

5. THE EXTREME MARCH–MAY 2012 WARM ANOMALY OVER THE EASTERN UNITED STATES: GLOBAL CONTEXT AND MULTIMODEL TREND ANALYSIS

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Introduction. We survey the globe for seasonal and annual mean surface temperature extremes that occurred during 2012. We define an extreme seasonal mean anomaly as one that ranks first, second, or third in the period of record, using the HadCRUT4 observations (Morice et al. 2012). Anomalous warmth over the eastern United States during March–May (MAM) is found to be particularly extreme and spatially extensive. To place this seasonal extreme warmth in the context of long-term climate change, we analyze the time series for this region, comparing observed trends with model simulations of internal climate variability and modeled responses to both anthropogenic and natural forcings using 23 Coupled Model Intercomparison Project phase 5 (CMIP5) models (Taylor et al. 2012).

Where did record or near-record seasonal mean surface temperatures occur in 2012? Global maps of the seasonal- and annual-mean temperature anomalies for 2012 are shown in Fig. 5.1 (left column). Maps in the right column depict where the anomalies were the first, second, or third most extreme in the record—either warm (red colors) or cold (blue colors). The results show a predominance of warm versus cold

extreme occurrences. For extreme annual means, the percent of global analyzed area with first, second, or third warmest in the record, starting as early as 1851, was 15.3% compared with zero cold extremes. The ratios of warm-extreme-to-cold-extreme percent areas were 6.2% : 0.1% for December–February (DJF); 7.7% : 0.2% for MAM; 11.4% : 0.7% for June–August (JJA); and 12.5% : 0.1% for September–November (SON).

A pronounced broader-scale feature in the extremes maps is the record MAM warmth over the eastern continental United States, which was also highly anomalous for the annual means. Much of the Mediterranean region experienced record or near-record JJA and SON warm anomalies. The SON map also shows near-record Atlantic Ocean warmth off the east coast of the United States, which spanned the time of occurrence and extratropical transition of Hurricane Sandy in this region. Other extreme seasonal warmth occurred near the Somali current (western Indian Ocean) during SON and other scattered locations around the globe.

How much did anthropogenic forcing contribute to the extreme eastern U.S. warm anomalies during MAM 2012? Having established where extreme seasonal

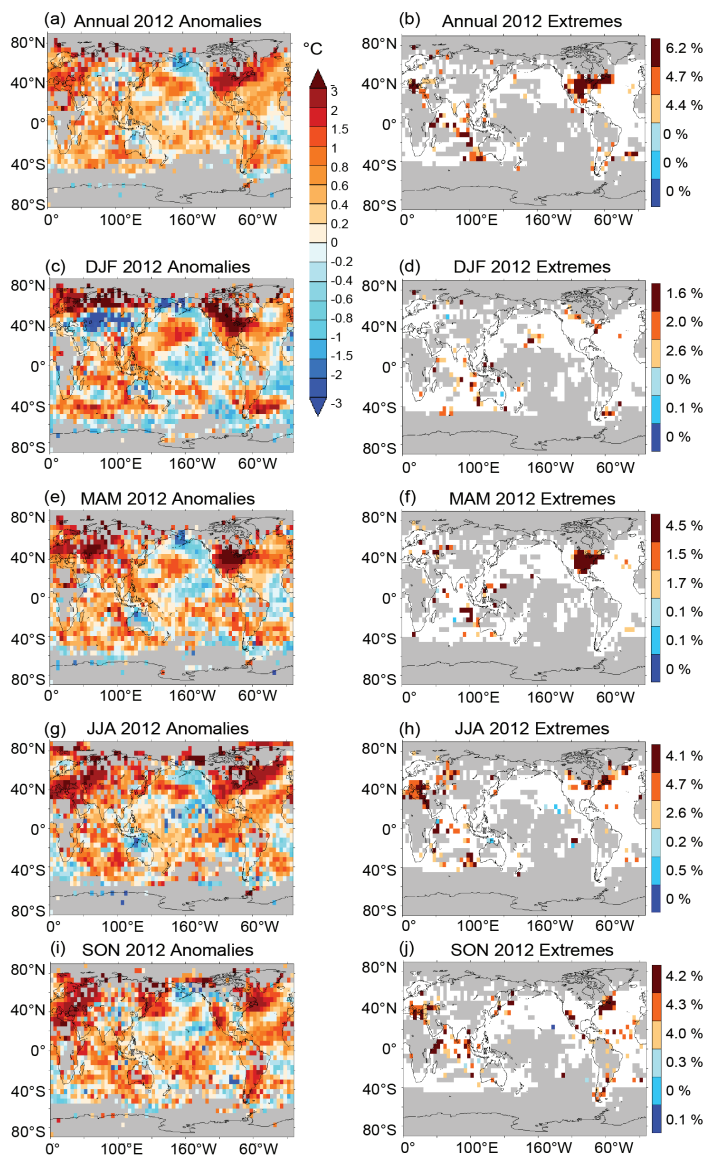


FIG. 5.1. (Left column) Annual (a) or seasonal (c), (e), (g), (i) mean surface air temperature anomalies ($^{\circ}\text{C}$) for 2012 (1961–90 base period) from the HadCRUT4 dataset. The seasons are DJF (Dec 2011–Feb 2012), MAM (Mar–May), JJA (Jun–Aug), and SON (Sep–Nov). (Right column) Colors identify grid boxes with annual (b) or seasonal (d), (f), (h), (j) mean warm anomalies that rank first (dark red), second (orange-red), or third (yellow-orange) warmest in the available observed record, with blue colors for cold extremes. Gray areas did not have sufficiently long records, defined here as containing at least 100 available annual or seasonal means, with an annual mean requiring at least four available months and a seasonal mean requiring at least two of three months to be available.

and annual mean temperatures occurred in 2012, we now examine the extensive warm anomalies over the eastern United States during MAM in more detail.

Using the Hegerl et al. (2009) guidance paper on detection and attribution methods, we first explore

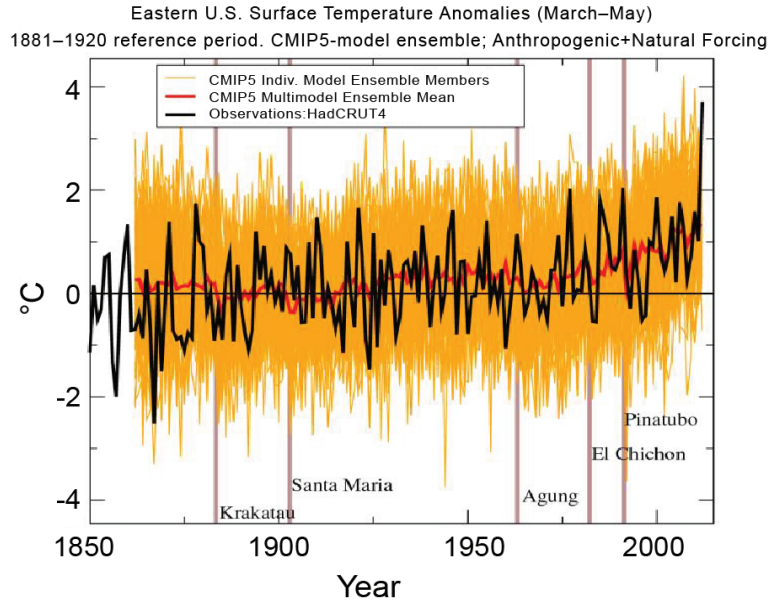
a “multistep attribution” approach. This involves, in general, assessments that attribute an observed change in a variable of interest (in this case, seasonal mean temperature extremes) to a change in climate and/or environmental conditions (in this case, century-long trends in seasonal mean temperatures), plus separate assessments that attribute the change in climate and/or environmental conditions to external drivers and external forcings. We first posit that it is likely that increases in seasonal mean temperatures caused by anthropogenic warming will eventually lead to increases in the extremes (e.g., record or near-record values) of seasonal mean temperatures, but that it may take a substantial record length for this signal to be apparent in the data.

The next step is to assess whether there is detectable warming that is attributable to anthropogenic forcing in the MAM mean temperatures for the eastern U.S. region. For this, we rely on a more extensive trend assessment study that provides further details on our methods and evaluation of model internal variability (Knutson et al. 2013).

Figure 5.2a shows the MAM time series averaged over the region of the eastern United States and southern Canada where the MAM 2012 anomalies were warmest in the record (dark red colors in Fig. 5.1f). The HadCRUT4 observations show a gradual rising trend, with a distinct positive anomaly in 2012 that was nearly twice as warm as the previous record season. The observations lay within the range of the CMIP5 ensemble members, although 2012 is near the upper edge of this range.

Figure 5.2b summarizes a trend analysis for the MAM eastern U.S. time series in Fig. 5.2a, comparing models and observations. Each of the models contributes equally to the multimodel distribution from which the percentiles are derived. The distribution of trends broadens for later start dates, because these represent shorter randomly sampled trends in the control runs, and models can produce larger trend rates by chance for smaller trend lengths. The spread of the All-Forcing (anthropogenic and natural combined) multimodel ensemble (pink) is slightly wider than that of the control run ensemble

(a) Temperature Time Series



(b) Trend Assessment

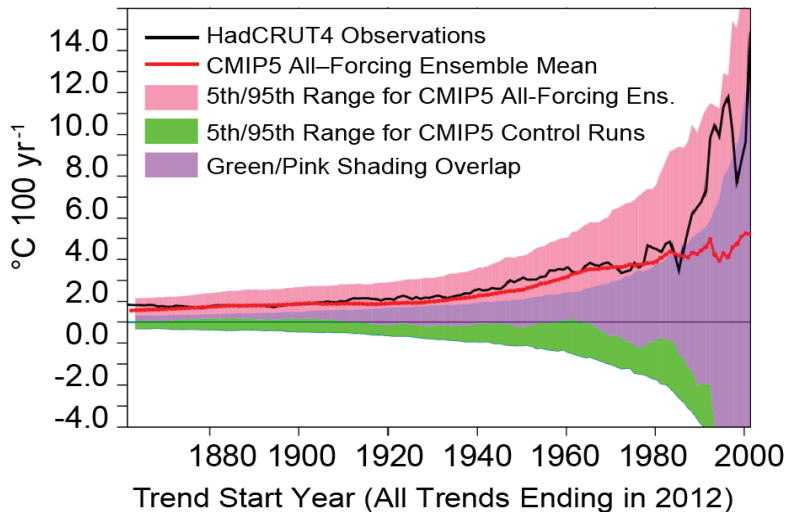


FIG. 5.2. (a) Time series of Mar–May (MAM) averaged surface air temperature anomalies ($^{\circ}\text{C}$) averaged over the region in Fig. 5.1f of record MAM warmth in the eastern United States and southern Canada during 2012. The black line depicts the observed (HadCRUT4) anomalies; the dark red line depicts the multimodel ensemble anomalies from the CMIP5 All-Forcing runs, with each of the 23 models weighted equally; and the orange lines are individual ensemble members making up the CMIP5 multimodel ensemble. The All-Forcing simulations for this region included both anthropogenic and natural forcings from about 1860 to the present, with data from RCP4.5 runs used to extend the time series through 2012 where necessary. All time series shown are adjusted to have zero mean over the period 1881–1920. (b) Trends ($^{\circ}\text{C } 100 \text{ yr}^{-1}$) in the area-averaged MAM mean surface temperature series in (a) as a function of starting year, with all trends ending in 2012. The black curve shows trends from observations (HadCRUT4). The thick red curve shows the ensemble mean trends from the 23-member CMIP5 All-Forcing ensemble. The pink shading shows the 5th–95th percentile range of the distribution of trends obtained by combining random samples from each of the 23 CMIP5 model control runs together with the corresponding model’s ensemble-mean forced trend (All-Forcing runs) to create a multimodel distribution of total trends that reflects uncertainty in both the forced response and the influence of internal climate variability. The green-shaded region shows the 5th–95th percentile range of the trends from the 23 model control runs. Purple shading indicates where the pink- and green-shaded regions overlap.

(green) because it also includes the uncertainty due to the different ensemble mean responses of the individual models. See Knutson et al. (2013) for more discussion and details.

The observed trends in Fig. 5.2b (black line) generally lie outside of the control run 5th–95th percentile range, indicating that (according to the model-generated variability) the observed trends are inconsistent with internal climate variability alone. The observed trend also lies within the pink- or purple-shaded region for all start dates, indicating that the observed MAM trends for the region are consistent with the CMIP5 All-Forcing multimodel ensemble. Using the control run internal variability as a surrogate for natural variability (generally a good assumption for relatively long trend lengths; see Knutson et al. 2013), we conclude that the observed trend is both inconsistent with natural variability and consistent with anthropogenic plus natural forcing runs, meaning that the warming in the observations is very likely attributable in part to anthropogenic forcing.

Since the anomalous warmth of MAM 2012 occurred in a region with detectable long-term anthropogenic warming, we conclude that anthropogenic forcing also likely contributed significantly to the observed anomalies of MAM 2012 over the eastern United States. A rough estimate of the anthropogenic contribution based on Fig. 5.2a would be about 35% (based on the modeled value of $\sim 1.3^{\circ}\text{C}$ near 2012 and the 2012 observed anomaly of $\sim 3.7^{\circ}\text{C}$). Under the assumption that the real-world uncertainty is well represented by the multimodel ensemble mean plus aggregated control-run distribution (i.e., that there is no change in the variability about the mean) and interpreting the difference between the All-Forcing and control-run distributions as the anthropogenic influence, we can conclude the following regarding the 2012 MAM eastern U.S. anomaly. This 3.7°C event was 2.8 times stronger than the expected ensemble-mean contribution of 1.3°C due to anthropogenic forcing in 2012—so, internal variability almost certainly played a substantial role. Based on the model ensemble, an event this warm or warmer would occur with probability 0.07% (unforced) or 0.85% (forced)—a factor of 12 increase in risk. Under the forced scenario, the fraction of risk of such an extreme warm event that is attributable to the forcing is $(0.0085 - 0.0007) / 0.0085 = 92\%$. These estimates of change in risk are sensitive to the baseline period assumed. Here we use the period 1881–1920 as the baseline; if we use 1861–2012 as the baseline period, the risk of the event increases by about a factor of 5

rather than 12, and the fraction of attributable risk is estimated as 78%. As a further sensitivity test, we examined the occurrence of anomalies larger than an alternative threshold equivalent to the second warmest MAM anomaly in the observed series (2.04°C in 1991). Anomalies exceeding this level occur about 11 times more often in the forced simulations than in the unforced runs.

Discussion and conclusions. From the viewpoint of seasonal or annual mean extreme temperatures, 2012 was characterized by a much greater occurrence globally of warm extremes than cold extremes. Notable large-scale regions with extreme seasonal warmth included the United States east of the Rocky Mountains during MAM and much of the Mediterranean region during July–November. The extreme warmth over the eastern United States occurred in a region where there has also been longer-term warming that our model-based assessment attributes at least in part to anthropogenic forcing.

Although the long-term warming during MAM over the eastern U.S. region of record 2012 warmth in Fig. 5.1f was assessed as detectable, a number of caveats apply. For example, when we tested the warming trends since 1901 for individual grid points around the globe, a number of grid points in the eastern U.S. region did not have significant trends (Supplementary Fig. S5.1i). Previous studies have suggested a lack of statistically significant long-term warming over the eastern United States; in particular, Portmann et al. (2009) discussed possible physical explanations for this feature and showed that there is a statistical relationship between the trends in daily maximum temperatures across the United States and the climatological mean precipitation. However, our results illustrate the potential effects of spatial averaging for this type of detection/attribution analysis. After averaging over the entire region of anomalous record warmth in the eastern United States, we *do* find a detectable trend-to-2012 across a wide range of possible start dates. Differences between our results and previous studies may also be due to the averaging area or season chosen and the inclusion of the very warm 2012 anomalies. Our region definition tends to enhance the influence of the very warm anomalies occurring in MAM 2012.

Other caveats to our analysis include remaining uncertainties in estimates of internal variability of the climate system, in climate forcing agents, and in model sensitivity to the forcings. We have found that the models' low-frequency (>10 yr) internal

climate variability in this region is larger than our current best estimate of the real climate system's low frequency internal variability (e.g., Fig. 2 of Knutson et al. 2013). If internal climate variability were in fact overestimated by the models, this would make it overly difficult for a climate signal to be detected above internal variability noise in our analysis, so the detection result would be robust to such a bias. Such a bias would also widen the envelope of the forced simulations, possibly obscuring an underestimate of the warming by the forced models.

The anthropogenic contribution to the extreme seasonal (MAM) warmth over the eastern United States can be estimated as about 35%, or in terms of risk, anthropogenic forcing leads to a factor of 12

increase in the risk of such an event according to our calculations. An important issue for future studies is to explore potential changes in the shape of the temperature distributions under climate change and its effect on the risk estimates for extreme events in the tails of the distribution.

The much larger fraction of global analyzed area with extreme warm seasonal-mean anomalies in Fig. 5.1 (right column), compared to the fraction of area with extreme cold seasonal-mean anomalies, suggests another future approach to multistep attribution. For example, we plan to further explore the rates of occurrence of seasonal warm and cold extremes in the observations and compare the observed changes with those simulated in the All-Forcing runs.