LENGTHENED ODDS OF THE COLD UK WINTER OF 2010/11 ATTRIBUTABLE TO HUMAN INFLUENCE

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The winter of 2010/11 began with the coldest December in the UK series dating back to 1910 and the second coldest December in the Central England Temperature (CET) record dating back to 1659 (Manley 1974), with a –5.3°C anomaly in the monthly average temperature relative to the 1961–90 mean. There were many adverse consequences of the extreme temperatures, including closed airports and schools. There was also the novel experience for many children, wherever they lived in the United Kingdom, of a white Christmas. Here we put the cold winter of 2010/11 into the long-term context of climate variability and change through an analysis of the 353 yr central England temperature record and the application of a new modeling system for attribution of extreme weather- and climate-related events. Because February was much milder, with a positive temperature anomaly of 2.6°C, we concentrate in this paper on the first two months of winter.

Figure 14 shows how the early part of the 2010/11 winter compares to the other winters in the central England temperature record. Both the combined 2-month mean temperature for December and January and the mean December 2010 temperature stand out as exceptionally cold, although in neither case was the temperature unprecedented in this unique multi-century instrumental record. The question we seek to answer is whether the chances of such cold winter temperatures were greater or less in 2010/11 as a result of human influence on climate.

Has human influence on climate changed the chances of cold winters? The main tool we use to address this question is the Met Office Hadley Centre attribution system (Christidis et al. 2012, manuscript submitted to *J. Climate*). This is based on HadGEM3-A, the atmospheric component of the model used for seasonal forecasting at the Met Office (Arribas et al. 2011) and which has a resolution of 1.25° longitude by 1.875° latitude and 38 vertical levels. We compare a 100-member ensemble of model simulations forced with observed SSTs and sea ice and current levels of greenhouse gases with two alternative 100-member ensembles in which human influence has been subtracted from the SSTs and sea ice and in which greenhouse gases and aerosols are reduced to preindustrial levels following a similar methodology to that of Pall et al (2011). Here, estimates of the change in SST due to human influence are derived from transient simulations of three coupled climate models, HadGEM1, HadGEM2-ES, and HadCM3. Further details of the attribution system are given in Christidis et al (2012, manuscript submitted to *J. Climate*).

Verification of model statistics against observations helps assess the trustworthiness of the attribution system. Based on a five-member ensemble of simulations forced with observed SSTs from 1960 to 2010, Christidis et al. (2012, manuscript submitted to *J. Climate*) concluded that the model has a realistic representation of UK temperature variability although its reliability in capturing the predictability of UK temperatures is not as high as for temperatures over the region affected by the Russian heat wave of 2010 (Christidis et al. 2012, manuscript submitted to *J. Climate*). Nevertheless the model is expected to produce a reliable estimate of the overall changed odds of cold winters in the United Kingdom due to human influence, all other factors being equal, even if the odds could additionally have been affected in recent years by factors we do not calculate here such as the recent minimum in solar activity (Ineson et al. 2011). As a further check on the robustness of the model-based results, we determine whether they are broadly consistent with observational estimates derived from the multicentury CET record.

Change of odds in the model. The change of odds of cold December and January temperatures in 2010/11 attributable to climate change can be seen in Fig. 15 (top), which shows the ratio of the probability of such cold temperatures in the current world (P1) to the world had human influence not affected climate (P0). The three estimates, based on attributable SST changes derived from the HadGEM1, HadGEM2-ES, and HadCM3 models, have median values of approximately 0.5, indicating that human influence has halved the probability of temperatures as cold as seen in 2010/11 with 5th–95th-percentile uncertainty ranges of 0.24–0.80, 0.25–0.70, and 0.26–0.82 depending on which coupled model is used to define the change in SSTs. In summary, model results indicate that human influence has reduced the odds by at least 20% and possibly by as much as 4 times with a best estimate that the odds have been halved.

Change of odds estimated from the CET record. An observationally based consistency check of these numbers is obtained by calculating empirically the number of times prior to 1910 CET was colder than 2010/11 (28 times) and comparing this to the number of times CET would have been colder than observed in 2010/11 if CET had warmed between 0.3 and 1 K because of human influence on climate (between 20 and 7 times, respectively). These representative values for CET human-induced warming span the range of human-induced SSTs in the vicinity of the United Kingdom according to the HadGEM1, HadGEM2-ES, and HadCM3 models. This corresponds to a reduction of probability of between 0.25 and 0.71 consistent with the estimates obtained from the model. A more direct but more approximate calculation (given the fewer number of data points available for the calculation) is to note that whereas temperatures colder than 2010/11 were observed only once in the last 30 years (P1 = 1/30) and temperatures as cold or colder twice (P = 2/30), colder temperatures were observed from 1 to 6 times in samples of 30-yr periods taken from the CET record before 1910. This difference in probabilities corresponds to a ratio of

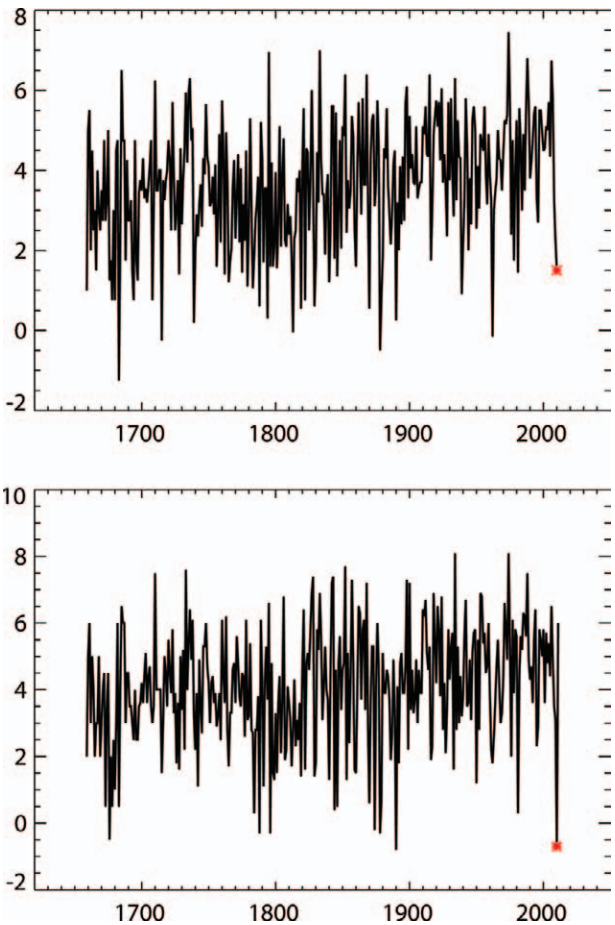

Fig. 14. Central England temperature averaged over (top) December and January combined and (bottom) December. Winter of 2010/11 shown as red stars. December/January 2010/11 was the thirty-fourth coldest December/January in the record and December was the second coldest December in the record.

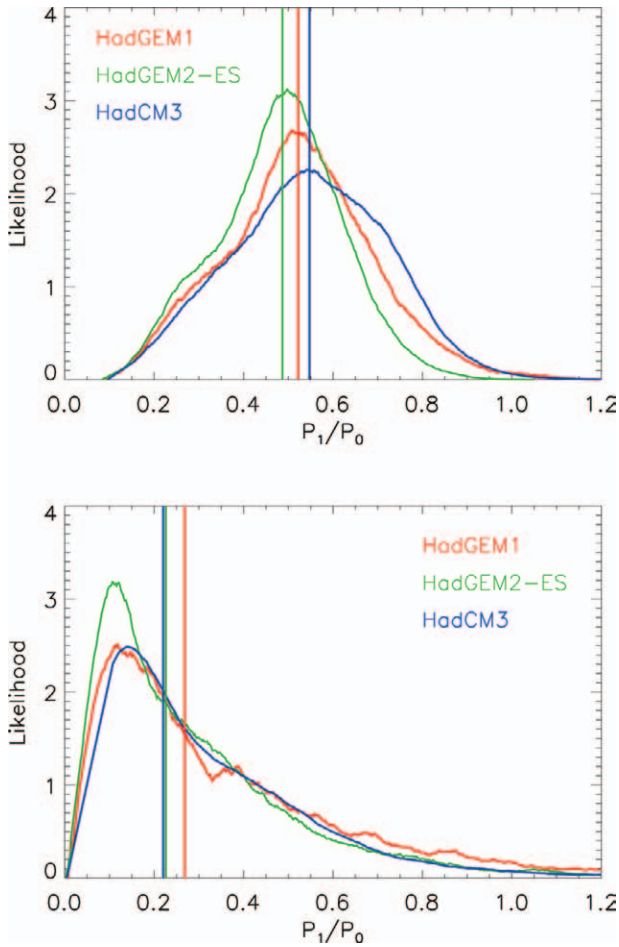

Fig. 15. Attributable change in probability (P1/P0) of (top) December/January temperatures as cold as observed in 2010/11 and (bottom) December temperatures as cold as observed in 2010, where P1 is the probability of a temperature as cold as that observed in the winter of 2010/11 in the current climate, and P0 is the probability of such cold temperatures had human influence not affected the climate of 2010/11. The uncertainty in this number is shown as likelihood distributions representing modeling uncertainty estimated by a bootstrap procedure (Christidis et al. 2012, manuscript submitted to *J. Climate*). Likelihood distributions are calculated for three specifications of alternative SSTs (red, green, and blue curves) estimated from simulations of the HadGEM1, HadGEM2-ES, and HadCM3 coupled climate models. The vertical lines mark the median values. A value of 0.5 indicates that the probability has halved and a value of 1.0 indicates there is no change.

probabilities of from 0.17 to 1 with a median value of 0.5, also consistent with the model-based estimates but with a larger range (due to the greater sampling uncertainty). In this calculation we assume P1 is equally likely to be 1/30 or 2/30 and we treat each overlapping 30-yr segment of CET before 1910 as equally representative of preindustrial temperatures.

For the single month of December 2010, the HadGEM3-A-based attribution system estimates that the ratio of probabilities P1/P0 lies between 0.06 and 1.00 (5th–95th percentiles) with a median of 0.27 when HadGEM1 SSTs are used and between 0.05 and 0.79 with a median of 0.23 when HadGEM2-ES SSTs are used and between 0.05 and 0.74 with a median of 0.22 when HadCM3 SSTs are used (Fig. 15, bottom). The larger uncertainties than for December and January combined are associated with a more extreme temperature excursion. Given the rare nature of this event in the observational record—only two occurrences of temperatures as cold as December 2010 have been seen since 1659 (Fig. 14)—it is not possible to make the same direct observationally based empirical calculation of the change in odds as was done for the combined December/January temperatures.

Conclusions. The winter of 2010/11 was a rare weather event, even in the context of the 352 years of the central England temperature record. Yet while the odds of such an event have lengthened as a result of human influence on climate, such unlikely events can still happen, as the winter of 2010/11 demonstrated. Further refinements of such calculations could include calculations of how the risk of extremely cold temperatures in a specific winter might vary as a result of natural factors, such as a minimum in the solar cycle (Ineson et al. 2011).

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