Journal of Hydrology 406 (2011) 97–112

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: A catchment-based study

A.L. Kay [a,*], S.M. Crooks [a], P. Pall [b,c], D.A. Stone [b,d,e]

[a] Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, UK
[b] AOPP, Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[c] Institute for Atmospheric and Climate Science, ETH Zurich, 8092 Zurich, Switzerland
[d] Tyndall Centre for Climate Change Research, Oxford University Centre for the Environment, Oxford, UK
[e] CSAG, Shell Environmental and Geographical Science Building, South Lane, Upper Campus, University of Cape Town, Private Bag X3, Rondebosch, Western Cape 7701, South Africa

ARTICLE INFO

Article history:
Received 17 February 2011
Received in revised form 4 May 2011
Accepted 10 June 2011
Available online 25 June 2011
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Ashish Sharma, Associate Editor

Keywords:
Climate change
Hydrological impacts
Flood frequency
Attribution
Uncertainty

SUMMARY

Although no single weather-related event can be directly attributed to climate change, new techniques make it possible to estimate how much the chance of an event has been altered by anthropogenic emissions. This paper looks at the floods that occurred in England in Autumn/Winter 2000, by using large ensembles of 1-year climate model simulations representing April 2000–March 2001. These represent an industrial climate and four estimates of an hypothetical non-industrial climate (without historical greenhouse gas emissions), and are used to drive hydrological models for eight catchments in England. The simulated flows are used to assess the impact of historical emissions on the chance of occurrence of extreme floods in each catchment, through calculation of the fraction of attributable risk (*FAR*). Combining results for the four non-industrial climates, positive median values of *FAR* indicate that, for all but one catchment, emissions are likely to have led to an increased chance of flooding in the October–December period. Definitive conclusions are difficult however, as there are wide bands of uncertainty in *FAR*, with distributions generally spanning no attributable difference in risk (*FAR* = 0). One catchment shows a decreased flood chance (negative median *FAR*), due to its high permeability, but an analysis of the effect of antecedent conditions shows that a longer period of climate data than 1 year is probably required to obtain more representative values of *FAR* for such catchments. The inclusion of snowfall/snowmelt is also shown to be important for floods over the October–March period, as the reduced likelihood of snowmelt-induced floods in the warmer temperatures of the industrial climate moderates the increased flood chance due to other sources of flooding.

1. Introduction

There is an increasing consensus among the global scientific community that our climate is changing and that this is mostly due to anthropogenic emissions of greenhouse gases (IPCC, 2007). Allied to this is an increasing concern about how the changing climate will impact upon our natural and built environment. Although no single event can be attributed, solely and directly, to climate change, new techniques make it possible to say something about how much the chance of an event has been affected by humanity's emissions of greenhouse gases (Allen, 2003; Stone and Allen, 2005). For instance, Stott et al. (2004) estimated that, with high likelihood, the chance of a European heatwave similar to that of Summer 2003 had been at least doubled by anthropogenic emissions.

This paper looks at the flood events that occurred in England in Autumn 2000. A report was commissioned by the UK Department for Environment Farming and Rural Affairs (Defra) shortly afterwards to consider the possibility that climate change had contributed to the flooding (CEH and Met Office, 2001). It concluded that the floods and rainfall of October/November 2000 were unusual in a historical context, and said that they were consistent with the potential effects of climate change but could not be directly attributed to them as they could not be distinguished from natural variability. A later study (Hall et al., 2005) aimed to consider the evidence presented in the above report more formally, and came to similar conclusions.

The recent "Seasonal Attribution Project" (http://climateprediction.net/content/seasonal-attribution-experiment) of the climate *prediction*.net experiment used public distributed computing to produce a large ensemble of climate model simulations, in order to compare the risk of the record wet autumn in the year 2000 with and without 20th Century anthropogenic greenhouse gas emissions. It concluded (Pall, 2006) that there was some evidence of an increased

---

[*] Corresponding author. Tel.: +44 01491 838800; fax: +44 01491 692424.
E-mail address: alkay@ceh.ac.uk (A.L. Kay).

doi:10.1016/j.jhydrol.2011.06.006

chance of high autumn precipitation totals over England and Wales due to emissions. Furthermore, after feeding the ensembles of daily precipitation data into a simple statistical rainfall–runoff model to simulate daily river runoff for England and Wales catchments (Pall et al., 2011), it was concluded that the England and Wales flood risk for Autumn 2000 (i.e. high runoff during autumn) had significantly increased: the best estimate (median) of the fraction of risk attributable to anthropogenic emissions was approximately 0.6. That is, the emissions had most likely increased the chance of such flooding by a factor of about 2.5, as the risk would only have been about 40% of its current level had anthropogenic emissions not occurred.

In this paper, data resulting from the ensemble experiments of Pall et al. (2011) are fed into continuous simulation rainfall–runoff models calibrated for eight catchments in England, four in the South–East and four in the North–East, each affected by flooding in Autumn 2000. The aim is to assess how much the chance of such flooding in each of the catchments has been influenced by anthropogenic emissions, and whether the results are dependent upon catchment characteristics. The use of continuous simulation models makes the results more robust to temporal and spatial variation of rainfall inputs and to antecedent conditions, so that differences due to catchment characteristics and location are better accounted for. In addition, a snowmelt module is applied, as the increased temperatures due to climate change are likely to mean a decreased chance of large snowmelt-induced flood events, and the effect of initial conditions is investigated.

A summary of the key features of the autumn 2000 flooding in England, and the conditions that led up to it, is given in Section 2, along with details on the catchments modelled. Section 3 describes the climate model ensemble data, the hydrological models, and the methodology followed. The results are presented and discussed in Section 4, with a summary and conclusions in Section 5.

2. The Autumn 2000 floods in England

2.1. Key features

This information is taken from CEH and Met Office (2001) and Marsh and Dale (2002).

2.1.1. Antecedent conditions

The winter of 1999–2000 (December–February) was wetter than average, as was Spring 2000 (March–May). But Summer 2000 (June–August) was drier than average, so late summer soil moisture deficits (SMDs; calculated using MORECS, the Met Office Rainfall and Evaporation Calculation System, Thompson et al., 1982) were close to the seasonal average in most lowland (southern and eastern) areas, and mostly well below average in western and northern areas, where only small deficits were carried into the autumn. Measured groundwater levels were above average throughout the period, due to several recent wet winters.

2.1.2. September 2000

Rainfall in September quickly reduced the lowland SMDs.

2.1.3. October and November 2000

There were a number of heavy rainfall events in early Autumn, with totals for the months of October and November generally amounting to two to three times the 1961–1990 average for those months over England and Wales. The rainfall totals for these two months combined were estimated to have a return period of 200 years or more over large parts of the country, with a number of individual rainfall events within the period also having return periods in excess of 100 years for certain parts of the country. This led to flooding affecting many different types of catchment: Larger basins with a groundwater component to their flows experienced extended periods of high flows, whilst smaller (impervious) catchments experienced sequences of high flow events. However, overall the floods were "notable more for their extent and duration … than their magnitude" (CEH and Met Office, 2001). Flooding affected much of the country at times during the last 3 months of 2000—the most extensive flooding for England and Wales since the snowmelt-generated floods of March 1947. The first significant flooding occurred in the second week of October, with some catchments still reaching peak flows in December (and well into 2001 in restricted cases).

2.2. Catchment details

Modelling is performed for eight catchments in England, four in the South–East and four in the North–East (Fig. 1 and Table 1), each of which was affected to some extent by flooding in Autumn 2000. Four physical properties for each catchment are given in Table 1; area, standard average annual rainfall (SAAR), elevation (mean and range: minimum–maximum) and percentage of the catchment with high permeability bedrock (BHP). Each region includes catchments with a range of areas and permeabilities, while those in the North–East have higher rainfall and higher mean and maximum altitude than those in the South–East. The range of elevation provides an indicator of slope, related to catchment response time. BHP is an indicator of how much of the river flow comes from stored groundwater sources: catchments with higher BHP typically have a longer response time and longer hydrological memory – flows are affected by rainfall and evaporation over preceding seasons and, in extreme situations, preceding years. How the climatic attributes combine with physical properties, unique to each catchment, determines how the flow regime responds to extreme events and changes in climate.

Fig. 2 shows, for each catchment, the observed flows over the period April 2000–March 2001 together with the mean, maximum and minimum flows from any observed data available from 1961 (see Table 1 for start year of flow record) up to April 2000, at three durations (1-day, 10-day and 30-day). These plots demonstrate the extremity of the flows in Autumn/Winter 2000 relative to flows in the recent past, particularly at longer durations. Fig. 2 also shows, for catchment 39001 (Thames @ Kingston), maximum and minimum flows for observed data from 1883. These demonstrate that, although Autumn 2000 was extreme relative to the period 1961–1999, it was not unprecedented in the longer historical context. Note that naturalised flows have been used for catchment 39001; this is the gauged river flow adjusted to take account of net abstractions and discharges upstream of the gauging station. Gauged flows have been used for all other catchments, where naturalised flows are unavailable.

3. Models, data and methods

3.1. The hydrological models and the snowmelt module

Two hydrological models are used; the Probability Distributed Model (PDM; Moore 1985, 2007), generally used for smaller catchments, and the Climate and LAnd-use Scenario Simulation In Catchments model (CLASSIC; Crooks and Naden, 2007), generally used for larger catchments. Here, CLASSIC is used for the two largest catchments, the Thames (39001) and Ouse (27009), whilst the PDM is used for the six smaller catchments (see Table 1). Both models are run at a daily time-step, which is considered appropriate given the area and responsiveness of each modelled catchment.

The PDM is a lumped rainfall–runoff model, requiring inputs of catchment-average rainfall and potential evaporation (PE; the