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4. U.S. HEAT WAVES OF SPRING AND SUMMER 2012 FROM THE FLOW-ANALOGUE PERSPECTIVE

JULIEN CATTIAUX AND PASCAL YIOU

Introduction. The contiguous United States experienced extremely high temperature anomalies during the year 2012, especially during spring and summer east of the Rocky Mountains (Fig. 4.1, top). This exceptional heat wave, causing important socio-environmental damages due to the heat stress, was associated with a severe drought, additionally accounting for the spreading of wildfires over broad regions. We aim to put such an episode in the context of

longer-term climate variability and change. However, this piece should be viewed as a “process-attribution” analysis rather than a formal attribution study (e.g., an evaluation of the anthropogenic fingerprint). Our focus is on the contribution of atmospheric circulation to the U.S. heat wave of spring-summer 2012, which we evaluate through a flow-analogue approach similar to the analysis of 2011 European temperatures by Cattiaux and Yiou (2012; hereafter CY12).

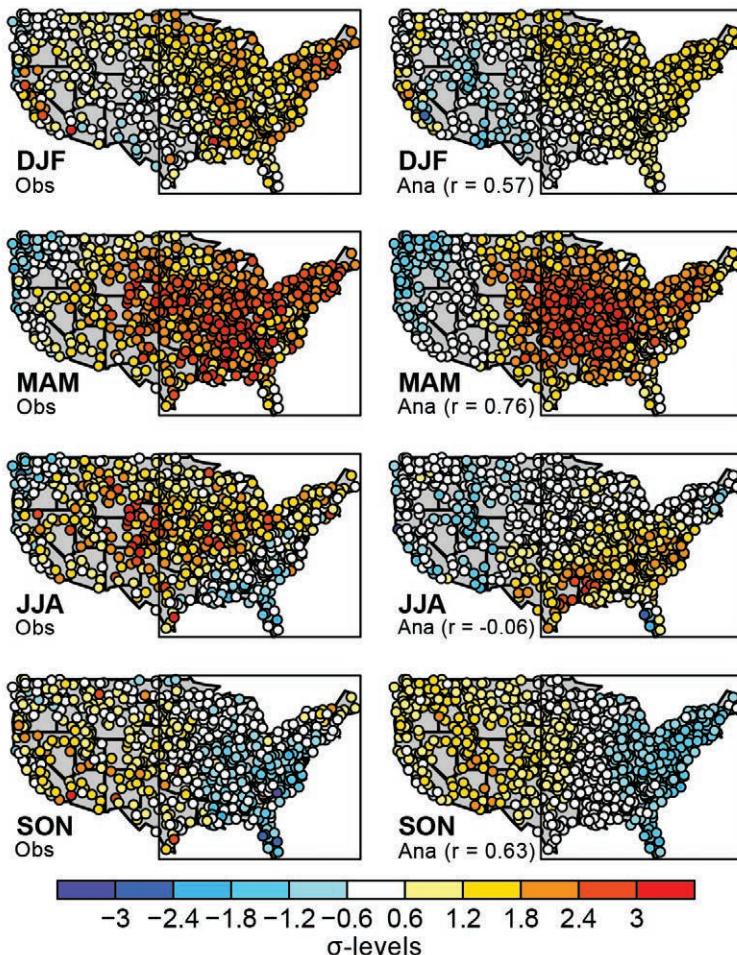


FIG. 4.1. (Left column) Observed temperatures of winter (DJF months), spring (MAM), summer (JJA), and autumn (SON) 2012, represented as normalized anomalies (σ -levels) relative to 1971–2000 climatological standards at each station. The box over the eastern United States encompasses the area retained for regionally averaged statistics throughout the paper (171 stations over 306). (Right column) The same for analog temperatures. Correlations with observed patterns are indicated in parentheses.

Data and methods. As the flow-analogue approach requires daily data, we use daily temperature observations from the Global Historical Climatology Network (GHCN Version 3.01; <http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/>) over more than 1218 U.S. stations, together with daily reanalyses of sea level pressure (SLP) provided by NCEP/NCAR (<http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>) over the period 1948–2012. Although GHCN daily data are not adjusted to account for inhomogeneities (Caussinus and Mestre 2004), we only consider values having passed all quality checks so that their monthly averages closely fit monthly temperatures homogenized over the United States by Menne et al. (2009; USHCN Version 2.5; <http://www.ncdc.noaa.gov/oa/climate/research/ushcn>), albeit slightly underestimating the recent warming (not shown). Unless otherwise specified, the following monthly or seasonal temperature statistics are, therefore, not altered by the need of using daily data for analogues. We retain 801 USHCN stations on the basis of (i) an altitude lower than 2000 m, (ii) the availability of more than 90% of daily values over the period 1948–2012, and (iii) only one station per $0.5^\circ \times 0.5^\circ$ box for spatial homogeneity (the one with the more data for 2012). These criteria are similar to those of CY12 for European stations and do not materially impact

our results. Finally, we compute anomalies relative to 1971–2000 climatological standards [mean and standard deviation (σ)]. Albeit similar results were obtained from daily minimum temperatures (not shown), we focus our analysis on daily maximum temperature, generally occurring in daytime.

How exceptional was 2012 in the United States? Over the United States, the year 2012 was characterized by anomalously high maximum temperatures persisting from the beginning of winter (including December 2011) to the end of summer over the major part of the country, followed by a slightly colder than normal autumn (Fig. 4.1, left). The amplitude of these anomalies was stronger over the eastern part of the country (box in Fig. 4.1), where, on average over all stations, all monthly temperatures were above normal with the exception of October 2012. Hence, 2012 constitutes the hottest calendar year on record over our period of study (1948–2012), while October 2011–September 2012 establishes the absolute warm

record for a 12-month period. In particular, two monthly records were broken in March and July 2012, with exceptional widespread departures of 3.7σ and 2.5σ , respectively. These were associated with two extreme heat waves in late March and early July, both marked by ten consecutive days with anomalies exceeding 2σ and breaking daily records (Fig. 4.2a). Particularly high temperatures were also observed in January and May 2012 over the eastern United States, with these two months ranking as fifth and third warmest January and May over the period of study with monthly departures of 1.5σ and 1.6σ , respectively. Overall, the spring 2012 departure (3σ) broke the previous spring record (Fig. 4.2b), while the summer 2012 departure (1.5σ) ranked eighth warmest summer since 1948, but the second warmest of the last two decades behind 2011 (Fig. 4.2c). These rankings are even higher when using USHCN adjusted monthly data, with summer 2012 getting up to the fourth position (not shown). Overall, with 49 days out of 184 presenting an anomaly of maximum

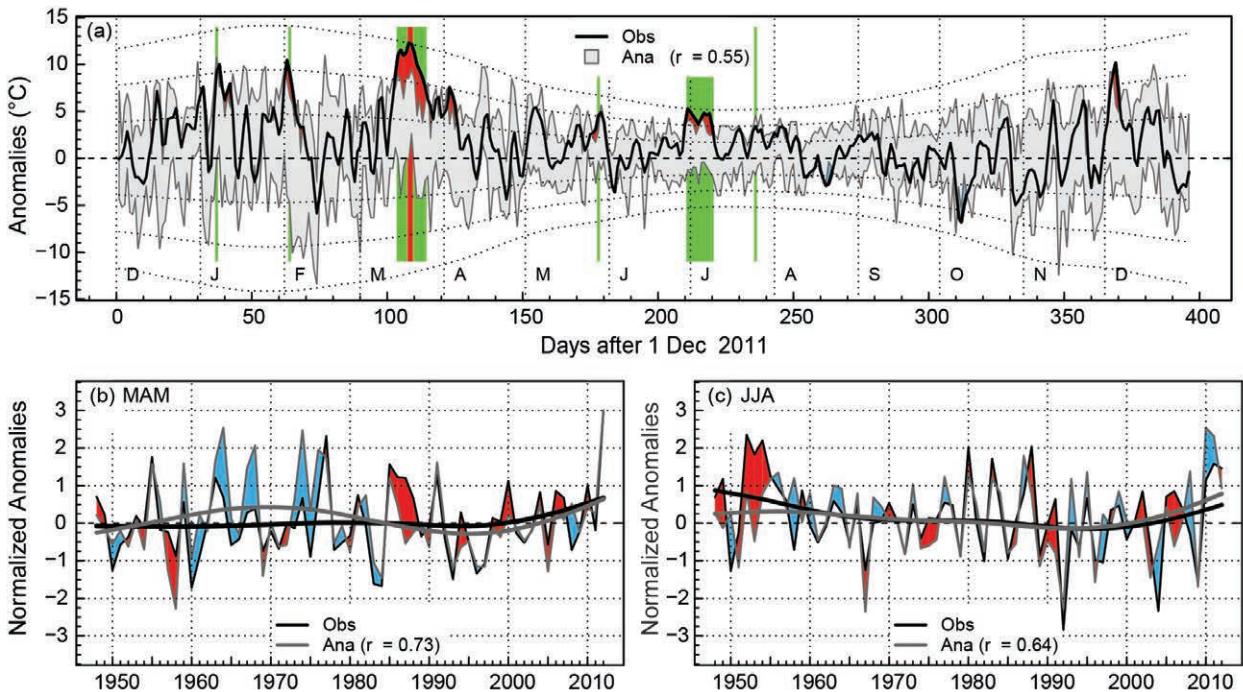


FIG. 4.2. (a) Daily anomalies ($^{\circ}\text{C}$) of observed (black line) and analog (gray spread encompassing the 10 values) eastern U.S. temperatures from Dec 2011 to Dec 2012, exhibiting exceptional heat waves in Mar and Jul. Dashed lines indicate climatological σ -levels (higher variability in winter than summer), and red (blue) indicates days with observed temperatures above (below) the 10 analog values. On average over the eastern United States, 25 daily records were broken in 2012 (green background shading), with two days (18–19 Mar) breaking a record for the 31-day window in which analogues are sampled (red background shading). (b) Spring (MAM) observed (black) and analog (gray) temperatures averaged over the eastern United States, represented as normalized anomalies (σ -levels) relative to the period 1971–2000, with 2012 breaking both observed and analog records. Smoothing by splines with four degrees of freedom is added, and red (blue) indicates years with observed temperatures above (below) analog ones. (c) Same as (b) for summer (JJA), with 2012 ranking as the eighth (fifteenth) warmest summer in observations (analogues).

temperature above the climatological level of 1.5σ , the persisting heat wave of spring-summer 2012 is unprecedented over the eastern United States in our observational record.

The flow-analogue methodology. The contribution of the large-scale atmospheric circulation to temperature anomalies of 1948–2012 is estimated from the same flow-analogue approach as used in CY12 (derived from Lorenz 1969). For each day, we select the 10 days with the closest atmospheric circulation among days of other years but within a moving window of 31 calendar days. This provides a range of 10 daily “analog” temperatures, which we compare to the actual observed temperature of the given day. Circulations are derived from SLP anomalies relative to a 1971–2000 climatology and are considered over a large area encompassing the U.S. domain (130°W – 60°W , 20°N – 50°N). While this method has been applied to both European temperatures and precipitation by many recent studies (Cattiaux et al. 2010; Vautard and Yiou 2009; Yiou et al. 2007), including in this collection (“Contribution of Atmospheric Circulation to Wet North European Summer Precipitation of 2012,” this issue), it has not been applied to U.S. surface variables. A prior step, therefore, consisted in (i) verifying whether atmospheric circulations explain a sizable fraction of the intra-seasonal to interannual variability of U.S. temperatures, and (ii) checking the quality of flow-analogues over the United States. We first verified that the discriminatory power of flow-analogues on U.S. daily and seasonal temperatures is similar to that found over Europe and larger in winter than in summer, which is consistent with correlation values found in the following paragraphs. On average, observed and analog SLP patterns are better correlated for the United States than for Europe ($r = 0.77$ instead of 0.68 in CY12’s Table 1), and the quality of 2012 analogues is close to the 1948–2011 mean. These elements support the relevance of applying the flow-analogue method to the United States. In addition, we verified that our results are insensitive to both the number of selected analogues (here we use ten, but we tested five and twenty) and the metrics used for assessing analogy (here we use the root mean square difference, and we tested the rank correlation and the Mahalanobis distance).

Large-scale circulations explain the hot record of spring 2012....For all seasons of 2012 except summer, mean analog temperatures (i.e., averaged over the 10 analog days for each day and then seasonally) reproduce both

the amplitudes and the geographical distributions of observed anomalies reasonably well (Fig. 4.1, right). In particular, flow-analogues fairly capture the extremely warm spring of 2012, with a rather high spatial correlation compared to springs of other years ($r = 0.76$ over U.S. stations, while the 1948–2012 median is $r = 0.49$). On average over the eastern United States, observed and analog spring temperature anomalies appear highly correlated at an interannual timescale ($r = 0.73$), and we find that atmospheric circulations fully explain the amplitude (3σ) of the 2012 record in maximum temperature (Fig. 4.2b). Interestingly, this is not the case for minimum temperatures, the observed anomaly of 3.3σ being larger than the analog one (2.3σ , not shown). Additionally, for daily timescales, extremely hot days of late March 2012 lie outside the analog range (Fig. 4.2a), suggesting that local processes, such as drought-related decreased evaporative cooling, may have amplified this particular heat wave in addition to the effects of the atmospheric dynamics. However, here we reach the limits of the flow-analogue methodology, since two days in March 2012 (18th and 19th) were hotter than all days of the 31-day window in which analogues are sampled (see red shading in Fig. 4.2a).

...but not the spatial pattern of the following warm summer. Conversely to spring, flow-analogues fail to capture the spatial pattern of the observed temperature anomaly of the summer 2012 ($r = -0.06$ over U.S. stations), even showing an opposite meridional gradient east of the Rockies (Fig. 4.1). However, summer anomalies of other years are generally better reproduced (the 1948–2012 median being $r = 0.37$), suggesting a particularly strong influence of regional processes during summer 2012, possibly linking with dry soils caused by the preceding spring heat wave (Mueller and Seneviratne 2012). Despite this geographical discrepancy, on average over the eastern United States, atmospheric circulations explain a large fraction of both the interannual variability of summer temperatures ($r = 0.64$) and the summer 2012 anomaly (1σ out of 1.5σ ; Fig. 4.2c). As for the March heat wave, extremely hot days of early July are found to be significantly warmer than their analogues (Fig. 4.2a). Overall, during both the spring and summer seasons, 22% of days were warmer than the maximum of the 10 analogues and 71% were warmer than the median, while expected statistical values would be respectively $1/11 = 9\%$ [0%–25%] and $1/2 = 50\%$ [30%–70%]. Brackets for 95% confidence intervals were derived from binomial quantiles assuming 20

independent days among the 184, i.e., a de-correlation time of about 10 days, which might, however, be a strong hypothesis in the case of persisting hot events involving long-memory processes such as soil moisture deficit.

Conclusions. In conclusion, the record hot spring of 2012 over the eastern United States can be mainly explained by atmospheric dynamics. Conversely, while large-scale circulations were favorable to anomalously high temperatures over this region in summer, other local factors, possibly linked to the exceptionally hot spring and the persisting drought throughout summer, shaped the spatial pattern of the following summer heat wave. In a long-term climate perspective, Fig. 4.2b reveals a positive trend over the last 20 years (1993–2012) in spring maximum temperatures

over the eastern United States, which is found to be statistically significant at the 5% level and consistent with the flow-analogue temperature reconstruction. By contrast, no significant trend is found in summer for maximum temperatures (Fig. 4.2c), albeit additional observations show a significant increase of 0.5σ per decade over the past 40 years (1973–2012) for minimum temperatures, partially explained by flow-analogues (not shown). This trend analysis, nevertheless, reaches the limits of daily unadjusted GHCN temperatures, since homogenized USHCN monthly temperatures exhibit a one-to-two times larger warming over recent years (but still not significant for summer maximum temperatures). The contribution of potential changes in circulation to the recent long-term warming in the United States, therefore, requires further research.

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

THOMAS R. KNUTSON, FANRONG ZENG, AND ANDREW T. WITTENBERG

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