3. LIKELIHOOD OF JULY 2012 U.S. TEMPERATURES IN PREINDUSTRIAL AND CURRENT FORCING REGIMES

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"The Event": July 2012 heat in the United States. The year 2012 was the warmest on record in the United States (NOAA 2013b), due in part to extremely high temperatures over much of the central and eastern United States during spring and summer. The summer heat was associated with one of the most severe droughts on record (Hoerling et al. 2013, manuscript submitted to *Bull. Amer. Meteor. Soc.*; Hoerling et al. 2013b). A suite of impacts has been ascribed to the drought and associated summer heat, including low (or even zero) crop yields (USDA 2013a), low livestock inventory (USDA 2013b), sharp increases in commodity prices (USDA 2013c), and at least 123 direct human deaths (with the number of additional deaths from heat stress not yet quantified) (NOAA 2013c). While much of the United States experienced severe heat during various periods of the summer, the month of July was the warmest on record for the contiguous United States, while June was the eighth warmest and August the thirteenth (NOAA 2013b).

The likely proximal causes of the summer 2012 severe heat were changes in the surface energy balance caused by severe rainfall deficits and the large-scale atmospheric conditions that contributed to those rainfall deficits (Hoerling et al. 2013, manuscript submitted to *Bull. Amer. Meteor. Soc.*; Hoerling et al. 2013b). Midlatitude severe heat events often co-occur with rainfall deficits (Madden and Williams 1978; Namias 1982; Hoerling et al. 2013a) and the associated atmospheric conditions and changes in surface energy balance that act to reinforce dry, hot conditions at the surface. These include positive geopotential height anomalies in the mid-troposphere (e.g., Chang and Wallace 1987; Meehl and Tebaldi 2004; Pal et al. 2004; Fischer et al. 2007a), which result in anticyclonic circulation anomalies and a relatively stable atmosphere, leading to decreased cloudiness and decreased precipitation along with decreased input of moisture and increased input of solar radiation at the surface. Such events are also often associated with negative soil moisture anomalies (e.g., Hong and Kalnay 2000; Schubert et al. 2004; Fischer et al. 2007b; Seneviratne et al. 2010; Hirschi et al. 2011; Quesada et al. 2012), which result in decreased surface evapotranspiration, leading to decreased latent cooling and increased surface air temperature. In addition, because surface moisture and temperature are influenced by precipitation and solar radiation, and because geopotential height is influenced by surface temperature, land-atmosphere coupling can amplify the severity of hot events (e.g., Fischer et al. 2007a,b). We, therefore, analyze the July 2012 circulation and soil moisture anomalies along with the surface temperature anomalies.

Quantifying the likelihood of a 2012-magnitude event. We use the Coupled Model Intercomparison Project Phase 5 (CMIP5) GCM experiments (Taylor et al. 2012) to quantify the likelihood of a 2012-magnitude event in the current and preindustrial forcing regimes. We define "a 2012-magnitude event" as the July 2012 anomaly from the 1979–2011 July mean. We use reanalysis to define the event, which allows us to quantify the frequency of anomalies in surface air temperature, 500-hPa geopotential height, and 0 cm–200 cm soil moisture within a framework that is physically consistent between the three variables and with the GCM calculation for the 1979–2011 ("20C") and preindustrial ("PI") forcing regimes. [The July 2012 temperature event is similar in National Centers for Environmental Prediction (NCEP), ERA-Interim, and observations; Supplementary Fig. S3.3 and S3.4.] In order to normalize across CMIP5 realizations of different lengths (Supplementary Table S3.1), we divide the CMIP5 20C and PI time series into 33-year

subperiods, yielding an ensemble of 24 20C periods and 134 PI periods. This subperiod length is chosen arbitrarily to be the length of the period from 1979 (the start of the satellite era, when we have higher confidence in the reanalysis) through 2011 (the year prior to the 2012 event). Before subdividing the CMIP5 time series, we bias-correct the mean and variability of the CMIP5 time series using the reanalysis values. (See Supplementary material for further details.)

How rare was July 2012 in the current forcing regime? The July 2012 temperature anomalies exceeded 1.6°C over much of the northern United States, with peak anomalies exceeding 4.0°C over the central United States (Fig. 3.1a). The temperature anomalies were outside the bounds of the 1979–2011 reanalysis over much of the northern Great Plains, Midwest, and Northeast (Fig. 3.1d and Supplementary Figs. S3.1, and S3.4) and outside the bounds of the last century

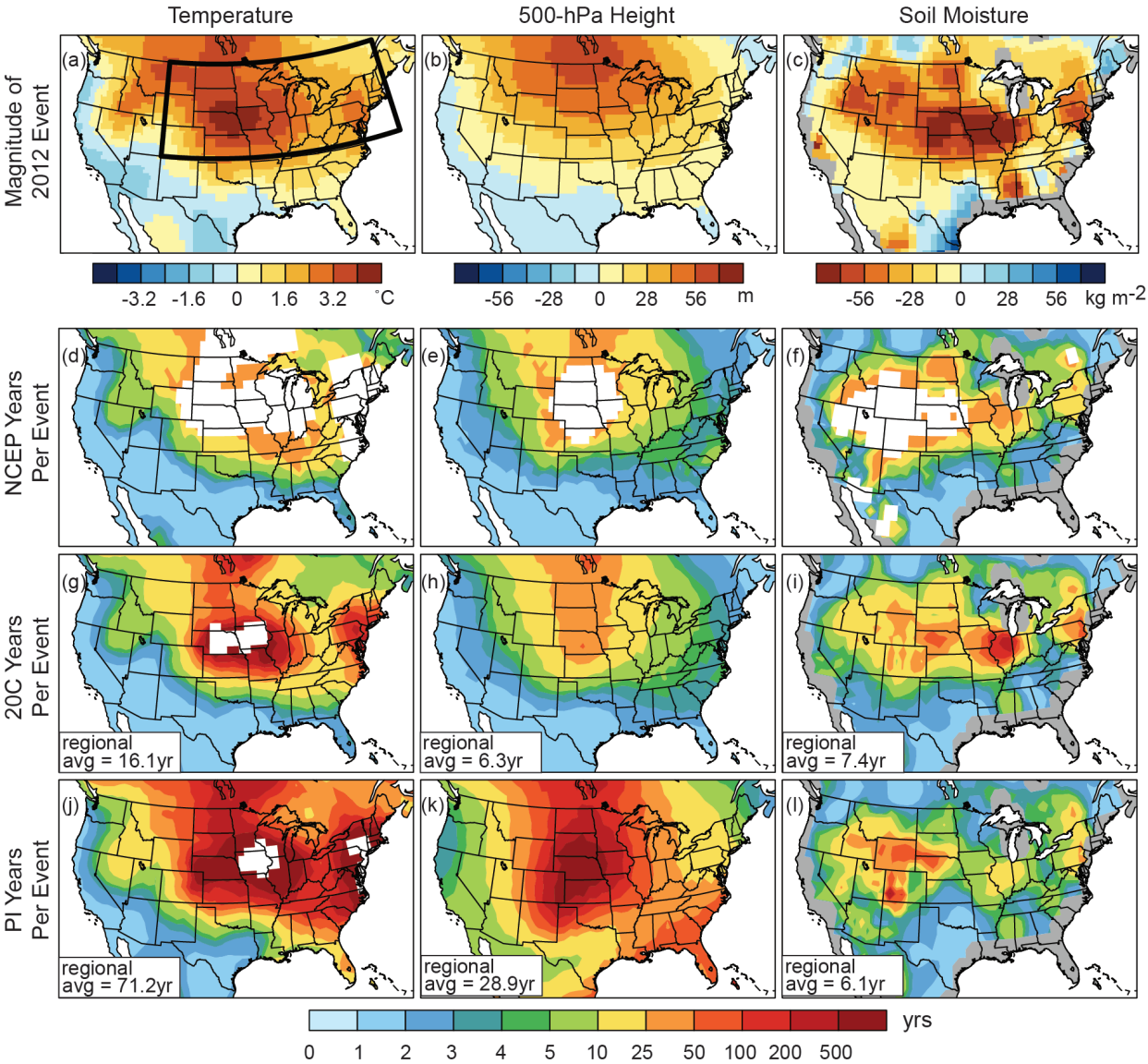

Fig. 3.1. The likelihood of a 2012-magnitude event. Top row shows the magnitude of the Jul 2012 event as an anomaly from the 1979–2011 mean. Other rows show the mean number of years required to achieve an event of the Jul 2012 magnitude in the 1979–2011 period of NCEP (second row), the 1979–2011 period (20C) of CMIP5 (third row), and the preindustrial period (PI) of CMIP5 (bottom row). White areas show where no event occurred in any 33-year period in any realization. Box in the upper left panel shows the region that is used in Fig. 3.2. The "regional avg" in (g)–(l) indicates the mean number of years required to achieve a 2012-magnitude event for the grid points within the regional box. White areas are ignored in the regional calculations in (g)–(l). See Online Supplemental material for details of the ensemble analysis.

of observations over much of the Midwest and Northeast (Supplementary Fig. S3.3). Likewise, the 500-hPa height anomalies were outside the bounds of the 1979–2011 reanalysis over much of the northern Great Plains (Fig. 3.1e and Supplementary Figs. S3.1, and S3.4) as were the soil moisture anomalies over areas of the Great Plains and Mountain West (Fig. 3.1f and Supplementary Figs. S3.1, and S3.4).

In contrast, the July 2012 temperature, 500-hPa geopotential height, and soil moisture anomalies were not outside the bounds of the 1979–2011 forcing regime over most of the United States (Figs. 3.1g, 3.1h, and 3.1i), suggesting that climate variability within the current forcing played an important role in the event. However, the temperature anomalies were a century-scale event over much of the north-central and northeastern United States (Figs. 3.1g, 3.1h, and 3.1i) and were far more rare (regional mean of 16.1 years per event) than either the geopotential height anomalies (6.3 years per event) or soil moisture anomalies (7.4 years per event). [The relative rarity of the July 2012 temperatures is also clearly revealed in the probability density functions (PDFs) of grid-point anomalies; Fig. 3.2.]

Is the likelihood of a 2012-magnitude event different in the current and preindustrial forcing regimes? Comparison of the CMIP5 20C and PI experiments reveals that a 2012-magnitude temperature event occurs more frequently in the current forcing than in the preindustrial forcing over almost all areas of the United States (Figs. 3.1g and 3.1j). The mean occurrence is more than four times as frequent in the 20C period over

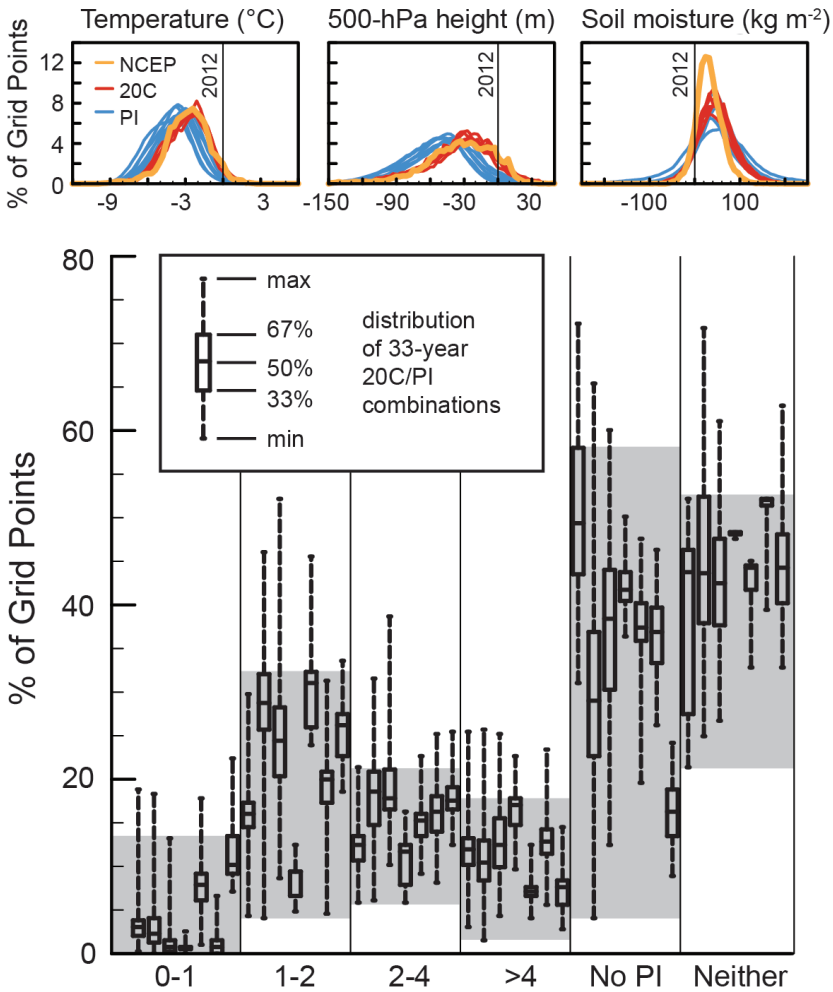

Fig. 3.2. (Top) Anomalies from the Jul 2012 mean in the 1979–2011 period of NCEP, the 1979–2011 period of CMIP5 (20C), and the preindustrial period of CMIP5 (PI), calculated over the north-central and northeastern United States (37°N–49°N, 251°E–290°E). (Bottom) The difference in the frequency of occurrence of a Jul 2012 temperature event over the north-central and northeastern United States between the PI and 20C forcings. The difference is calculated by comparing the occurrence at each grid point in all possible combinations of 33-year 20C and PI periods from each CMIP5 model, enabling probabilistic quantification of the likelihood that a 33-year period in the 20C forcing yields a different frequency of occurrence than a 33-year period in the PI forcing. The percentage of grid points are binned by magnitude of difference, calculated as the number of occurrences in the 20C period divided by the number of occurrences in the PI period for which there was at least one occurrence in the PI period. The "No PI" bin includes grid points where there was at least one event in the 1979–2011 period but no event in the preindustrial period. The "Neither" bin includes grid points where there was no event in either the 1979–2011 or PI period. Each box-and-whisker shows the distribution of grid point values in a given CMIP5 model in a given magnitude bin. The gray field in each bin encompasses the lowest 67% of values in 100% of the CMIP5 models. For example, between 4% and 33% of grid points exhibit a 2012-magnitude temperature event one to two times as frequently in the 20C forcing in at least 67% of the 33-year period combinations of 100% of the CMIP5 models.

the north-central and northeastern United States (Figs. 3.1g and 3.1j), with large areas requiring a mean of greater than ten 33-year PI periods to achieve a 2012-magnitude temperature event but a mean of less than five 33-year 20C periods (Supplementary Fig. S3.2). The mean occurrence of the 2012-magnitude geopotential height is also more than four times as frequent in the current forcing than the preindustrial forcing (Figs. 3.1h and 3.1k), with large areas of the central United States requiring a mean of greater than ten PI periods but less than two 20C periods (Supplementary Fig. S3.2). In contrast, most areas of the north-central and northeastern United States exhibit greater frequency of a 2012-magnitude soil moisture event in the preindustrial forcing (Fig. 3.1i) than in the current forcing (Fig. 3.1l). However, the soil moisture anomalies should be viewed with caution, as different reanalysis datasets exhibit different patterns and magnitudes of anomalies across the United States (Fig. 3.1, and Supplementary Fig. S3.4), and there is greater discrepancy between the reanalysis and 20C simulations for soil moisture than for temperature or geopotential height (Fig. 3.2, and Supplementary Fig. S3.4). (We note that a 2012-magnitude soil moisture event occurs more often in the 20C simulations than in the PI simulations over much of the western United States in both reanalysis datasets that we evaluate; Fig. 3.1, and Supplementary Fig. S3.4.)

Like the regional mean (Figs. 3.1g and 3.2), the PDF of grid-point anomalies reveals a shift towards more frequent occurrence of 2012-magnitude temperatures over the north-central and northeastern United States in the 20C simulations (Fig. 3.2). To quantify the difference in likelihood of a 2012-magnitude temperature event over this region, we compare the fractional difference in occurrence between all possible combinations of 33-year periods in the CMIP5 PI and 20C simulations (Fig. 3.2). Following the Intergovernmental Panel on Climate Change (IPCC) uncertainty guidance (Mastrandrea et al. 2011), we frame this analysis around a likelihood threshold of 67%. This probabilistic analysis reveals >67% likelihood that a 2012-magnitude temperature event is more frequent in the PI forcing over less than 14% of the grid points. In addition, there is >67% likelihood that a 2012-magnitude temperature event is one to two times as frequent in the 20C forcing over 4%–33% of the grid points, two to four times as frequent in the 20C forcing over 6%–21% of the grid points, and more than four times as frequent in the 20C forcing over 2%–18% of the grid points. Further, there is >67% likelihood that 4%–58% of the grid points would experience a 2012-magnitude temperature event in a 33-year period of the current forcing but not in a 33-year period of the preindustrial forcing. However, there is also >67% likelihood that 21%–52% of the grid points would not experience a 2012-magnitude event in a given 33-year period of the current forcing.

Conclusions. Our analyses of the CMIP5 global climate model ensemble suggest that the likelihood of extreme July temperature anomalies is greater in the current forcing than in the preindustrial forcing. In particular, the mean occurrence of 2012-magnitude temperatures is more than four times as frequent over the north-central and northeastern United States in the current forcing. The mean occurrence of 2012-magnitude geopotential height anomalies is also more than four times as frequent, suggesting increased likelihood of the atmospheric conditions that often occur in conjunction with severe heat at the surface. Further, although there are important uncertainties in the soil moisture conditions, the July 2012 soil moisture anomalies were substantial within the context of the past three decades, and the May–July precipitation was "much below normal" over much of the central United States (NOAA 2013b), suggesting that surface drying could have amplified the temperature event (as in Fischer et al. 2007b; Quesada et al. 2012). The role of changes in ocean conditions (e.g., Supplementary Fig. S3.5) requires further investigation.

The CMIP5 simulations also suggest that the July 2012 temperatures remain a century-scale event over large areas even in the current forcing regime. Indeed, it is very likely (Mastrandrea et al. 2011) that more than a fifth of the north-central and northeastern United States would not experience a 2012-magnitude event in a given 33-year period of the current forcing. The continued rarity of the July 2012 temperatures in the current forcing regime likely arises from the fact that record rainfall deficits played a critical role in shaping the 2012 severe heat. Given the considerably lower signal-to-noise ratio of the summer precipitation response to global warming over the central and eastern United States (relative to the summer temperature response; e.g., Diffenbaugh et al. 2011), occurrence of the most severe heat events is likely to continue to be strongly regulated by rainfall variability.