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Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000

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Interest in attributing the risk of damaging weather-related events to anthropogenic climate change is increasing[1]. Yet climate models used to study the attribution problem typically do not resolve the weather systems associated with damaging events[2] such as the UK floods of October and November 2000. Occurring during the wettest autumn in England and Wales since records began in 1766[3,4], these floods damaged nearly 10,000 properties across that region, disrupted services severely, and caused insured losses estimated at £1.3 billion (refs 5, 6). Although the flooding was deemed a 'wake-up call' to the impacts of climate change at the time[7], such claims are typically supported only by general thermodynamic arguments that suggest increased extreme precipitation under global warming, but fail[8,9] to account fully for the complex hydrometeorology[4,10] associated with flooding. Here we present a multi-step, physically based 'probabilistic event attribution' framework showing that it is very likely that global anthropogenic greenhouse gas emissions substantially increased the risk of flood occurrence in England and Wales in autumn 2000. Using publicly volunteered distributed computing[11,12], we generate several thousand seasonal-forecast-resolution climate model simulations of autumn 2000 weather, both under realistic conditions, and under conditions as they might have been had these greenhouse gas emissions and the resulting large-scale warming never occurred. Results are fed into a precipitation-runoff model that is used to simulate severe daily river runoff events in England and Wales (proxy indicators of flood events). The precise magnitude of the anthropogenic contribution remains uncertain, but in nine out of ten cases our model results indicate that twentieth-century anthropogenic greenhouse gas emissions increased the risk of floods occurring in England and Wales in autumn 2000 by more than 20%, and in two out of three cases by more than 90%.

Recent widespread UK floods—such as in spring 1998, autumn 2000, winter 2003 and summer 2007—have prompted debate as to whether these particular events are attributable to anthropogenic climate change[6,7,13–15]. This is an ill-posed question, given uncertainty in the antecedent conditions; many untraceable factors, anthropogenic or natural, may have contributed to any individual event[13,16]. Indeed, observed UK fluvial-flood and high-flow trends for recent decades suggest no clear evidence for any change above that of natural variability[17,18], mirroring the mixed picture in observed precipitation changes[19,20].

For this reason, only general explanations are usually offered for any expected increase in flooding[15]; these typically involve thermodynamic arguments for precipitation extremes increasing with atmospheric water vapour in a warming world. Although oversimplified[8,9], these arguments offer a physically plausible first guess. For example, following this simple thermodynamic framework, one may scale observed daily autumn precipitation extremes in England and Wales around the year 2000 by the reduction in atmospheric water vapour had estimated twentieth-century surface warming attributable to anthropogenic greenhouse gas emissions[21,22] not occurred. That suggests the probability of severe daily precipitation for these autumns is roughly 33% higher than had these emissions and resulting warming not occurred (Supplementary Figs 1, 2).

Scaling observed precipitation, however, cannot rigorously quantify the change in probability of a specific type of complex weather-related event. Only by explicitly modelling climates encompassing all possible weather states consistent with antecedent uncertainty for the period of interest, both with and without anthropogenic drivers, can one address a well-posed question: what fraction of the event probability is attributable to the anthropogenic drivers[13,16]? If we can assume an unchanging relationship between hazard and resulting damage, then event probability becomes a proxy for risk.

Such an attribution framework was used to assess the contribution of anthropogenic drivers to European heatwave risk in summer 2003[23]. However, that study used a relatively low-resolution climate model with a limited number of simulations, and assumed unchanging variability about an anthropogenic trend in mean summer temperatures. This is not appropriate for UK flooding, which is a smaller spatio-temporal-scale phenomenon subject to greater variability that may change under anthropogenic drivers[2,15].

Here we develop this attribution framework, and assess the contribution of twentieth-century anthropogenic greenhouse gas emissions to flood risk in England and Wales in autumn (September to November) 2000. We use a seasonal-forecast-resolution climate model, and account for any anthropogenic change in variability by generating 'time-slice' simulations under two driving scenarios constructed for autumn 2000: a realistic scenario representing the actual climatic conditions (A2000), and a hypothetical scenario representing the climatic conditions as they might have been had twentieth-century anthropogenic greenhouse gas emissions not occurred (A2000N).

The model is HadAM3-N144, with a global horizontal resolution of 1.25° longitude by 0.83° latitude, and 30 vertical hybrid-pressure levels[24]. As atmosphere–ocean feedbacks were not believed to play a major role during autumn 2000[10,25], we use an atmosphere-only model, with sea surface temperatures (SSTs) and sea ice as bottom boundary conditions.

The A2000 scenario attempts to represent realistic autumn 2000 conditions in the model by prescribing greenhouse gas and other atmospheric pollutant (sulphate aerosol, ozone) concentrations for that time, as well as prescribing observed[26] SSTs and sea ice (see Methods). The A2000N scenario attempts to represent hypothetical autumn 2000 conditions in the model by altering the A2000 scenario as follows: greenhouse gas concentrations are reduced to year 1900 levels; SSTs are altered by subtracting estimated twentieth-century warming attributable to greenhouse gas emissions, accounting for uncertainty; and sea ice is altered correspondingly using a simple empirical SST–sea ice relationship determined from observed[26] SST and sea ice. The attributable SST warming is derived from estimates[21,22] that used

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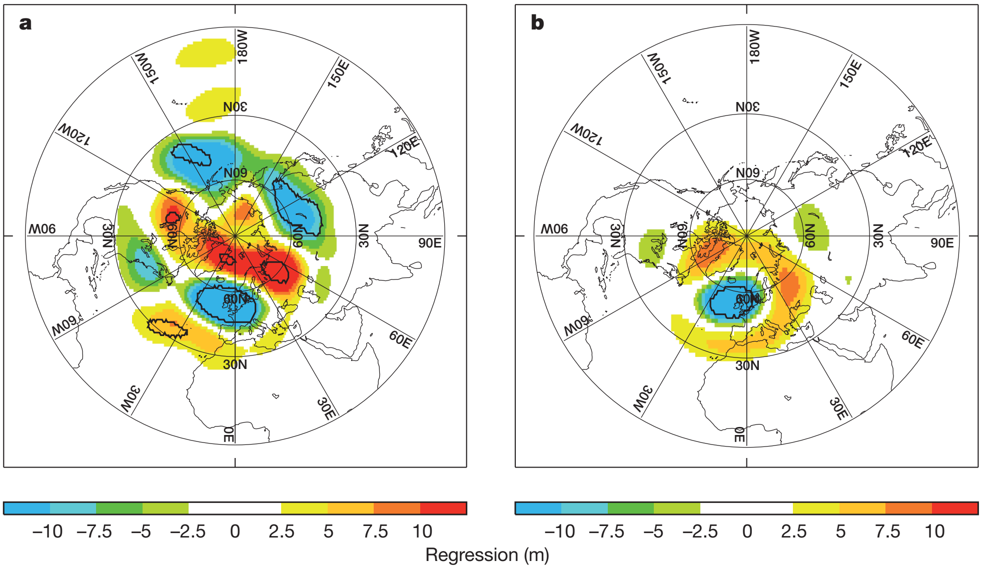

Figure 1 | Synoptic structure of Northern Hemisphere autumns. Regression pattern (m) of mean autumn 500-hPa geopotential height against total autumn England and Wales precipitation normalized by one standard deviation. **a**, For all autumns before autumn 2000 in ERA-40 (1957–99). **b**, For all simulations in the A2000 climate. Bold contours denote areas significant at 1%, assuming 43-member samples (number of ERA-40 autumns) and normally distributed regression variables. Hemispheric correlation of the two patterns is 0.69, falling within the 0.57–0.87 (5th–95th percentile) range of Monte Carlo bootstrap correlations between the A2000 pattern and patterns constructed using random 43-member sub-samples of A2000 simulations.

well-established 'optimal fingerprinting' analysis[1,2]. Specifically, four spatial patterns of attributable warming were obtained from simulations with four coupled atmosphere–ocean climate models (HadCM3, GFDLR30, NCARPCM1 and MIROC3.2), and pattern amplitudes and associated uncertainties were constrained by historical observations (see Methods). Hence the full A2000N scenario actually comprises four scenarios with a range of SST patterns and sea ice, reflecting the uncertainty in large-scale anthropogenic greenhouse gas warming.

Numerous model simulations are required under both the A2000 and A2000N scenarios to capture what was considered a relatively unpredictable, rare event[3,4,13,16,25]. Thus under each scenario we generate an ensemble of several thousand one-year weather simulations covering the autumn 2000 period, with perturbed initial conditions. This is beyond available conventional supercomputing resources, so we used a global, publicly volunteered distributed computing network, using architecture developed under the climate*prediction*.net project[11,12]. The resulting large A2000 and A2000N ensembles of weather simulations respectively constitute our estimates of realistic and hypothetical autumn 2000 climates.

Autumn 2000 weather was characterized by a general eastwards displacement of the North Atlantic jet stream from its climatological position, bringing intense systems further into western Europe[10]. This displacement was associated with a commonplace but anomalously strong 'Scandinavia' atmospheric circulation pattern (a Rossby-wave-like train of tropospheric anomalies in geopotential height, extending from the subtropical Atlantic across Eurasia, with a cyclone over the UK and a strong anticyclone over Scandinavia). This Scandinavia pattern was itself catalysed by anomalous tropical Atlantic and South American upper-tropospheric convergence, and a possible weak secondary northern mid-Atlantic SST feedback[10]. A regression of mid-tropospheric geopotential height against England and Wales precipitation for all previous autumns (1957–99) in the observation-based ERA-40 reanalysis[27] certainly yields a structure (Fig. 1a) remarkably similar to the Scandinavia pattern.

We use a seasonal-forecast-resolution model that better represents the extra-tropical jets than lower-resolution counterparts typically used for climate simulations[24]. Indeed, the ERA-40 pattern is consistent with the analogous synoptic pattern in our A2000 climate (Fig. 1b): it also displays a negative centre over the UK subsumed in a Rossby-wave-like train over the Atlantic-Eurasian region. Although a weak test, because ERA-40 autumns originate from different years with differing conditions whereas A2000 autumns originate from simulations with autumn 2000 conditions alone, this comparison nevertheless provides some confidence in the model's ability to represent the relevant synoptic conditions.

Autumn 2000 flood episodes involved sequences of intense weather systems bringing heavy multi-day precipitation pulses to catchments that became saturated[4]. Hence we examine daily river runoff, which is a better measure of flooding than total precipitation. We synthesize this runoff using a relatively simple precipitation-runoff model[28], derived from a coupled land-surface and river-routeing scheme with empirically estimated and optimized hydrologic parameters for England and Wales catchments (see Methods). We feed England and Wales total daily precipitation time-series from all our climate model simulations into this model to produce ensembles of synthetic daily river runoff associated with our A2000 and A2000N climates. To test if this runoff adequately represents autumn variability, we compare it with ERA-40 runoff, similarly synthesized using precipitation from all available autumns (1958–2001). Figure 2 demonstrates that England and Wales runoff variability in our A2000 climate is representative of that in ERA-40 autumns over a range of timescales.

We compare the runoff ensembles for A2000 and A2000N climates via occurrence frequency (or equivalently, 'return time') curves in Fig. 3. A given magnitude of runoff event generally occurs more frequently in the A2000 climate (a decreased return time), and so is more probable in any given autumn, relative to all four estimates of A2000N climate.

We thus estimate the fraction of flood risk in England and Wales in autumn 2000 that is attributable to twentieth-century anthropogenic greenhouse gas emissions. This is represented via the change in probability of a severe daily river runoff event, assuming an unchanging relationship between that hazard and resulting damage (this

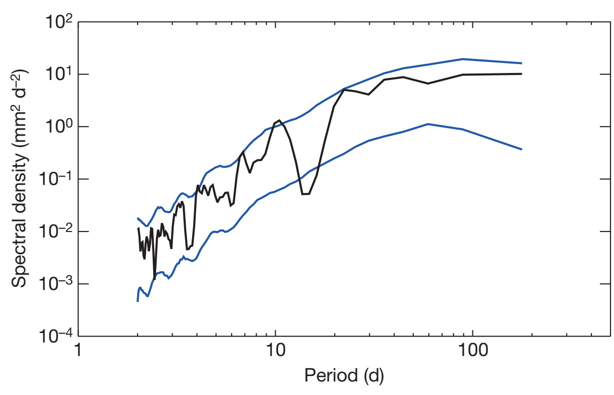

Figure 2 | Power spectra of daily river runoff for England and Wales autumns. Black line shows the spectrum for runoff synthesized from ERA-40 precipitation in all available autumns (1958–2001). Pair of blue lines marks the 5–95% confidence interval of the spectrum for runoff synthesized from all precipitation simulations in the A2000 climate.

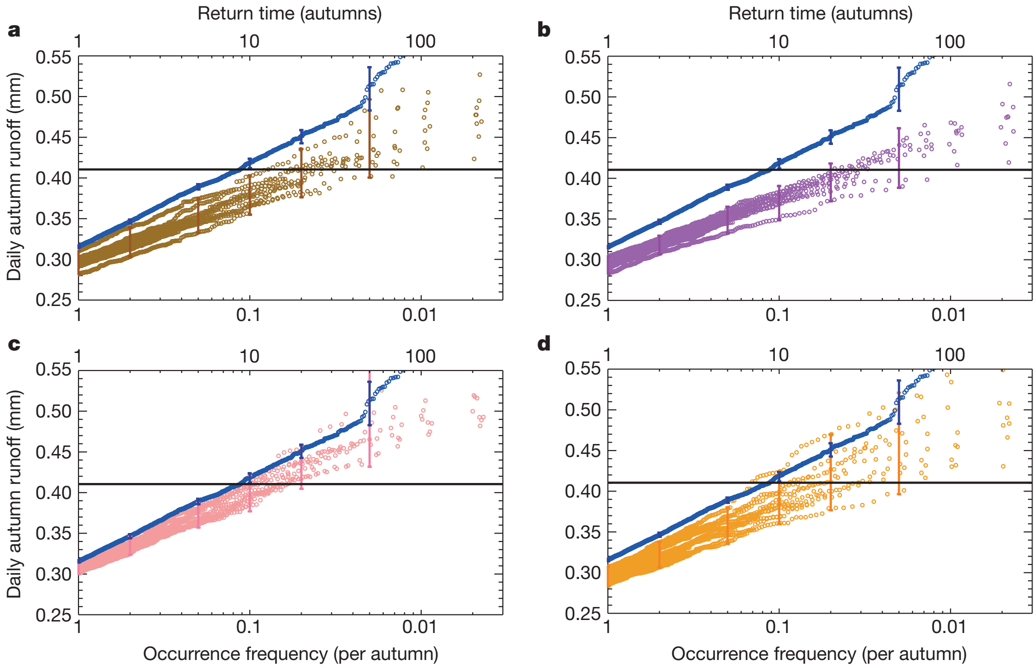

Figure 3 | Change in occurrence frequency of daily river runoff for England and Wales autumn 2000. **a**–**d**, Occurrence frequency curves of runoff (circles) synthesized from all precipitation simulations in A2000 and A2000N climates. Top axis of each panel is equivalent return time. Each panel shows identical A2000 runoff (blue). A2000N runoffs differ, being in climates generated using attributable SST warming estimates from HadCM3 (**a**; brown), GFDLR30 (**b**; purple), NCARPCM1 (**c**; pink) and MIROC3.2 (**d**; orange), with 10 curves corresponding to equiprobable amplitudes of warming. Bars represent 5–95% confidence intervals (see Methods). Horizontal line marks the highest autumn 2000 runoff synthesized from ERA-40 precipitation (0.41 mm).

focuses on hydrometeorological contributions to risk: other factors, such as the changing built environment, could also have contributed through changing vulnerability). As the observed floods involved a range of multi-day protracted flows rather than flash events[4], these flows are also reflected in high daily values. Hence we define 'severe' to be anything exceeding the highest observation-based daily runoff for autumn 2000, as synthesized from ERA-40 precipitation (0.41 mm, denoted by the horizontal line in Fig. 3). R and R_N are then the fraction of runoff events in the A2000 and A2000N climates respectively that exceed this threshold. It follows that the fraction of attributable risk is FAR $= 1 - R_N/R$ (refs 13, 16). Uncertainty in this calculation is estimated using a Monte Carlo bootstrap sampling procedure on pairs of A2000 and A2000N runoff ensembles in Fig. 3 (see Methods).

The resulting distributions of FAR in Fig. 4 (coloured histograms) show significantly (at the 10% level) increased flood risk in the A2000 climate relative to all four estimates of A2000N climate. Assuming that these estimates effectively span uncertainty in the true A2000N climate, through the range of attributable SST warming estimates used in generating them, the full increase is given by the aggregate distribution (black histogram). It shows that the increase in risk of occurrence of floods in England and Wales in autumn 2000 that is attributable to twentieth-century anthropogenic greenhouse gas emissions is very likely (nine out of ten cases) to be more than 20%, and likely (two out of three cases) to be more than 90% (all to one significant figure).

This assessment assumes that attributable SST warming estimates can simply be subtracted from the SSTs observed in 2000, with seasonal to interannual modes of SST variability otherwise remaining unchanged. Although anthropogenic influence on such modes is indeed very uncertain[1], this assumption of additivity may be inappropriate for events highly dependent on them[29]. However, the dependence of UK autumn 2000 precipitation on such modes appears minor[10,25], justifying our approach here.

The range of FAR estimated using our explicit-modelling framework (Fig. 4, black histogram) is approximately consistent with the FAR estimated using observations in the simple thermodynamic framework (Supplementary Fig. 2), and this consistency between approaches of vastly different complexity suggests our results are physically plausible. Allied to this, the range appears independent of any response to rising greenhouse gases of the key atmospheric mode of variability relevant to UK autumnal precipitation (Supplementary Fig. 3). Hence our results should be relatively insensitive to the choice of modelling tools, but exploring sensitivity to choice of atmospheric and hydrologic model, and SST modes, remains a priority. So does further evaluation of our modelling set-up, although evaluation of extreme event statistics is hampered by limited historical records. We assume that any bias in England and Wales flooding between the A2000 climate and ERA-40 applies identically to the A2000N climate. This assumption is impossible to test explicitly, especially considering that absolute biases can be difficult to assess owing to variation between observation-based values themselves[3,27]. Crucially, however, most runoff occurrence frequency curves in Fig. 3 remain approximately linear over a range of extreme values, so our FAR estimate would be consistent over a range of bias-corrected flood thresholds.

We have developed a 'probabilistic event attribution' framework that quantifies the anthropogenic contribution to flood risk. We stress that

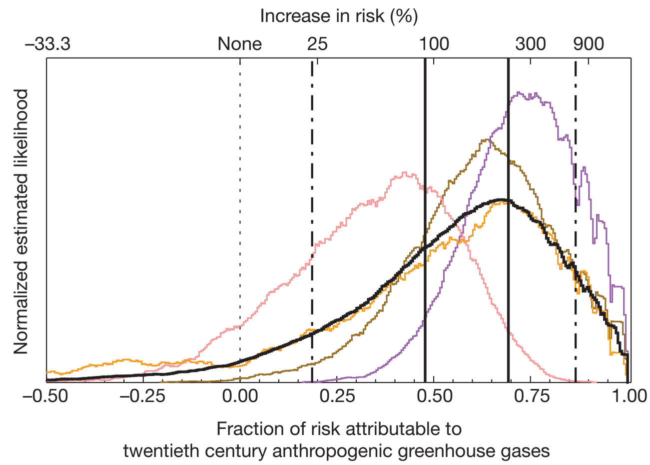

Figure 4 | Attributable risk of severe daily river runoff for England and Wales autumn 2000. Histograms (smoothed) of the fraction of risk of severe synthetic runoff in the A2000 climate that is attributable to twentieth-century anthropogenic greenhouse gas emissions. Each coloured histogram shows this fraction of attributable risk (FAR) with respect to one of four A2000N climate estimates in Fig. 3 (with corresponding colours). The aggregate histogram (black) represents the FAR relative to the full A2000N climate, with the dot-dashed (solid) pair of vertical lines marking 10th and 90th (33rd and 66th) percentiles. Top axis is equivalent increase in risk.

our results relate to autumn 2000-type floods. But other event-types, such as snow-melt floods, might have become less likely under anthropogenic climate change: our framework provides a method for also assessing those likelihoods. Furthermore, just because an event-type becomes more likely does not guarantee it will become even more likely in future—but it does highlight a potential impact of climate change.

With many purported climate change impacts being reported—many related to extreme weather—an objective method of distinguishing actual impacts is urgently needed. Our assessment is for the greenhouse gas contribution only: the total anthropogenic contribution would also require consideration of climate drivers such as sulphate aerosols and ozone. However, the recently launched Adaptation Fund, intended to finance climate change adaptation activities in developing nations, operates under the auspices of the United Nations Framework Convention on Climate Change that specifically defines 'climate change' as due to greenhouse gas emissions[30]. By demonstrating the contribution of such emissions to the risk of a damaging event, our approach could prove a useful tool for evidence-based climate change adaptation policy.

METHODS SUMMARY

A2000 climate. HadAM3-N144 simulations run under the A2000 scenario were initially perturbed using a conventional next-day-difference technique, and started in April 2000 as wet spring conditions preceded autumn 2000[4]. The climate contains an ensemble of 2,268 one-year simulations.

A2000N climate. HadAM3-N144 simulations with similarly produced initial perturbations ran under four A2000N scenario estimates, constructed using attributable surface warming patterns from HadCM3, GFDLR30, NCARPCM1 and MIROC3.2. These spatial patterns each have an uncertainty distribution on their amplitude[21,22], estimated through optimal fingerprinting analysis[1,2]. We scaled each pattern by deciles of this distribution, yielding 10 equiprobable estimates. Hence there are 10 curves per A2000N climate estimate in Fig. 3. These four climate estimates contain ensembles of 2,158, 2,159, 2,170 and 2,070 one-year simulations respectively.

Estimating runoff confidence intervals and FAR. We estimated runoff sampling uncertainty in Fig. 3 by Monte Carlo bootstrap sampling the A2000 ensemble, and each of the 10 scaling-ensembles per A2000N climate estimate. Corresponding confidence intervals are shown for the A2000 curve and the collective 10 curves in each A2000N climate estimate. For each sampled A2000–A2000N ensemble pair, we computed change in exceedance probability of our severe threshold, and hence FAR. The distributions of these FARs are coloured histograms in Fig. 4.

Precipitation-runoff model. Our runoff synthesis was derived from a coupled hydrologic–hydraulic scheme describing land-surface and river-routeing processes, respectively. The hydrologic component was forced by precipitation constructed from ERA-40 using an analogue Monte Carlo method with statistical downscaling, and calibrated for 11 England and Wales catchments using observed runoff data. The hydraulic component was calibrated for these catchments using gauge flow statistics. We fitted a linear transfer function precipitation-runoff model[28] to long simulations with this scheme, with parameters accounting for different runoff timescales. This model was fed our climate model and ERA-40 precipitation, assuming it was uniformly falling rainfall.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions M.R.A., D.A.S, P.P. and P.A.S. designed the probabilistic event attribution framework. P.P. and T.A. implemented the framework, generating HadAM3-N144 climate model simulations using climate*prediction*.net distributed computing architecture, and feeding them into the precipitation-runoff model for England and Wales catchments designed and developed by D.L. and A.G.J.H. P.A.S. and T.N. contributed estimates of attributable warming using coupled climate models. P.P., D.A.S., M.R.A., A.G.J.H. and P.A.S. wrote the paper.

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METHODS

Generating the A2000 climate. All HadAM3-N144 simulations began with a climatological April base state obtained from running the model under average 1979–96 AMIP2 (Atmospheric Model Inter-comparison Project number 2) conditions[24]. For each simulation, this state was initially perturbed via a unique adjustment to its atmospheric potential temperature (but not other variables, owing to distributed computing bandwidth constraints). These perturbations were derived from next-day surface differences in the AMIP2 simulation, and applied to model grid boxes with a vertical taper. Preliminary tests showed almost full divergence between perturbed simulations on all vertical levels within a model fortnight.

Each perturbed simulation then ran under the A2000 scenario that prescribed the following conditions in the model for the period April 2000 to March 2001: global-mean time-mean major greenhouse gas and halocarbon concentrations, obtained via the Carbon Dioxide Information Analysis Center[31,32]; the approximate annual-mean effect of sulphate aerosols, via modification of cloud droplet effective radius using cloud albedo responses to sulphate emissions pre-estimated from versions of the Hadley Centre atmospheric model with an interactive sulphur cycle and predicted cloud droplet number concentration[33]; zonal-mean monthly-mean ozone, extrapolated from 1990 estimates using a Hadley Centre chemical transport model and chlorine estimates for the troposphere and stratosphere respectively (C. Johnson, personal communication); weekly-mean observed[26] SSTs and sea ice, interpolated to suit the 360-day HadAM3-N144 year. All other conditions (for example, solar forcing, land surface properties) were kept at the base state or at model default settings.

All simulations ran under Windows and Linux operating systems, in a global network of publicly-volunteered computers using climate*prediction*.net[11,12] client-server distributed computing architecture.

We fed each completed simulation's England and Wales total daily precipitation time-series from April 2000 onwards into our precipitation-runoff model[28], to synthesize September 2000 to November 2000 daily river runoff. Thereby we fed both the model's baseflow storage term accounting for preceding long-term processes and the model's convolution filter accounting for preceding short-term processes, in synthesizing the runoff for 1 September onwards. (We also note that for ERA-40, precipitation in non-30-day months is first scaled to accommodate for the 30-day HadAM3-N144 months.)

Generating the A2000N climate. All HadAM3-N144 simulations began with initially perturbed April base states similar to those for the A2000 climate. Each perturbed simulation then ran under the A2000N scenario constructed by altering A2000 scenario gases, SSTs, and sea ice, as described below (all other conditions left as in the A2000 scenario).

To construct A2000N gases, A2000 greenhouse gas and halocarbon concentrations were reduced to year 1900 annual-mean global-mean estimates taken from historical forcing data sets[34].

To construct corresponding A2000N SSTs, A2000 SSTs were altered by subtracting estimated twentieth-century warming attributable to greenhouse gas emissions (Supplementary Figs 4–6).

To construct corresponding A2000N sea ice, A2000 sea ice was altered using the A2000N SSTs, and a simple empirical SST–sea ice relationship determined from observed gridded weekly-mean SST and sea ice data[26]. Aggregating these observed data over years 2000 to 2001 and all grid boxes, we constructed a scatter plot of sea ice fractional grid box coverage versus SST, for Northern and Southern Hemispheres separately. In each hemisphere we applied a linear fit to the scatter, with one end anchored at the freezing point of sea water corresponding to 100% sea ice coverage. This linear SST–sea ice relationship was then applied to the change from A2000 to A2000N SSTs at each HadAM3-N144 grid box, to determine corresponding change in sea ice fractional coverage there. Finally, this sea ice change was subtracted from the A2000 sea ice to produce corresponding A2000N sea ice, and in this way we preserved the scatter characteristics of sea ice coverage.

Similarly to the A2000 simulations, all A2000N simulations were generated using distributed computing, and fed into the precipitation-runoff model.

Calibrating the precipitation-runoff model. The coupled hydrologic–hydraulic scheme operates on a 10-m-resolution digital terrain model, with the hydrologic component strongly based on TOPMODEL[35] and the hydraulic component implementing a Muskingum-Cunge scheme. The hydrologic component runs in 3-h time steps (to capture the intra-day evaporation cycle) and was calibrated against observed[36] daily mean river runoff time-series available for 1986–95. The hydraulic component runs in 5-min time steps (mainly for stability) and was calibrated against return period statistics of the observed daily maxima at gauging stations available from as far back as 1883 to 2006. Parameters were optimized by minimizing the root-mean-squared error (RMSE) so that mismatches of high deviations (runoff peaks) were more heavily penalized; thus the scheme is expected to perform well for wet periods.

The scheme is evaluated in Supplementary Table 1, via RMSE and correlation against the observed 1986–95 daily mean river runoff for each of the 11 England and Wales catchments. RMSE varies between catchments, with higher values typically reflecting higher mean runoff. Importantly, correlation is good for all catchments and is perhaps a more insightful indicator of performance given the issues with assessing change in absolute biases and extremes noted in the main text.

For computational efficiency, we fitted a linear transfer function precipitation-runoff model[28] to 1,000 years of continuous daily river runoff time-series generated with the calibrated scheme, for the largest (area-wise) gauges in each catchment. This transfer function has a fast and slow component, accounting for direct surface runoff and baseflow processes respectively, with the latter incorporating a linear reservoir storage term active from the first day of input precipitation. Briefly, after computing each day's storage, fast and slow components are both passed through a convolution filter accounting for their lumped travel times to and within the catchment's river channel. Thus while this filter only has a 12-day memory, longer-term memory is accounted for via the storage term. This approach is reasonable, given that the ground saturated quickly at the beginning of autumn 2000 and remained that way[4], so that while preceding wet spring conditions may have had some importance, shorter-term precipitation dominated flooding. Indeed, changes in 10-day and less rainfall events over recent decades have been implied[37] as being relevant to UK autumnal flooding.

The model is evaluated in Supplementary Table 2, in terms of England and Wales totals across catchments as considered in the main text. We only show correlations, both for the reasons above and because here we are more interested in how accurately precipitation is translated to runoff (that is, high/low runoff following high/low precipitation). The performance is reasonable and, though poorer for extremes reflecting the limitations of a relatively simple transfer function, is comparable to the coupled scheme's performance and is better for autumnal than annual runoff.

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