Wilby, R.L. 2012. An alternate approach to assessing climate risks. *Eos*, **92**, 401-403.
- Burt, T.P. and Ferranti, E.J.S. 2012. Changing patterns of heavy rainfall in upland areas: a case study from northern England. *International Journal of Climatology*, **32**, 518-532.
- Cameron, D. 2006. An application of the UKCIP02 climate change scenarios to flood estimation by continuous simulation for a gauged catchment in the northeast of Scotland, UK (with uncertainty). *Journal of Hydrology* **328**, 212-226.
- Cameron, D., Beven, K. and Naden, P. 2000. Flood frequency estimation under climate change (with uncertainty). *Hydrology and Earth System Sciences* **4**, 393-405.
- Crook, J.A. and Forster, P.M. 2011. A balance between radiative forcing and climate feedback in the modelled 20th century temperature response. *Journal of Geophysical Research – Atmospheres*, **116**, D17108.
- Curry, J.A. and Webster, P.J. 2011. Climate science and the uncertainty monster. *Bulletin of the American Meteorological Society*, **92**, 1667-1682.
- Ekström, M., Fowler, H.J., Kilsby, C.G. and Jones, P.D. 2005. New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies. *Journal of Hydrology*, **300**, 234-251.
- Environment Agency (EA), 2011. *Adapting to climate change: Advice for flood and coastal erosion risk management authorities*. Environment Agency, Bristol, 31pp.
- Evans, E.p., Ashley, R., Hall, J.W., Penning-Rowsell, E.C., Saul, A., Sayers, P.B., Thorne, C.R. and Watkinson, A. 2004. *Foresight Flood and Coastal Defence Project: Scientific Summary*. Office of Science and Technology, London, 366pp.
- Feser, F., Rockel, B., von Storch, H., Winterfeldt, J. and Zahn, M. 2011. Regional climate models add value to global climate model data. *Bulletin of the American Meteorological Society*, **92**, 1181-1192.
- Fowler, H. J. and Wilby, R.L. 2010. Detecting changes in seasonal precipitation extremes using regional climate model projections: Implications for managing fluvial flood risk. *Water Resources Research*, **46**, W03525, doi:10.1029/2008WR007636

- Fowler, H.J. and Ekström, M. 2009. Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *International Journal of Climatology*, **29**, 385-416.
- Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T.R., Hegerl, G. C. and Razuvaev, V. N. 2005. Trends in intense precipitation in the climate record. *Journal of Climate* **18**, 1326-1350.
- Hannaford, J. and Marsh, T.J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology*, **28**, 1325-1338.
- Harding, B.L., Wood, A.W. and Prairie, J.R. 2012. The implications of climate change scenario selection for future streamflow projection in the Upper Colorado River Basin. *Hydrology and Earth System Sciences*, **9**, 847-894.
- Hawkins, E. and Sutton, R. 2010. The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, **37**, 407-418.
- Haylock, M.R., Cawley, G.C., Harpham, C., Wilby, R.L. and Goodess, C.M. 2006. Downscaling heavy precipitation over the UK: a comparison of dynamical and statistical methods and their future scenarios. *International Journal of Climatology*, **26**, 1397-1415.
- Held, I.M. and Soden, B.J. 2006. Robust responses of the hydrological cycle to global warming. *Journal of Climate*, **19**, 5686-5699.
- Hurrell, J., Meehl, G.A., Bader, D., Delworth, T.L., Kirtman, B. and Wielicki, B. 2009. A unified modeling approach to climate system prediction. *Bulletin of the American Meteorological Society*, **90**, 1819-1832.
- Jenkinson, A.F. and Collison, F.P. 1977. *An initial climatology of gales over the North Sea*. Synoptic Climatology Branch Memorandum No. 62, Meteorological Office, Bracknell.
- Jones, P.D. and Kelly, P.M. 1982. Principal component analysis of the Lamb catalogue of daily weather types: Part 1, annual frequencies. *Journal of Climate*, **2**, 147-157.
- Jones, P.D., Harpham, C. and Briffa, K.R. 2013. Lamb weather types derived from reanalysis products. *International Journal of Climatology*, **33**, 1129-1139.
- Jun, M., Knutti, R. and Nychka, D.W. 2008. Spatial analysis to quantify numerical model bias and dependency: how many climate models are there? *Journal of the American Statistical Association*, **103**, 934-947.
- Katzav, J. 2011. Should we assess climate model predictions in light of severe tests? *Eos*, **92**, 195.
- Kay, A.L. and Jones, D.A. 2012. Transient changes in flood frequency and timing in Britain under potential projections of climate change. *International Journal of Climatology*, **32**, 489-502.
- Kay, A.L., Crooks, S.M., Pall, P. and Stone, D.A. 2011. Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: a catchment-based study. *Journal of Hydrology*, **406**, 97-112.
- Kay, A.L., Jones, R.G. and Reynard, N.S. 2006. RCM rainfall for UK flood frequency estimation. II. Climate change results. *Journal of Hydrology*, **318**, 163-172.
- Keenlyside, N.S., M. Latif, M., Jungclaus, J., Kornblueh, L. and Roeckner, E. 2008. Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, **453**, 84-88.
- Knutti, R. 2008. Why are climate models reproducing the observed global surface warming so well? *Geophysical Research Letters*, **35**, L18704.

- Knutti, R. 2010. The end of model democracy? An editorial comment. *Climatic Change*, **102**, 395-404.
- Lavers, D.A., Allan, R.P., Wood, E.F., Villarini, G., Brayshaw, D.J. and Wade, A.J. 2011. Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters*, **38**, L23803.
- Kundzewicz, Z.W. and Stakhiv, E.Z. 2010. Are climate models “ready for prime time” in water resources management applications, or is more research needed? *Hydrological Sciences Journal*, **55**, 1085-1089.
- Lamb, H.H. 1972. *British Isles weather types and a register of the daily sequence of circulation patterns*. *Geophysical Memoirs* 116. London: HMSO.
- Lavers, D.A., Allan, R.P., Wood, E.F., Villarini, G., Brayshaw, D.J. and Wade, A.J. 2011. Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters*, **38**, L23803.
- Lenderink, G., and van Meijgaard, E. 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, **1**, 511-514.
- Liepert, B.G. and Previdi, M. 2012. Inter-model variability and biases of the global water cycle in CMIP3 coupled climate models. *Environmental Research Letters*, **7**, 014006.
- Macdonald, N., Phillips, I.D. and Mayle, G. 2010. Spatial and temporal variability of flood seasonality in Wales. *Hydrological Processes*, **24**, 1806-1820.
- Malby, A.R., Whyatt, J.D., Timmis, R.J., Wilby, R.L. and Orr, H.G. 2007. Long-term variations in orographic rainfall: analysis and implications for upland catchments. *Hydrological Sciences Journal*, **52**, 276-291.
- Marsh, T., Cole, G. and Wilby, R.L. 2007. Major droughts in England and Wales, 1800-2006. *Weather*, **62**, 87-93.
- Masson, D. and Knutti, R. 2011. Climate model genealogy. *Geophysical Research Letters*, **38**, L08703
- Merz, B., Vorogushyn, S., Uhlemann, S., Delgado, J. and Hundsdoerfer, Y. 2012. More efforts and scientific rigour are needed to attribute trends in flood time series. *Hydrological Processes*, **16**, 1379-1387.
- Met Office Climate: Observations, Projections and Impacts
<http://www.metoffice.gov.uk/media/pdf/t/r/UK.pdf>
- Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. 2009. *UK Climate Projections Science Report: Climate change projections*. Met Office Hadley Centre, Exeter.
- Murphy, C., Harrigan, S., Hall, J. and Wilby, R.L. 2013. Assessing climate driven trends in mean- and high- river flows from a network of reference stations in Ireland. *Hydrological Sciences Journal*, **58**, 755-772.
- O’Gorman, P.A. and Schneider, T. 2009. The physical basis for increases in precipitation extremes in simulations of 21st century climate change. *Proceedings of the National Academy of Science*, **106**, 14773-14777.
- Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D. and Allen, M.R. 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470**, 382-386.

Pattison, I. and Lane, S.N. 2012. The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK. *International Journal of Climatology*, **32**, 1971-1989.

Pielke Sr., R., K. Beven, G. Brasseur, J. Calvert, M. Chahine, R. Dickerson, D. Entekhabi, E. Foufoula-Georgiou, H. Gupta, V. Gupta, W. Krajewski, E. Philip Krider, W. K.M. Lau, J. McDonnell, W. Rossow, J. Schaake, J. Smith, S. Sorooshian, and Wood, E. 2009. Climate change: The need to consider human forcings beside greenhouse gases. *Eos*, **90**, 413.

Pielke, R.A. Sr. and Wilby, R.L. 2012. Regional climate downscaling – what’s the point? *Eos*, **93**, 52-53.

Pirtle, Z., Meyer, R. and Hamilton, A. 2010. What does it mean when climate models agree? A case for assessing independence among general circulation models. *Environmental Science and Policy*, **13**, 351-361.

Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A. and Reynard, N.S. 2010b. Regionalisation of the impact of climate change on flood flows using a scenario-neutral approach: application in Great Britain. *Proceedings of the British Hydrological Society Third International Symposium*, Newcastle, UK. Ramsbottom, D., Sayers, P. and Panzeri, M. 2012. Climate change risk assessment for the floods and coastal erosion sector. UK Climate Change Risk Assessment, Defra Project Code GA0204. HR Wallingford, 272pp.

Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L. and Reynard, N.S. 2010a. Scenario-neutral approach to climate change impact studies: application to flood risk. *Journal of Hydrology*, **390**, 198-209.

Ramsbottom, D., Sayers, P. and Panzeri, M. 2012. *Climate change risk assessment for the floods and coastal erosion sector*. UK Climate Change Risk Assessment. Defra, London.

Randall, D.A. et al. 2007. Climate models and their evaluation. In: Solomon, S. et al. (eds.) *Climate Change 2007: The Physical Science Basis – Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp589-662.

Reichler, T. and Kim, J. 2008. How well do coupled models simulate today’s climate? *Bulletin of the American Meteorological Society*, **89**, 303-311.

Reynard, N.S., Crooks, S.M., Kay, A.L. and Prudhomme, C. 2009. *Regionalised Impacts of Climate Change on Flood Flows*. R&D Technical Report FD2020/TR, CEH, Wallingford.

Rial, J.A., Pielke Sr, R.A., Beniston, M., Claussen, M., Canadell, J., Cox, P., Held, H., de Noblet-Ducoudré, N., prinn, R., Reynolds, J.F. and Salas, J.D. 2004. Nonlinearities, feedbacks and critical thresholds within the Earth’s climate system. *Climatic Change*, **65**, 11-38.

Robson, A.J. 2002. Evidence for trends in UK flooding. *Philosophical Transactions of the Royal Society London A*, **360**, 1327-1343.

Schindler, A., Maraun, D., Toreti, A. and Luterbacher, J. 2012. Changes in the annual cycle of heavy precipitation across the British Isles within the 21st century. *Environmental Research Letters*, **7**, 044029.

Shukla, J., Palmer, T.N., Hagedorn, R., Hoskins, B., Kinter, J., Marotzke, J., Miller, M. and Slingo, J. 2010. Toward a new generation of world climate research and computing facilities. *Bulletin of the American Meteorological Society*, **91**, 1407-1412.

Stephens, G.L., L’Ecuyer, T., Forbes, R., Gettleman, A., Golaz, J.-G., Bodas-Salcedo, A., Suzuki, K., Gabriel, P. and Haynes, J. 2010. Dreary state of precipitation in global models. *Journal of Geophysical Research*, **115**, D24211.

Sutton, R.T. and Dong, B. 2012. Atlantic Ocean influence on a shift in European climate in the 1990s. *Nature Geoscience*, **5**, 788-792.

Sweeney, J.C. and O'Hare, G.P. 1992. Geographical variations in precipitation yields and circulation types in Britain and Ireland. *Transactions of the Institute of British Geographers*, **17**, 448-463.

Taylor, C.M., de Jeu, R.A.M., Guichard, F., Harris, P.P. and Dorigo, W.A. 2012. Afternoon rain more likely over drier soils. *Nature*, **489**, 423-426.

van Oldenborgh, G.J., Doblas-Reyes, F.J., Wouters, B. and Hazeleger, W. 2012. Decadal prediction skill in a multi-model ensemble. *Climate Dynamics*, **38**, 1263-1280.

Warren, R., Arnell, N., Berry, P., et al. 2010. *The Economics and Climate Change Impacts of Various Greenhouse Gas Emissions Pathways: A comparison between baseline and policy emissions scenarios*. AVOID Report, AV/WS1/D3/R01.

Wilby, R. L. 2006. When and where might climate change be detectable in UK river flows? *Geophysical Research Letters*, **33**, L19407, doi:10.1029/2006GL027552.

Wilby, R.L. 2012. Utility of climate model scenarios for water policy, investment and operational decisions. Report on behalf of the World Bank, Washington DC, 45pp.

Wilby, R.L. and Harris, I. 2006. A framework for assessing uncertainties in climate change impacts: low flow scenarios for the River Thames, UK. *Water Resources Research*, **42**, W02419.

Wilby, R.L. and Keenan, R. 2012. Adapting to flood risk under climate change. *Progress in Physical Geography*, **36**, 349-379.

Wilby, R.L. and Quinn, N.W. 2013. Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. *Journal of Hydrology*, **487**, 109-121.

Wilby, R.L., Beven, K.J. and Reynard, N.S. 2008. Climate change and fluvial flood risk in the UK: More of the same? *Hydrological Processes*, **22**, 2511-2523.

Wilby, R.L., O'Hare, G. and Barnsley, N. 1997. The North Atlantic Oscillation and British Isles climate variability 1865-1995. *Weather*, **52**, 266-76.

Ziegler, A.D., Maurer, E.P., Sheffield, J., Nijssen, B., Wood, E.F. and Lettenmaier, D. 2005. Detection time for plausible changes in annual precipitation, evapotranspiration, and streamflow in three Mississippi River sub-basins. *Climatic Change*, **72**, 17-36.