Quantifying the risk of extreme seasonal precipitation events in a changing climate

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Increasing concentrations of atmospheric carbon dioxide will almost certainly lead to changes in global mean climate[1]. But because—by definition—extreme events are rare, it is significantly more difficult to quantify the risk of extremes. Ensemble-based probabilistic predictions[2], as used in short- and medium-term forecasts of weather and climate, are more useful than deterministic forecasts using a 'best guess' scenario to address this sort of problem[3,4]. Here we present a probabilistic analysis of 19 global climate model simulations with a generic binary decision model. We estimate that the probability of total boreal winter precipitation exceeding two standard deviations above normal will increase by a factor of five over parts of the UK over the next 100 years. We find similar increases in probability for the Asian monsoon region in boreal summer, with implications for flooding in Bangladesh. Further practical applications of our techniques would be helped by the use of larger ensembles (for a more complete sampling of model uncertainty) and a wider range of scenarios at a resolution adequate to analyse average-size river basins.

The autumn and winter of 2000/2001 were the wettest on record over England and Wales, with widespread flooding[5]. Throughout the period, there was a general sense of concern that such heavy and prolonged precipitation was attributable in some measure to anthropogenic global warming. In attempting to address such societal concerns, we pose the question: how does anthropogenic forcing influence the probability of occurrence of unusually large seasonal precipitation amounts?

Specifically, we consider the dichotomous event E_n, defined to occur if the total seasonal precipitation at a specific location exceeds n standard deviations (σ) above the mean (μ). (Here μ and σ are location-dependent and seasonally dependent climate statistics, associated with twentieth-century levels of atmospheric CO_2.) We restrict attention to $n = 2$ and $n = 3$, and use the conventional meteorological delineation (December–February, March–May, June–August and September–November) of seasons.

The methodology of ref. 6, based on the risk of any dichotomous climate event E, is used to analyse the changing probability of the extreme events E_2 and E_3, as determined by an ensemble of climate projections. Here we use 80-year integrations from the CMIP2 (second coupled model intercomparison project) multi-model ensemble of 19 global coupled ocean–atmosphere climate models[7] as discussed in the recent IPCC assessment[1]. The benefit of the multi-model ensemble (over a single-model ensemble) accrues from its sampling some of the inevitable uncertainties in the computational representation of the equations of climate[8]. The first (control) ensemble was run with a constant twentieth-century CO_2 concentration (about 330 p.p.m.v.), and the second (greenhouse) ensemble with a transient compound increase in CO_2 of 1% per year. This increase in CO_2 is somewhat faster than is anticipated for the twenty-first century, but its use can be justified from the neglect of other anthropogenic greenhouse gases in CMIP2. More specifically, the global-mean radiative forcing due to the 70-year doubling of CO_2 in the CMIP2 experiments (3.7 W m^{-2}) is in the mid-range of the IPCC projections of the change in radiative forcing from 1990 to 2060 (2.6–5.0 W m^{-2} for different forcing scenarios). Although it would be desirable to repeat this analysis based on other trace-gas scenarios, sufficiently large multi-model ensembles with alternative scenarios do not at present exist.

The control CMIP2 ensemble is used to define a 'baseline' twentieth-century probability of E_n, whilst the probability of E_n at the time of CO_2 doubling is estimated from years 61–80 of the CMIP2 greenhouse ensemble. Figure 1a shows the probability of

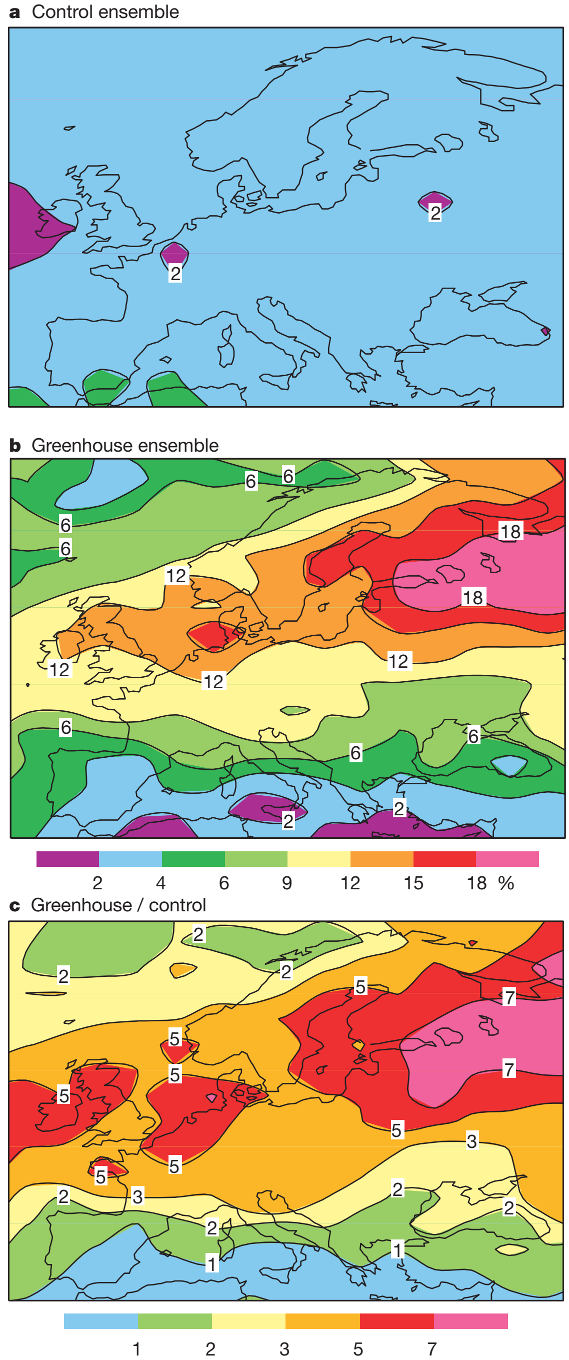

Figure 1 The changing probability of extreme seasonal precipitation for Europe in boreal winter. **a**, The probability (in %) of a 'very wet' winter defined from the control CMIP2 ensemble with twentieth-century levels of CO_2 and based on the event E_2: total boreal winter precipitation greater than the mean plus two standard deviations. **b**, The probability of E_2 but using data from the greenhouse ensemble with transient increase in CO_2, and calculated around the time of CO_2 doubling (years 61–80 from present). **c**, The ratio of valies in **b** to those in **a**, giving the change in the risk of a 'very wet' winter, arising from human impact on climate.

occurrence of E_2 over Europe from the control ensemble in boreal winter. As would be expected, there is an approximately 2.5% probability of occurrence (consistent with an expected return period of about 40 years). Figure 1b shows the probability of E_2 at the time of CO_2 doubling. Over much of central and northern Europe, the probability has increased to over 12% (consistent with an expected return period of about 8 years), associated with enhanced storm-track activity and 'wetter' storms. By contrast, over parts of the Mediterranean and Northern Africa, the probability of E_2 at the time of CO_2 doubling has decreased.

In Fig. 1c we show the ratio of the probabilities in Fig. 1b and a, giving a measure of the changing risk of E_2 resulting from anthropogenic forcing. Over parts of northern Europe, including much of the United Kingdom, $r \approx 5$. Defining a 'very wet' winter as one in which E_2 occurs, and with the caveats that the greenhouse ensemble is based on an idealized anthropogenic forcing scenario, and that the CMIP2 ensemble may not necessarily span all model uncertainties, we can give the following assessment: the probability of occurrence of a very wet winter over the UK is estimated to increase by a factor of 5 over the next 50–100 years, due to man's effect on climate.

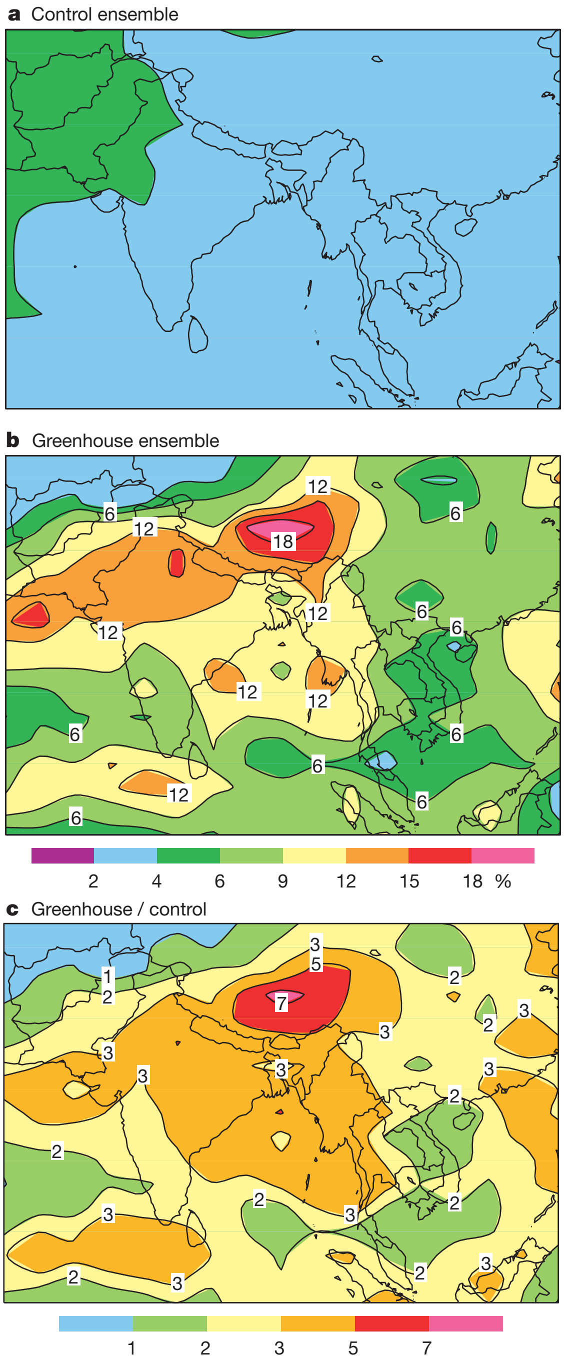

Figure 2 As Fig. 1 but for total boreal summer precipitation in the Asian monsoon region.

Corresponding estimates of the changing probability of E_2 over the Asian monsoon region in boreal summer are given in Fig. 2. Note that regions of enhanced probability of E_2 intersect the catchment basin of the Brahmaputra River in particular, but also those of the Ganges and Meghna rivers. Over and above the effects of sea-level rise (not the subject of the present study), this implies an increased risk of flooding in Bangladesh. Figures 1 and 2 extend earlier results[9] on extremes in daily precipitation to the seasonal timescale and to a multi-model ensemble.

We consider that such probabilistic projections have greater potential value than deterministic projections from either single integrations or from the 'consensus' approach used extensively in the recent IPCC assessment. To show this, a generic 'cost-loss' binary-decision model used to assess the economic utility of ensemble weather forecasts and seasonal predictions[3,4] was adapted for the climate-change timescale. (We retain the symbols C and L in this adaptation, though their meaning is somewhat different from the original 'cost of protecting against E' and 'loss due to the occurrence of E'.)

Although such a model is too simple to apply quantitatively to specific realistic decision problems, its underlying formulation deals here with an imagined set of individuals faced with a long-term investment decision: buy either domestic property A (which is sited in a visually attractive location, but which might be prone to flooding), or domestic property B (which is insensitive to weather, but which lies in an area that is likely to be earmarked for high-density development). We assume that all values are measured relative to some inflation-adjusted index, and base the calculations on anticipated climate change over the next 80 years. If no extreme events E_n occur, then the value of A is expected to exceed that of B by an amount C. On the other hand, the value of A will linearly decrease by an amount ΔL every time E_n occurs.

We assume, for simplicity and to minimize sampling effects, that the devaluation ΔL applies if E_n occurs, irrespective of season. For each grid point, let $p(t_{ij})$ denote an estimate of the probability of occurrence of E_n for season i ($i = 1, \ldots, 4$) and year j ($j = 1, \ldots, 80$). Then the expected devaluation of A due to E_n is $\Sigma_{j=1}^{80}\Sigma_{i=1}^{4} p(t_{ij})\Delta L = \bar{p}L$, where $\bar{p}$ is the average probability of occurrence of E_n over the 80-year period, and $L = \Delta L \times 320$. Hence, a rational risk-neutral decision strategy is: buy A if $C > \bar{p}L$, buy B if $C < \bar{p}L$, and toss a coin in the rare case that $C = \bar{p}L$.

Imagine three groups of individuals, each uniformly distributed around the (land points of the) globe. The individuals in group 1 estimate $\bar{p}$ from the probability of occurrence of E_n in the full greenhouse ensemble. By contrast, the individuals in group 2 estimate $\bar{p}$ from the number of occurrences of E_n in a single randomly chosen member of the greenhouse ensemble. (For example, they might rely on a specific national model.) The individuals in group 3 estimate $\bar{p}$ from the number of occurrences of E_n in the greenhouse-ensemble consensus projection.

We estimate the value of the investments made by these three groups, assuming that the true number of occurrences of E_n during the 80-year period is given by a randomly chosen member of the greenhouse ensemble (which is excluded from the climate prediction data set). The value is compared with a lower reference value based on the estimate $\bar{p}$ given by the control ensemble, and an upper reference value based on knowing the truth in advance.

Let M_i denote the expected value of investments for all individuals in subset i at year 80, as aggregated over all land grid points of the

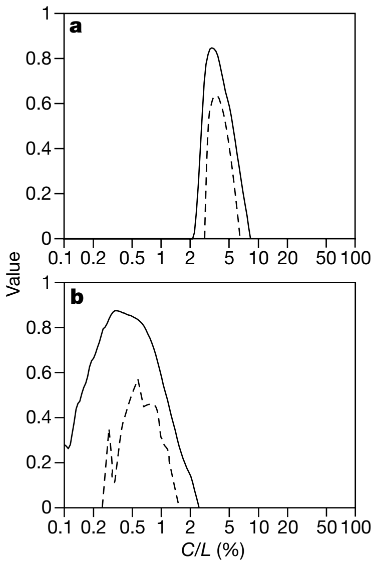

Figure 3 The potential economic value of probabilistic projections of climate change based on a generic binary decision model (see text for details). *C* and *L* are possible financial losses, relative to some reference index, associated with two alternative investments. Solid lines, value based on the CMIP2 greenhouse ensemble probability of E_n over the next 80 years. Dashed lines, value based on an estimate of E_n from a single member of the CMIP2 greenhouse ensemble. When value is zero or less, the corresponding estimate of the probability of E_n is no better than an estimate based on the control ensemble. A value of one would correspond to a perfect decision strategy. **a**, $n = 2$; **b**, $n = 3$.

globe. This value is illustrated in terms of the non-dimensional quantity $V_i = (M_i - M_l)/(M_u - M_l)$, where M_l and M_u are the lower and upper reference values respectively. Hence if $V_i = 0$, then the estimate of $\bar{p}$ of subset i is no better than an estimate which assumes that the climate of the twenty-first century will be the same as that of the twentieth century. On the other hand, perfect investment decisions have a value $V_i = 1$. In calculating V_i we average over all choices of verifying model. For V_2 we also average over all choices of forecast model.

Figure 3 shows V_1 and V_2 for $n = 2$ and $n = 3$, as a function of C/L. We do not show V_3 because it is never greater than zero. The reason for this is straightforward: the number of occurrences of extreme climate events is severely underestimated in the consensus projection. This arises because ensemble averaging tends to produce smooth fields which are unrealistically biased towards the climate-mean state.

If C/L is either sufficiently small, or sufficiently large, then accurate ensemble forecasts are clearly not needed to make good investment decisions (buy B or A, respectively). Hence, the greenhouse ensemble only has positive economic value (compared with the baseline value M_l) for a subset of possible C/L. This ensemble tends to be most valuable (compared with M_l) when C/L is comparable with the control ensemble estimate of $\bar{p}$. As $\bar{p}$ is smaller for E_3 than for E_2, then the greenhouse ensemble provides value for smaller C/L, when decisions are based on the occurrences of E_3 rather than E_2. It can be seen that the value of the greenhouse ensemble is never less than the value of a single deterministic projection, and that, overall, the difference in value between the ensemble and the single deterministic projection is larger for E_3 than for E_2. This is because the relative unreliability of the single deterministic projection is larger for E_3 than for E_2.

In fact, much larger ensembles are needed to provide reliable estimates of the probability of E_3 on a regional basis (for example, specific to the UK or for Bangladesh). Moreover, more research is needed to develop sound methodologies for representing model uncertainty in climate-prediction ensembles[10]. In addition, such extreme-event risk analysis would benefit from an increase in the resolution of present-day climate models (with grid sizes of hundreds of kilometres). For example, it would clearly be of more direct relevance for the decision problem discussed above if E was defined by some specific river bursting its banks during a particular season. However, estimating the future risk of this type of event would require feeding climate model output into a basin-specific hydrological model. In general, climate model grid sizes of the order of ten kilometres would be necessary to simulate precipitation statistics adequately over a typical catchment area (though for rivers with large catchment basins, such as the Brahmaputra, coarser climate model grids may be adequate). An ability to estimate reliably the probability of extreme climate events is an important factor in defining future computational requirements for the climate change problem. □

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Increasing risk of great floods in a changing climate

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Radiative effects of anthropogenic changes in atmospheric composition are expected to cause climate changes, in particular an intensification of the global water cycle[1] with a consequent increase in flood risk[2]. But the detection of anthropogenically forced changes in flooding is difficult because of the substantial natural variability[3]; the dependence of streamflow trends on flow regime[4,5] further complicates the issue. Here we investigate the changes in risk of great floods—that is, floods with discharges exceeding 100-year levels from basins larger than 200,000 km^2—using both streamflow measurements and numerical simulations of the anthropogenic climate change associated with greenhouse gases and direct radiative effects of sulphate aerosols[6]. We find that the frequency of great floods increased substantially during the twentieth century. The recent emergence of a statistically