AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2015JD023598

Special Section:
Fast Physics in Climate Models: Parameterization, Evaluation and Observation

Key Points:
- Recent spatiotemporal patterns of CONUS temperature extremes
- Warm extremes: strongest increase in the NE and Midwest
- Spring experiencing the strongest and most widespread increases in warm extremes

Supporting Information:
- Figure S1
- Figure S2
- Figure S3
- Figure S4

Correspondence to:
T. P. Albright,
talbright@unr.edu

Citation:
Mutiibwa, D., S. J. Vavrus, S. A. McAfee, and T. P. Albright (2015), Recent spatiotemporal patterns in temperature extremes across conterminous United States, *J. Geophys. Res. Atmos.*, *120*, 7378–7392, doi:10.1002/2015JD023598.

Received 28 APR 2015
Accepted 17 JUN 2015
Accepted article online 21 JUN 2015
Published online 6 AUG 2015

Recent spatiotemporal patterns in temperature extremes across conterminous United States

Denis Mutiibwa[1], Steven J. Vavrus[2], Stephanie A. McAfee[1], and Thomas P. Albright[1]

[1]Department of Geography, University of Nevada, Reno, Reno, Nevada, USA, [2]Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA

Abstract With a warming climate, understanding the physical dynamics of hot and cold extreme events has taken on increased importance for public health, infrastructure, ecosystems, food security, and other domains. Here we use a high-resolution spatial and temporal seamless gridded land surface forcing data set to provide an assessment of recent spatiotemporal patterns in temperature extremes over the conterminous United States (CONUS). We asked the following: (1) How are temperature extremes changing across the different regions of CONUS? (2) How do changes in extremes vary on seasonal, annual, and decadal scales? (3) How do changes in extremes relate to changes in mean conditions? And (4) do extremes relate to major modes of ocean-atmosphere variability? We derive a subset of the CLIMDEX extreme indices from the North American Land Data Assimilation phase 2 forcing data set. While there were warming trends in all indices, daytime temperature extremes warmed more than nighttime. Spring warming was the strongest and most extensive across CONUS, and summer experienced the strongest and most extensive decrease in cold extremes. Increase in winter warm extremes appeared weakening relative to the rapid 1950–1990 increase found in previous studies. The Northeast and Midwest experienced the most warming, while the Northwest and North Great Plains saw the least. We found changes in average temperatures were more associated with changes in cold extremes than warm extremes. Since 2006 there have been 5 years when more than 5% of the U.S. experienced at least 90 warm days, something not observed in the previous 25 years. The unusually warm first decade of 21st century could have been associated with the warm conditions of near El Niño–Southern Oscillation-neutral phase of the decade, and possibly amplified by anthropogenic forcing. The widespread, lengthy, and severe extreme hot events documented here during the past three decades underscore the need to implement thoughtful adaptation plans in the very near future, to the growing evidence of increasing warm extremes across United States.

1. Introduction

Extreme weather events have severe impacts on societies, economies, and ecosystems and are often the focus of risk management [*Benestad et al.*, 2008]. Over recent decades extreme climate events such as heat waves and droughts have become more frequent, intense, and widespread across the United States and the entire globe [*Intergovernmental Panel on Climate Change (IPCC)*, 2012; *Donat et al.*, 2015]. Because of these events' disproportionate impact on society and ecosystems, understanding climate extremes has become more urgent than tracking changes in mean climate due to climate change [*Zhang et al.*, 2005; *IPCC AR5: Climate Change*, 2013].

Among extreme weather events, temperature extremes have acute implications on hydrology, infrastructure, public health, and ecosystems. Recent studies have indicated that warm extremes are becoming more frequent and persistent in many parts of the conterminous U.S. (CONUS). The national average summer temperature in2011 was the second warmest on record, nearly identical to the summer of 1936 [*Crouch et al.*, 2012]. The extreme warmth of summer 2012 was considered extraordinary in terms of intensity and extent across CONUS. In June 2012, more than 3200 daily record highs were set or tied across the country [*NOAA*, 2012]. These extreme warm events cause the highest number of fatalities among weather related events across CONUS [*Herring et al.*, 2014; *Borden and Cutter*, 2008; *IPCC AR5: Climate Change*, 2013]. Due to heat stress and increased evaporative demand, persistent warm extremes also have devastating implications on agricultural, water resources, and ecosystems. In 2012 the U.S. Department of Agriculture declared about 63% of CONUS (1692 counties) disaster areas due to extremely warm and dry conditions that caused massive crop failures and severe water shortages. Warm extremes have also been linked to increased wildlife mortality [*Jiguet et al.,* 2006; *McKechnie and Wolf*, 2009; *Albright et al.,* 2011]. Thus, understanding temporal and spatial trends, and future changes in both hot and cold temperature extremes has important implications for climate adaptation and regional resilience.

A number of studies have assessed extremes in different regions of the United States [e.g., *Abatzoglou et al.*, 2014; *Bumbaco et al.*, 2013; *Herring et al.*, 2014; *Brown et al.*, 2010; *Wolfe et al.*, 2008; *Field et al.*, 2007; *Cayan et al.*, 1999]. These studies have provided an important context for understanding societal [*Kunkel et al.*, 2013] and ecosystem [*Albright et al.*, 2011] impacts; however, they used disparate data sets and metrics to define extreme events. Consequently, the resulting spatial patterns and trends can conflict and become difficult to synthesize into a single continental-scale database. For example, in the recent National Climate Assessment [*Melillo et al.*, 2014], temperature extremes in the Southeast and Midwest were presented as days above 95°F and days below 32°F; in the Northeast temperature extremes were presented as days above 90°F; the Great Plains temperature extremes were defined as the hottest 2% days; and for the Southwest and Northwest no spatial distribution of extremes was presented. A few studies have characterized temperature extremes across the U.S. using point station data [*Peterson et al.*, 2013a, 2013b; *Meehl et al.*, 2009; *Gleason et al.*, 2008; *Higgins et al.*, 2002]. Weather stations across CONUS are on average spaced 20–60 km [*Linacre*, 2003], with wider gaps in the southwest, depriving these studies homogeneity and continuous spatial representation of extremes on regional and local scales. Global-scale studies have described U.S. extremes; however, these employ coarse spatial scales offering insufficient detail at regional and local scales. Projected changes in extremes are particularly affected by coarse scales because extreme events are often smaller in extent than the effective spatial resolution of global climate models [*Klein Tank et al.*, 2009]. These spatial scaling issues thus limit the application of projected changes in extremes on regional and local scale, particularly in sectors such as food security, health, and water resources, which typically require high-resolution climate inputs to feed into their impact models [*Klein Tank et al.*, 2009].

This study presents a detailed assessment of the spatial and temporal variability of temperature extremes across all regions of CONUS using a single seamless high spatial and temporal resolution gridded data set, with a consistent time period, method, and definition of extreme weather events. Both warm and cold extremes were investigated over the 1979–2012 period, which are important years in the recent warming cycle of CONUS climate, because 80% of warming in CONUS temperatures since 1895 has occurred during this period [*Menne and Williams*, 2009]. We used a recently available gridded hybrid data set, and a set of extreme climate indices developed to homogenize monitoring and estimation of extreme weather events from daily climate records [*Zhang et al.*, 2011]. We define daily warm and cold extremes as temperatures above or below the local 90th or 10th percentile threshold, respectively, of the climatological distribution for a calendar day. We explored extraordinary years of extremes to illustrate the heterogeneity in spatial patterns and intensity of extremes across CONUS within the scale of 1 year. We further address the following suite of questions: (1) How are temperature extremes changing across the different regions of CONUS? (2) How do changes in extremes vary on seasonal, annual, and decadal scales? (3) How do changes in extremes relate to changes in mean conditions? And 4) do extremes relate to major modes of ocean-atmosphere variability?

2. Methods

2.1. North American Land Data Assimilation System 2 Forcing Data Set

The data set used in this analysis is the multi-institution North American Land Data Assimilation System 2 (NLDAS-2) data derived from the analysis fields of the National Centers for Environmental Prediction North American Regional Reanalysis (NARR). The NARR fields are used to generate NLDAS-2 forcing fields that are spatially interpolated from 32 km to one-eighth degree resolution and temporally disaggregated from 3-hourly to hourly resolution [*Cosgrove et al.*, 2003]. At this spatial and temporal resolution, NLDAS-2 has an appealing advantage for simulation of land surface processes. The data are available from 1979 on the NASA's Goddard Earth Science Data and Information Services Center website; http://disc.sci.gsfc.nasa.gov/.

2.2. Expert Team on Climate Change Detection and Indices CLIMDEX Indices

This study used the CLIMDEX relative thresholds [*Karl et al.*, 1999; *Peterson et al.*, 2001] that were developed by the joint World Meteorological Organization Commission on Climatology (CCl) and the Climate Variability and

Prediction Expert Team on Climate Change Detection and Indices. Warm and cold extremes were investigated using four indices that are based on percentile temperature thresholds: maximum temperature ($T_{\max}$) 90th percentiles (TX90) for the warm days, $T_{\max}$ 10th percentiles (TX10) for the cold days, minimum temperature ($T_{\min}$) 90th percentiles (TN90) for the warm nights, and $T_{\min}$ 10th percentiles (TN10) for the cold nights. The study presents spatial and temporal patterns of exceedance rates of the four indices on seasonal, annual, and decadal scales. These relative indices allow spatial comparisons over large areas because they sample the local probability distribution of temperature at each location [*Klein Tank and Können*, 2003]. Also, these indices are considered statistically robust and have high signal-to-noise ratio [*Zhang et al.,* 2011], a key factor in detecting changes in climate.

We chose 1981–2010 as the 30 year climatological (base) period compatible with NLDAS data that are available only since 1979, and a 5 day moving window centered on the calendar day of interest was applied on the entire base period to account for mean annual cycle [*Frich et al.,* 2002]. This ensured that extreme temperature exceedance of percentile thresholds occur with equal probability throughout the year [*Klein Tank and Können*, 2003]. The bootstrapping method described by *Zhang et al.* [2005] was applied on the base period to remove inhomogeneities in the time series, which hamper trend analysis [*Zhang et al.,* 2011].

2.2.1. Percentile Threshold Estimation

The *p*th percentile (Q*p*) at a grid for a specific date was computed by linear interpolation of two values closest to the percentile in the sorted 30 days of that specific date in the 30 year block. That is,

$$Q_p = (1-f)y_{(j)} + fy_{(j+1)}$$

where p is the 10th or 90th percentile,

$$j = \lfloor p(n+1) \rfloor, \text{which is the largest integer not greater than } p(n+1).$$
$$f = p(n+1) - j$$

where $y_{(j)}$ is the jth largest value in the sample for $1 \le j < n$, Q*p* is set to the smallest or largest value in the sample when $j < 1$ or $j > n$, respectively. The Q*p* values corresponding to $p < 1/(n+1)$ were set to the smallest value in the sample, and those corresponding to $p > 1/(n+1)$ were set to the largest value in the sample.

2.2.2. Exceedance Rates

At each grid cell, exceedance rates were computed by counting days with $T_{\max}$ and $T_{\min}$ above TX90 and TN90, respectively, and days with $T_{\max}$ and $T_{\min}$ below TX10 and TN10, respectively, for each season and year [*Jones et al.,* 1999; *Frich et al.,* 2002; *Zhang et al.,* 2005]. *Zhang and Yang* [2004] developed and maintains an interface to compute all 27 CLIMDEX indices in R programming environment referred to as RClimdex. This program computes indices and exceedance rates from station/point/single pixel climate data. Our spatial CLIMDEX indices and exceedance rates were computed in the Interactive Data Language (IDL) programming environment. To validate the procedure, NLDAS data from eight pixels were extracted and used to compute the exceedance rates in RClimDex for the 33 study years. The results were comparable to IDL computed CLIMDEX exceedance rates, with coefficient of determination of 0.99, root-mean-square difference of 0.93 days, and mean bias of 0.78 days. The marginal differences may originate from different bootstrapping and percentile calculation methods used in RClimDex. Hereafter, the exceedance rates of TX90, TX10, TN90, and TN10 are referred to as warm days, cold days, warm nights, and cold nights, respectively.

In addition to evaluating pixel level trends, we evaluated regional changes in extremes by dividing CONUS into the National Climate Assessment regions (http://www.globalchange.gov/ncadac). We further divided the Great Plains region into North and South to better track observed changes in extremes. These climate regions Northeast (NE), Southeast (SE), Midwest (MW), North Great Plains (NGP), South Great Plains (SGP), Northwest (NW), and Southwest (SW) are shown in Figure 1. To determine exceedence rates and trends of each climate region, we first averaged the daily $T_{\max}$ and $T_{\min}$ of all grids in the region, and then applied the CLIMDEX and trend methods described above.

2.3. Kendall Tau Trend Method

The Kendall tau, a nonparametric method [*Kendall*, 1948], was used to determine trends in seasonal and annual extreme days, and seasonal and annual $T_{\max}$ and $T_{\min}$. The benefits of nonparametric methods are

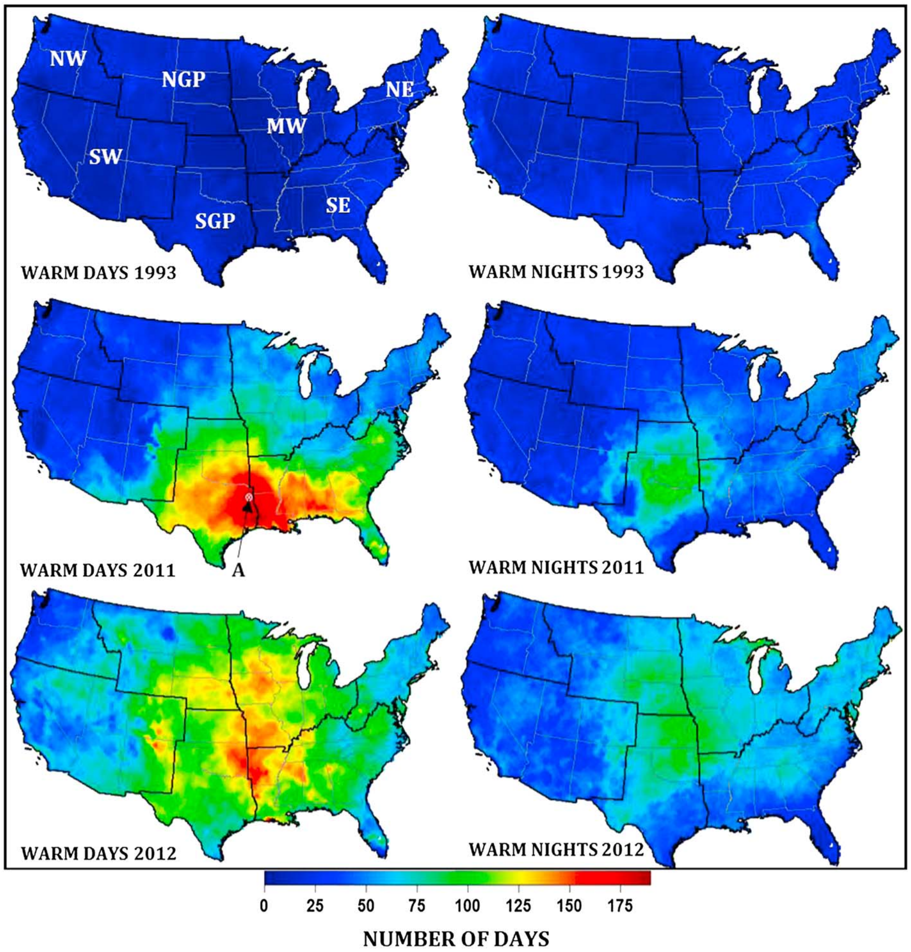

Figure 1. The exceedance rate (number of days) of warm days and warm nights across CONUS in 1993, 2011, and 2012. Point "A": location of Marshall, TX, meteorological station.

that the statistical assumption of normality is not strictly necessary and the test statistics are less impacted by outliers. This method has been widely used to compute trends in climatic and hydrological series [e.g., *Peterson et al.,* 2008; *Zhang et al.,* 2000; *Donat et al.,* 2013]. The method is applied on ranked values; therefore, Kendall tau estimates are relative measures of strength and direction of actual trends. The trend estimates (Kendall tau) were tested at the 0.05 significance level. Seasons were categorized as follows: winter (December to February), spring (March to May), summer (June to August), and fall (September to November).

2.4. Ocean-Atmospheric Indices

We investigated the teleconnection patterns, based on Pearson correlation coefficients, between temperature extremes and the three major modes of ocean-atmospheric variability known to modulate weather and climate across the U.S. The influence of the El Niño–Southern Oscillation (ENSO) on temperature extremes across CONUS was investigated using the Multivariate ENSO Index (MEI) [*Wolter and Timlin*, 1993]. The other two modes of climate variability we examined are the Arctic Oscillation (AO) *Thompson and Wallace*, 1998] and the Pacific/North American indices (PNA) [*Wallace and Gutzler*, 1981]. The monthly data for all three indices were obtained from NOAA Earth System Research Laboratory (ESRL) website: http://www.esrl.noaa.gov/psd/data/climateindices/list/index.html.

3. Results

3.1. Extreme Years

During the study period, 2012 experienced the most frequent and widespread warm days and nights, combined with the fewest cold days across CONUS (Figure 1). Oklahoma and Arkansas were at the

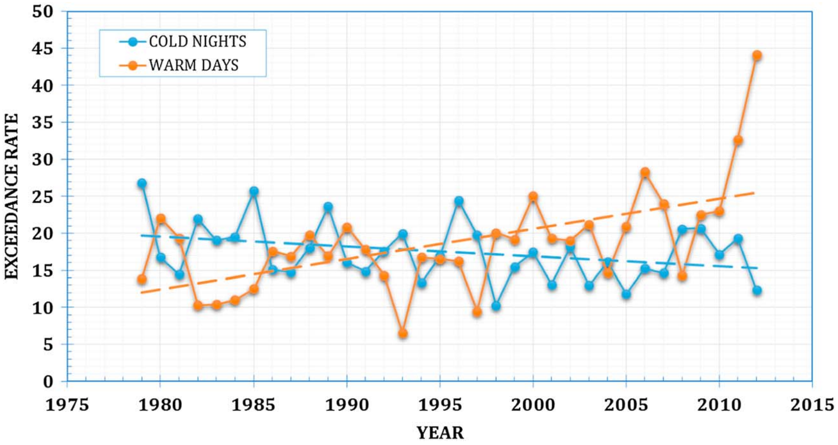

Figure 2. CONUS average number of warm days and cold nights from 1979 to 2012.

epicenter of the 2012 warmth (Figure 1). During this year, residents of central U.S. lived through over 120 warm days and over 80 warm nights, contributing to a CONUS-wide average of 44 warm days, more than twice the average (19 days) of the entire study period (Figure 2). Nearly half (47%) of the U.S. experienced more than 90 warm days, and 15.6% experienced more than 120 warm days (Figure 3). Although 2012 had the most numerous and widespread high numbers of warm nights, the fewest cold nights across CONUS were observed in 1998. Still, 2012 was an extraordinarily warm year both daytime and nighttime [*Peterson et al.*, 2013a, 2013b]. Year 2011 was a close second in terms of extensive warm days (Figure 1). There were, on average, 33 warm days over CONUS (Figure 2). About 25% of the U.S. experienced more than 90 warms days, and 14% experienced more than 120 warm days (Figure 3). These warm days were concentrated in the SGP and SE regions, with more than 140 warm days in parts of the south central U.S. As corroboration for the exceptional warmth in this region, we downloaded United States Historical Climatology Network climate data for a station near Marshall, Texas (point A in Figure 1). Using RClimDex program [*Zhang and Yang*, 2004], we identified 122 warm days in the station data, which was slightly lower than the station pixel value of 131 days obtained using NLDAS-2 data, but still indicated extreme warmth. Slight differences were anticipated [*Abatzoglou*, 2011] between the number of extremes derived from measured point station data and modeled 0.125° grid size NLDAS-2 data. According to *Hoerling et al.* [2012], the 2011 extreme hot summer across Texas was 2.9°C above the 1981–2010 mean, and the probability of the record high number of warm days in the region was approximately doubled by human contribution to climate change. *Rupp et al.* [2015] found the likelihood occurrence of the 2011 unusually high summer temperature at about 10 times greater due to anthropogenic emissions. The years 2006 and 2000 had the

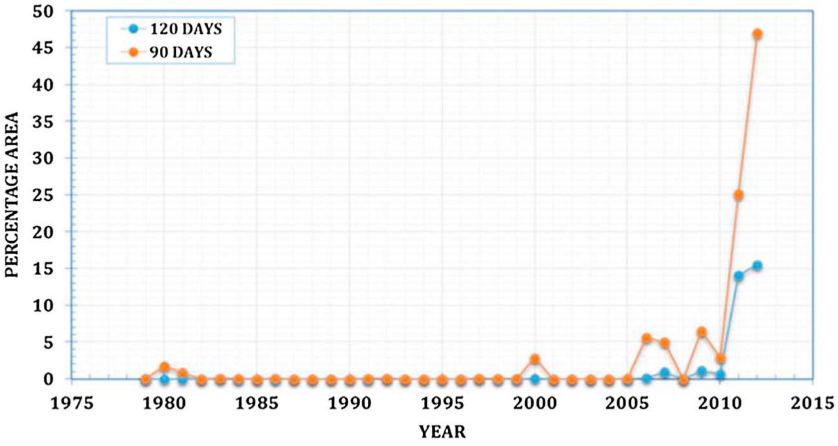

Figure 3. Percentage area of CONUS with warm days exceeding 90 days and 120 days from 1979 to 2012.

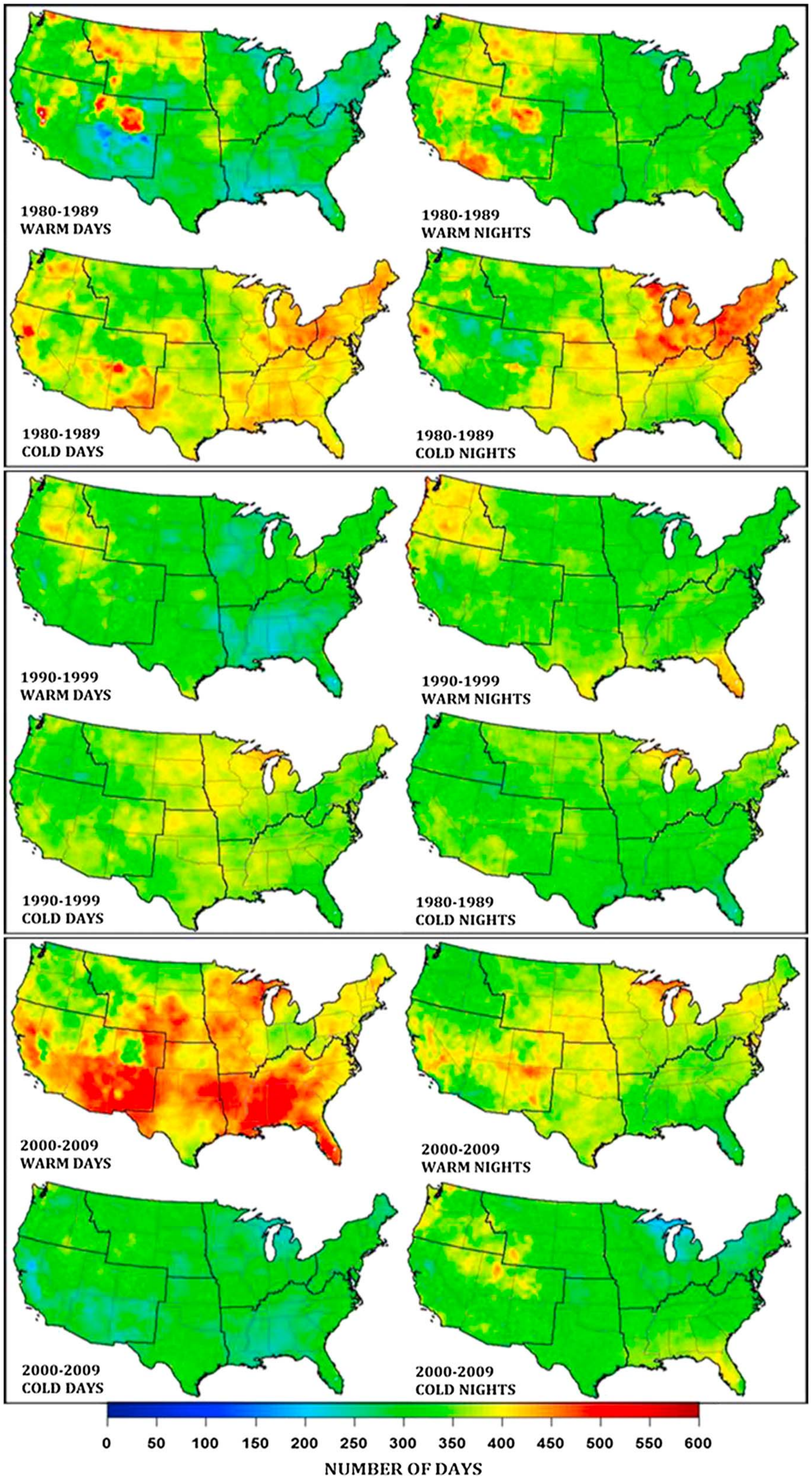

Figure 4. Decadal variability of CONUS temperature extremes from 1980 to 2009 (1980–1989, 1990–1999, and 2000–2009). The decadal temperature extremes were computed as the sum of all warm days and cold nights over each 10 year period.

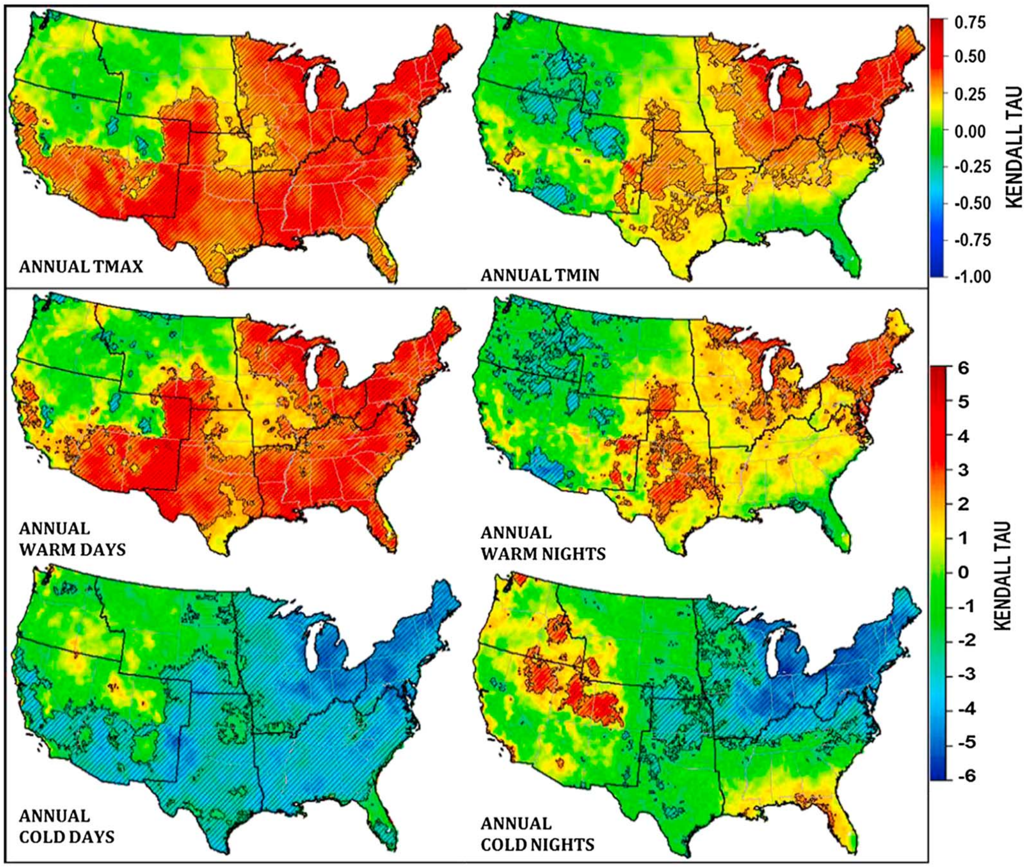

Figure 5. CONUS map of trends in annual $T_{\max}$, $T_{\min}$, warm days, cold days, warm nights, and cold nights for the period 1979 to 2012. The hatching showing areas where the trends were significant. Increase in redness represents increases in number of extremes and increase in blueness represents decreases in number of extremes.

third and fourth highest average number of warm days across CONUS (Figure 2). In 1993, CONUS experienced the fewest warm days and warm nights during the study period (Figure 2). The country also experienced numerous cold days and cold nights that year. The years 1992 and 1993 are known to have experienced a global cooling that was attributed to the eruption of Mount Pinatubo, Philippines, in late 1991 [*Hansen et al.,* 1992].

During the study period, there was a notable strong increase in the occurrence of warm days and a decrease in cold nights (Figure 2). The top 5 years with the highest CONUS-wide average of warm days all occurred after 1999 (2012, 2011, 2007, 2006, and 2000). Since 2006, there have been 5 years when more than 5% of the U.S. experienced at least 90 warm days. This was not observed in any year between 1979 and 2005. The CONUS-wide average of warm days had a significant positive trend (Kendall tau 0.40), whereas the cold nights had an insignificant negative trend (Kendal tau −0.19, Figure 2). Recent statistical studies using other data sets also confirm that the number of warm extremes is strongly increasing [*Coumou and Rahmstorf*, 2012; *Hansen et al.,* 2012] and cold extremes are decreasing.

3.2. Decadal Variability in Temperature Extremes

Decadal variability in temperature extremes was analyzed by summing temperature extremes during each of the three decades of our study (1980s, 1990s, and 2000s). In the 1980s CONUS experienced more cold extremes than warm extremes (Figure 4). All regions except the NGP experienced more cold days than warm days. The eastern region and SGP experienced more cold nights than warm nights, with some areas in the NE and MW experiencing more than 450 cold nights (Figure 4). Extremes in the 1990s were moderate across CONUS. Nighttime warm and cold extremes appeared even for much of the country,

Table 1. CONUS Regional Estimates of Annual, Winter, Spring, Summer, and Fall Trends (Kendall tau) in T_{max}, T_{min}, Warm Days, Cold Days, Warm Nights, and Cold Nights

	T_{max}	T_{min}	Warm Days	Cold Days	Warm Nights	Cold Nights
			Annual			
NE	**0.42**	**0.40**	**2.91**	−**3.81**	**2.12**	−**3.95**
MW	**0.35**	**0.30**	**2.27**	−**3.14**	1.68	−**3.05**
SE	**0.38**	0.12	**2.69**	−**2.85**	0.73	−0.72
NGP	0.08	0.02	0.29	−1.32	−0.31	−0.76
SGP	**0.33**	0.21	**2.21**	−**2.60**	1.56	−1.48
NW	0.00	−0.16	−0.28	−0.34	−1.65	0.92
SW	**0.21**	−0.04	1.50	−1.61	−0.43	0.29
			Winter			
NE	0.20	**0.25**	0.59	−2.42	0.26	−2.88
MW	0.20	0.21	0.78	−**2.38**	0.42	−**2.55**
SE	**0.23**	0.12	1.31	−**2.04**	0.37	−1.35
NGP	0.03	0.02	−1.09	−1.56	−1.47	−1.50
SGP	**0.26**	0.11	1.37	−**2.19**	0.33	−1.21
NW	−0.07	−0.09	−1.48	−0.59	−1.83	−0.27
SW	−0.04	−0.16	−0.62	0.13	−1.30	0.95
			Spring			
NE	**0.26**	0.20	1.76	−**2.26**	0.88	−**2.54**
MW	0.20	0.18	1.53	−**2.10**	1.35	−**2.25**
SE	**0.31**	0.18	**2.37**	−**2.18**	0.77	−1.30
NGP	−0.06	−0.10	−0.40	−0.20	−0.65	−0.05
SGP	0.24	0.17	1.82	−1.88	1.28	−1.38
NW	−0.16	−0.24	−1.41	0.70	−1.95	1.46
SW	0.14	−0.02	1.05	−1.10	−0.02	0.22
			Summer			
NE	**0.30**	**0.26**	1.76	−**3.58**	0.63	−**3.52**
MW	0.23	0.07	1.73	−**2.60**	0.38	−2.16
SE	**0.27**	−0.04	1.60	−**2.85**	0.06	−0.56
NGP	0.12	0.03	0.44	−1.42	−0.09	−0.73
SGP	0.19	0.16	1.41	−1.78	0.82	−2.04
NW	0.15	−0.02	0.24	−1.63	−0.76	−0.20
SW	0.22	0.06	1.37	−**2.16**	−0.18	−1.40
			Fall			
NE	**0.33**	**0.32**	1.39	−**3.07**	0.88	−**2.75**
MW	**0.31**	0.17	**2.10**	−**2.53**	0.70	−1.86
SE	0.20	−0.07	1.48	−**2.40**	−1.02	−0.54
NGP	0.18	0.09	1.19	−0.58	0.69	−0.37
SGP	0.22	0.01	0.84	−1.83	−0.20	−0.80
NW	0.12	−0.05	0.66	−0.09	−0.47	0.83
SW	0.22	0.02	1.35	−1.04	−0.46	0.43

[a]Bold numbers symbolize significant trends.

except in the NW and Florida. During daytime, cold extremes were more frequent than warm extremes for much of CONUS. In contrast, the first decade of the 21st century was extraordinary warm, with the number of warm days increasing sharply (Figure 4). States in the SW, (New Mexico and Arizona) and SE (Arkansas, Mississippi, Alabama, and Florida) experienced particularly high numbers of warm days—more than 500. The increase in warm nights was not as strong as the rise in warm days.

3.3. Temporal and Spatial Patterns of Temperature Extremes

3.3.1. Annual and Seasonal Trends

Annual maximum temperatures increased significantly across much of CONUS (~71%), with the exception of the NW and NGP regions (Figure 5 and Table 1). The trends in warm days closely mirrored T_{max} trends. The corresponding decrease in cold days was the most extensive significant change in extremes across CONUS (about 70%). Of all seasons, spring daytime trends of average temperatures and extremes had the most resemblance of annual daytime trends (Figure S2 in the supporting information). About 47% and 45% of CONUS experienced a significant increase in spring T_{max} and warm days, respectively, the most extensive

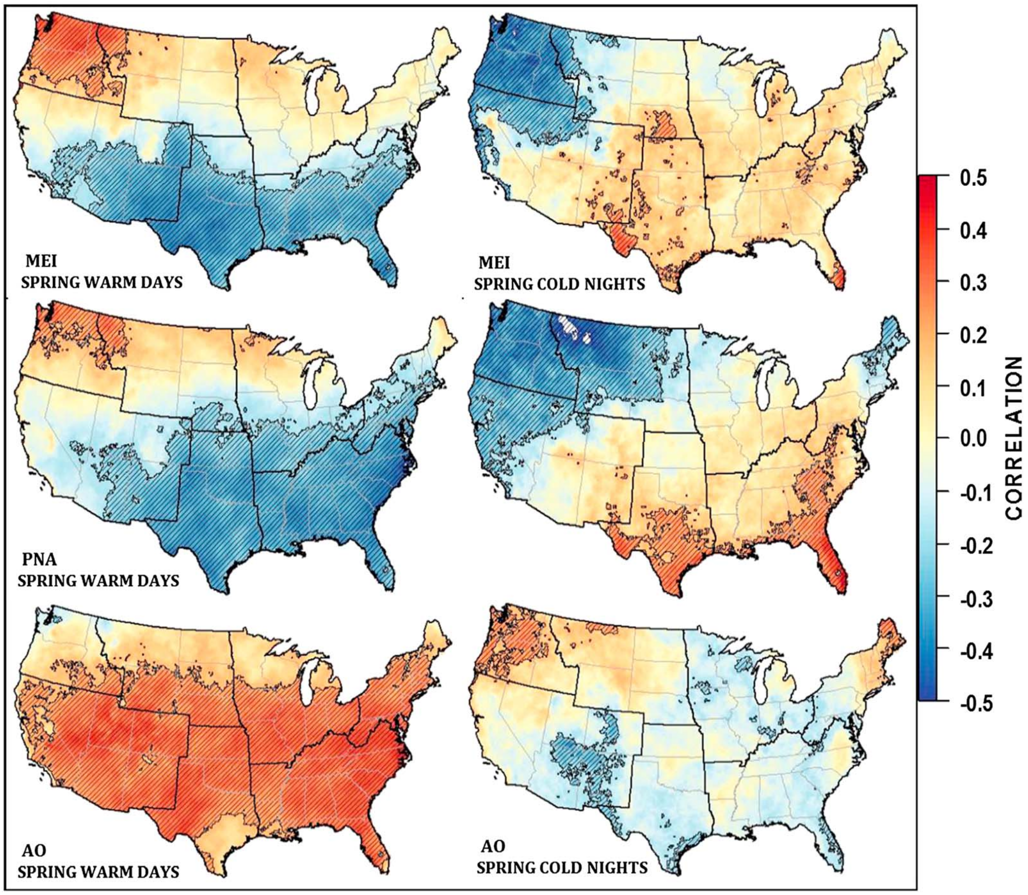

Figure 6. Correlation of temperature extremes (warm days and cold nights) with MEI, PNA, and AO indices during *spring* over the period 1979 to 2012. The hatching showing areas where the correlation was significant.

significant increase among the seasons. Summer increases in T_{max} occurred almost everywhere, with significant increases covering about 45% of CONUS (Figure S3). The frequency of warm days in summer also increased almost across the entire CONUS, though these trends were less significant. For the cold days, almost the entire CONUS experienced a decrease in their frequency, with significant decreases covering about 66% of the country predominantly in the NE, MW, SE, and SW (Table 1). This decrease in summer cold days was the most widespread manifestation of seasonal change in climate across CONUS. Similar to summer, fall T_{max} increased across most of the country (Figure S4), and the increases were significant in the NE, MW, and several areas in the south. The frequency of fall warm days also increased across much of CONUS, but with less significance than during summer. Decreases in fall cold days were widespread and significant in the NE, MW, and SE, covering 46% of CONUS. During winter, there were marginal changes in warm days. However, cold days became less frequent for most of the country with more than 45% of CONUS experiencing a significant decrease in their occurrence (Figure 1a).

Nighttime trends in temperatures were more spatially variable and less significant than in daytime. Annual T_{min} increased significantly in the NE, MW, and SGP, but only in the NE were the overall regional trends in warm nights significantly increasing (Table 1). The frequency of cold nights decreased significantly in the MW and NE. In Florida the frequency of warm nights decreased and cold nights became more common; these trends occurred in all seasons, though most notable in summer and fall (Figures S3 and S4). During spring, trends in warm nights broadly resembled trends in T_{min} although the significant patterns differed. In summer, subdued changes in T_{min} corresponded with modest changes in the frequency of warm nights. Decreases in summer cold nights were the most significant in extent, covering about 33% of CONUS. Likewise, changes in fall nighttime warm extremes were modest and insignificant. In winter, warm nights changed little outside of the western region. Winter cold nights decreased in all regions outside of the SW, with trends significant in the NE, MW, and parts of NGP.

Changes in average temperatures may be a cause or feedback of changes in temperature extremes, a research question beyond the scope of this study. However, we observed that daytime changes in T_{max} were more associated with changes in cold days than in warm days. This was evident in annual, summer, fall, and winter trends. Nighttime T_{min} changes were also more associated with changes in cold nights as observed in annual, summer, fall, and winter trends.

3.4. Modes of Climate Variability and Temperature Extremes

The association between modes of climate variability and extremes on annual scale has been discussed in numerous studies. Herein, we focus on the teleconnection between major models of variability and temperature extremes during spring, the season that had the most spatial similarities with annual extremes in trend patterns. There was a strong and significant negative relationship between ENSO and spring warm days in the southern regions (SW, SGP, and SE) of CONUS (Figure 6). In the NW, the relationship between ENSO and warm days was significantly positive. At nighttime the relationship between ENSO and spring cold nights was only significant in the NW. PNA is one of the most prominent modes of low-frequency variability in the Northern Hemisphere extratropics [*Wallace and Gutzler*, 1981]. The association of PNA with extremes was strongest in winter and spring, greatly weakened in summer, and restrengthened in late fall. During spring, PNA association with warm days was spatially similar to ENSO but extended further north (Figure 6). The PNA also had a stronger association with nighttime cold extremes in the NW, which extended into the NGP and northern parts of California and Nevada. PNA, however, has relatively little impact on the net change in the number of extremes over a region, since the change in warm extremes associated with a PNA phase is countered by an almost similar change in cold extremes in the opposite PNA phase [*Barnston and Livezey*, 1987]. Another mode, the AO, had the most extensive strong relationship with warm extreme across CONUS. The spring warm days and AO relationship was significantly positive for much of the country. However, at night the relationship with cold extremes was weak. During winter, AO and cold nights exhibited a strong positive teleconnection particularly in California and Nevada. Like PNA, AO also has relatively little influence on the net change in the number of extreme [*Higgins et al.,* 2002].

4. Discussion

4.1. How Are Temperature Extremes Changing Across CONUS?

Consistent with expectations, there was a considerable regional variation in these changes in extremes attributed to regional influence of internal climate variability [*Wallace et al.,* 2012; *Hegerl et al.,* 2004]. However, some of the regional variations were surprising and not consistent with other studies. As expected warm extremes were increasing and cold extremes were decreasing for much of CONUS. The NE and MW had the most persistently significant increases in average temperatures and decreases in cold extremes. In all seasons, both daytime and nighttime cold extremes in the NE decreased significantly, though recent cold winters along the eastern seaboard may moderate these trends. *Horton et al.* [2012] showed that NE temperatures have increased at a rate of 0.09°C per decade (almost 1.1°C) between 1895 and 2011. Other studies [*Frumhoff et al.,* 2007; *Wake et al.,* 2008; *Hayhoe et al.,* 2008] described the warming temperatures in the NE as one of the evident manifestations of climate change.

The lack of warming (“warming hole”) in the central U.S. as documented previously [*Pan et al.,* 2004; *Weaver*, 2012] is evident in both warm days and T_{max} annual trends of our study, however, the warming hole over the SE described by *Meehl and Arblaster* [2012] is not apparent in our analysis. *Carter et al.* [2014] and *Kunkel et al.* [2012] noted that the SE has experienced the smallest temperature increase in recent years. In our study, while daytime temperatures in the SE increased, changes in SE nighttime average and extreme temperatures were never significant. In Florida, T_{min} decreased, as did the frequency of warm nights. The increase in SE daytime temperatures coupled with slight nighttime cooling may explain why *Kunkel et al.* [2012] found insignificant changes in SE mean temperatures. *Portmann et al.* [2009] identified the SE as one of the few places in the world displaying an overall cooling trend, hence describing the SE as a warming hole. They attributed the warming hole to land-atmosphere interaction. But *Meehl et al.* [2012] attributed it to the decadal and multidecadal variabilities linked to the Atlantic and Pacific Oceans.

With the exception of winter, the NW and NGP trends in extremes were largely flat during daytime and nighttime. *Abatzoglou et al.* [2014] observed similar results in the NW during the 1997–2012 period; however, in a staggered trend analysis, they noted that increases in average temperatures were significant for every starting year before 1977. The SW is the hottest and driest region of the U.S. [*Garfin et al.,* 2014] and our results show the region is getting warmer. The daytime warm extremes increased and cold extremes decreased across the region. Increases in spring and fall temperatures, in particular, are contributing to a lengthening hot season in the region. The frost-free season (i.e., growing season) in the region during the past three decades has significantly lengthened compared to the 1901–2010 average [*Hoerling et al.,* 2013]. This increase in frost-free season may exacerbate heat and water stress on the forests and crops, further increasing the risk of wild fires.

4.2. How do Changes in Extremes Vary on Seasonal, Annual, and Decadal Scales?

Annual temperature metrics have been the most cited global indicators of climate change; however, annual temperatures tend to average out seasonal variations, and annual exceedance rates of extremes are summations of seasonal exceedance rates that aggregate seasonal variations. Seasonal temperatures at regional scales provide more salient links to climate impacts that may be otherwise masked in annual temperature [*Abatzoglou et al.,* 2014]. Our study found that spring, more than any other season, was associated with the most clear patterns of warming and most closely mirrored annual trends (Figure S2). Although this finding distinguishes our analysis from many others, spring warming has been highlighted in studies of changing phenology [*Schwartz and Reiter*, 2000; *Menzel et al.,* 2006; *Karl et al.,* 2012] and has been associated with a general lengthening of growing season [*Westerling et al.,* 2006; *Easterling et al.,* 1997]. Given the importance of spring conditions for agriculture, snow hydrology, and animal growth and reproductive success, this invites further research.

In comparison to 1950–1990 winter warm days, which were strongly increasing [*Higgins et al.,* 2002], our results show recent trends in winter warm days, especially in the northern regions, were largely flat or decreasing. Although more modest than spring warming, aspects of summer warming are worth noting. Between 2001 and 2010, summer temperatures approached or exceeded records of the 1930s [*National Climate Assessment and Development Advisory Committee*, 2013], indicating that norm conditions may already have moved out of their historical bounds. In 2012, there were extensive areas of record-setting average and extreme temperatures during spring and summer [*Karl et al.,* 2012; *Peterson et al.*, 2013b], consistent with the large numbers of warm days and nights identified in this study. The number of warm days during summer is expected to dramatically increase over much of CONUS by late 21st century. Climate models project that warm days that are ranked among the hottest 5% in 1950–1979 will occur at least 70% of the time by 2035–2064 across CONUS if global warming continues (*Duff and Tebaldi*, 2012). In other words, what is extremely hot today will become the new normal.

On decadal scale, there was a shift in extremes, from more cold extremes in the 1980s to more warm extremes in the 2000s. The 1980s may appear relatively cool compared to the 2000s, but CONUS warm extremes have been increasing since the mid-1970s [*Gleason et al.,* 2008]. The moderate warm extremes of the 1990s could have been associated with the prevalent El Niño phase of ENSO during the decade. El Niño phase is normally associated with cooler and wetter conditions across much of the southern CONUS [*Hoerling and Kumar*, 2000]. The global cooling in the years after the 1991 eruption of Pinatubo [*Hansen et al.,* 1992] could also have tempered warm extremes in the 1990s. There is always considerable decadal variability in extremes. For instance, the 1930s were relatively warm and the 1960s and1970s relatively cool; however, the 2000s were unusually warm [*Peterson et al.,* 2013a, 2013b]. Between 2000 and 2009, there were a few weak El Niño events in 2002–2003, 2004–2005, and 2006–2007, and weak to moderate La Niña events in 2005–2006, 2007–2008, and 2008–2009. Thus, the mean ENSO phase in the 2000s was about neutral with MEI value of 0.08. The ENSO-neutral phase is normally associated with warmer conditions, particularly in winter [*Higgins et al.,* 2002]. Therefore, these ENSO conditions, possibly amplified by anthropogenic forcings could have contributed to the unusually warm conditions of the 2000s. Although this study does not disentangle natural and anthropogenic forcings contribution to changes in temperature extremes, *Meehl et al.* [2007b] showed that the significant increase in warm extremes starting in late 1970s could only be captured in models with anthropogenic forcing.

4.3. How do Changes in Extremes Relate to Changes in Mean Conditions?

This study found that the relationship between average temperatures and temperature extremes varied seasonally. However, it emerged that changes in $T_{\min}$ and $T_{\max}$ was more associated with changes in cold extremes than warm extremes. Annually and in all seasons, daytime trends in average temperatures and temperature extremes were stronger than at nighttime. In fact, increases in annual $T_{\max}$ and decreases in cold days were the most widespread significant changes across U.S. In recent years, it has been observed that about twice as many warm days as cold days are observed across the U.S. [*Meehl et al.,* 2009; *Coumou and Rahmstorf*, 2012].

4.4. Do Extremes Relate to Major Modes of Ocean-Atmosphere Variability?

Our results show that the teleconnections of the three modes are strong in several regions of CONUS and could partially explain the variation in trends of extremes and predict warm spring seasons. In general, warm extremes have been steadily increasing starting from the mid-1970s, and this has corresponded with a time of significant change in atmospheric circulation over North America and the Pacific [*Trenberth*, 1990; *Trenberth and Hurrell*, 1994]. ENSO cycles are associated with the most regional temperature variations; yet these cycles tend to have relatively little impact on the seasonal mean temperatures of CONUS as a whole, since regional anomalies tend to cancel over the course of a season [*Higgins et al.,* 2002]. For the extremes, however, the impact on may be greater, since the relationship between ENSO and extremes varied significantly across regions, with the strongest influence occurring in the southern regions and NW. Besides, extreme anomalies (difference between warm and cold extremes) during daytime or nighttime may not offset in regions of strong ENSO influence because there is a stronger association between ENSO and warm extremes than cold extremes. Future El Niño teleconnections over CONUS are projected to shift eastward and northward due in part to warming climate driven by shifts in the midlatitude base state atmospheric circulation [*Meehl et al.,* 2007a]. Consequently, extreme warm events during El Niño events are projected to increase in intensity for much of CONUS. The PNA, although considered to have relatively little impact on the net change in extremes over a region, can also have a significant influence on CONUS extremes. For instance, the decrease in warm days between 1979 and 1987 (in Figure 2) was observed by *Trenberth* [1990] to have a strong association with PNA during that period.

5. Conclusion

This study presented a synoptic and spatially explicit perspective of recent CONUS trends in daytime and nighttime temperature extremes. We observed substantial strong evidence of a warming CONUS, notably driven by daytime and spring season warming of both average and extreme conditions. Winter warm extremes were marginally changing, indicating a weakening in strong trends between 1950 and 1990 observed in previous studies. Summertime was experiencing the strongest and most widespread decrease in cold extremes. There was considerably regional variation, with the North Great Plains and the Northwest as notable exceptions to strong warming trends in other regions. For 5 years between 2006 and 2012, more than 5% of U.S. experienced at least 90 warm days, occurrences not observed in the previous 25 years. The unusually warm first decade of 21st century could have been associated with the warm conditions of near ENSO-neutral phase during the decade, and likely amplified by the anthropogenic forcings. Our findings highlight the importance of investigating and considering spatial and temporal heterogeneity in extremes and associate impacts. Improved spatial precision and temporal resolution of trends and forecasts in climatic extremes as presented in this study may thus contribute to efforts toward improving our adaptation and resilience to climate change at local and regional scales. An important unknown is the degree to which these patterns will persist in the coming decades.

Acknowledgments
This research was carried out with funding provided by the NASA New Investigator in Earth Science NNX13AB65G (T.P.A. and D.M.) and the NASA Biodiversity and Ecological Forecasting Program NNH10ZDA001N-BIOCLIM, award F12AP00423 (S.V. and T.P.A.). The NLDAS-2 forcing data set was downloaded from NASA's Goddard Earth Science Data and Information Services Center website; http://disc.sci.gsfc.nasa.gov/. The monthly data for all three indices of modes of climate variability were obtained from NOAA Earth System Research Laboratory (ESRL) website: http://www.esrl.noaa.gov/psd/data/climateindices/list/index.html.

References

Abatzoglou, J. T. (2011), Development of gridded surface meteorological data for ecological application and modeling, *Int. J. Climatol.*, *33*, 121–131, doi:10.1002/joc.3413.

Abatzoglou, J. T., D. E. Rupp, and P. W. Mote (2014), Understanding seasonal climate variability and change in the Pacific Northwest of the United States, *J. Clim.*, *27*(5), 2125–2142, doi:10.1175/JCLI-D-13-00218.1.

Albright, T. P., A. M. Pidgeon, C. D. Rittenhouse, M. K. Clayton, C. H. Flather, P. D. Culbert, and V. C. Radeloff (2011), Heat waves measured with MODIS land surface temperature data predict changes in avian community structure, *Remote Sens. Environ.*, *115*(1), 245–254, doi:10.1016/j.rse.2010.08.024.

Barnston, A. G., and R. E. Livezey (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns, *Mon. Weather Rev.*, *115*, 1083–1126.

Benestad, E. R., D. Chen, and I. Hanssen-Bauer (2008), *Empirical-Statistical Downscaling*, World Scientific Co., N. J., London.

Borden, K., and S. L. Cutter (2008), Spatial patterns of natural hazard mortality in the United States, *Int. J. Health Geogr.*, *7*(64), 31, doi:10.1186/1476-072X-7-64.

Brown, J. P., S. R. Bradley, and T. F. Keimig (2010), Changes in extreme climate indices for the Northeastern United States, 1870–2005, *J. Clim.*, *23*, 6555–6572, doi:10.1175/2010JCLI3363.1.

Bumbaco, K. A., K. D. Dello, and N. A. Bond (2013), History of Pacific Northwest heat waves: Synoptic patterns and trends, *J. Appl. Meteorol. Climatol.*, *52*, 1618–1631.

Carter, L. M., J. W. Jones, L. Berry, V. Burkett, J. F. Murley, J. Obeysekera, P. J. Schramm, and D. Wear (2014), Southeast and the Caribbean, in *Climate Change Impacts in the United States: The Third National Climate Assessment*, edited by J. M. Melillo, T. C. Richmond, and G. W. Yohe, chap. 17, pp. 396–417, U.S. Global Change Research Program, doi:10.7930/J0NP22CB.

Cayan, D. R., K. T. Redmond, and L. G. Riddle (1999), ENSO and hydrologic extremes in the western United States, *J. Clim.*, *12*, 2881–2893.

Cosgrove, B. A., et al. (2003), Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project, *J. Geophys. Res.*, *108*(D22), 8842, doi:10.1029/2002JD003118.

Coumou, D., and S. Rahmstorf (2012), A decade of weather extremes, *Nat. Clim. Change*, *2*, 491–496, doi:10.1038/NCLIMATE1452.

Crouch, J., R. R. Heim Jr., and C. Fenimore (2012), Regional climates, United States, in: "State of the climate in 2011", *Bull. Am. Meteorol. Soc.*, *93*(7), S165–S167.

Donat, M. G., L. V. Alexander, H. Yang, I. Durre, R. Vose, and J. Caesar (2013), Global land-based datasets for monitoring climatic extremes, *Bull. Am. Meteorol. Soc.*, *94*, 997–1006.

Donat, M. G., A. D. King, J. T. Overpeck, L. V. Alexander, I. Durre, and D. Karoly (2015), Conditions leading to extraordinary heat during the 1930s US Dust Bowl, *Clim. Dyn.*, doi:10.1007/s00382-015-2590-5.

Easterling, D. R., et al. (1997), Maximum and minimum temperature trends for the globe, *Science*, *277*, 364–367.

Field, C. B., et al. (2007), North America, in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, chap. 14, 976 pp., Cambridge Univ. Press, Cambridge, U. K.

Frich, P., L. V. Alexander, P. Della-Marta, B. Gleason, M. Hay-lock, A. M. G. Klein Tank, and T. Peterson (2002), Observed coherent changes in climatic extremes during the second half of the twentieth century, *Clim. Res.*, *19*, 193–212.

Frumhoff, P. C., J. J. McCarthy, J. M. Melilo, S. C. Moser, and D. J. Wuebbles (2007), Confronting climate change in the U.S. Northeast: Science, impacts and solutions, in *Synthesis Report of the Northeast Climate Impacts Assessment (NECIA)*, Union of Concerned Scientists (UCS), Cambridge, Mass.

Garfin, G., G. Franco, H. Blanco, A. Comrie, P. Gonzalez, T. Piechota, R. Smyth, and R. Waskom (2014), *Southwest. Climate Change Impacts in the United States: The Third National Climate Assessment*, edited by J. M. Melillo, T. (T. C.) Richmond, and G. W. Yohe, chap. 20, pp. 462–486, U.S. Global Change Research Program, doi:10.7930/J08G8HMN.

Gleason, K. L., J. H. Lawrimore, D. H. Levinson, T. R. Karl, and D. J. Karoly (2008), A revised U.S. climate extremes index, *J. Clim.*, *21*, 2124–2137, doi:10.1175/2007JCLI1883.1.

Hansen, J., A. Lacis, R. Ruedy, and M. Sato (1992), Potential climate impact of Mount Pinatubo eruption, *Geophys. Res Lett.*, *19*(2), 215–218, doi:10.1029/91GL02788.

Hansen, J., M. Sato, and R. Ruedy (2012), Perception of climate change, *Proc. Natl. Acad. Sci. U.S.A.*, *109*, E2415–E2423, doi:10.1073/pnas.1205276109.

Hayhoe, K., C. P. Wake, B. Anderson, X. Z. Liang, E. Maurer, J. Zhu, J. Bradbury, A. DeGaetano, A. M. Stoner, and D. Wuebbles (2008), Regional climate change projections for the northeast U.S., *Mitigation Adapt. Strategies Global Change*, *13*, 425–436.

Hegerl, G. C., F. W. Zwiers, P. A. Stott, and V. V. Kharin (2004), Detectability of anthropogenic changes in annual temperature and precipitation extremes, *J. Clim.*, *17*, 3683–3700.

Herring, S. C., M. P. Hoerling, T. C. Peterson, and P. A. Stott (2014), Explaining extreme events of 2013 from a climate perspective, *Bull. Am. Meteorol. Soc.*, *95*, S1–96.

Higgins, R. W., A. Leetmaa, and V. E. Kousky (2002), Relationships between climate variability and winter temperature extremes in the United States, *J. Clim.*, *15*, 1555–1572, doi:10.1175/1520-0442(2002)015<1555:RBCVAW>2.0.CO;2.

Hoerling, M. P., and A. Kumar (2000), Understanding and predicting extratropical teleconnections related to ENSO, in *El Niño and the Southern Oscillation: Multi-scale Variations and Global and Regional Impacts*, edited by H. F. Diaz and V. Markgraf, pp. 57–88, Cambridge Univ. Press, Cambridge, U. K.

Hoerling, M. P., M. Dettinger, K. Wolter, J. Lukas, J. Eischeid, R. Nemani, B. Liebmann, and K. E. Kunkel (2013), Present weather and climate: Evolving conditions Assessment of Climate Change in the Southwest United States, in *A Report Prepared for the National Climate Assessment*, edited by G. Garfin et al., chap. 5, pp. 74–97, Island Press, Washington, D. C. [Available at http://swccar.org/sites/all/themes/files/SW-NCA-color-FINALweb.pdf.]

Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J. W. Nielsen-Gammon, P. Pegion, J. Perlwitz, X.-W. Quan, and T. Zhang (2012), Anatomy of an extreme event, *J. Clim.*, *26*, 2811–2832, doi:10.1175/JCLI-D-12-00270.1.

Horton, R., W. Solecki, and C. Rosenzweig (2012), Climate change in the northeast: A sourcebook. Draft technical input report prepared for the U.S. National Climate Assessment. [Available at http://downloads.usgcrp.gov/NCA/Activities/nca_ne_ full_report_v2.pdf.]

Intergovernmental Panel on Climate Change (IPCC) (2012), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, edited by C. B. Field et al., 582 pp., Cambridge Univ. Press, Cambridge, U. K., and New York.

IPCC AR5: Climate Change (2013), The Physical Science Basis, in *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., 1535 pp., Cambridge Univ. Press, Cambridge, U. K., and New York.

Jiguet, F., R. Julliard, D. C. Thomas, O. Dehorter, E. S. Newson, and D. Couvet (2006), Thermal range predicts bird population resilience to extreme high temperatures, *Ecol. Lett.*, *9*, 1321–1330.

Jones, P. D., E. B. Horton, C. K. Folland, M. Hulme, D. E. Parker, and T. A. Basnett (1999), The use of indices to identify changes in climatic extremes, *Clim. Change*, *42*, 131–149.

Karl, T. R., N. Nicholls, and A. Ghazi (1999), CLIVAR/GCOS/WMO workshop on indices and indicators for climate extremes: Workshop summary, *Clim. Change*, *42*, 3–7.

Karl, T. R., et al. (2012), U.S. temperature and drought: Anomalies of spring and summer 2011–12 and trends, *Eos Trans. AGU*, *93*, 473, doi:10.1029/2012EO470001.

Kendall, M. (1948), *Rank Correlation Methods*, Charles Griffin, London.

Klein Tank, A. M. G., and G. P. Können (2003), Trends in Indices of daily temperature and precipitation extremes in Europe, 1946–99, *J. Clim.*, *16*, 3665–3680.

Klein Tank, A. M. G., F. W. Zwiers, and X. Zhang (2009), *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation*, 56 pp., World Meteorol. Organ., Geneva, Switzerland.

Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J. G. Dobson (2012), Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 9. Climate of the contiguous United States.

Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, J. Rennells, A. DeGaetano, and J. G. Dobson (2013), Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 1, Climate of the Northeast U.S. NOAA Tech. Rep. NESDIS 142–1. 87 pp., National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D. C. [Available at http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-1-Climate_of_the_Northeast_U.S.pdf.]

Linacre, E. (2003), *Climate Data and Resources: A Reference and Guide*, Routledge, London.

McKechnie, A. E., and B. O. Wolf (2009), Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves, *Biol. Lett.*, *6*(2), 253–256.

Meehl, G. A., and J. M. Arblaster (2012), Relating the strength of the tropospheric biennial oscillation (TBO) to the phase of the Interdecadal Pacific Oscillation (IPO), *Geophys. Res. Lett.*, *39*, L20716, doi:10.1029/2012GL053386.

Meehl, G. A., C. Tebaldi, H. Teng, and T. C. Peterson (2007a), Current and future U.S. weather extremes and El Niño, *Geophys. Res. Lett.*, *34*, L20704, doi:10.1029/2007GL031027.

Meehl, G. A., J. M. Arblaster, and C. Tebaldi (2007b), Contributions of natural and anthropogenic forcing to changes in temperature extremes over the United States, *Geophys. Res. Lett.*, *34*, L19709, doi:10.1029/2007GL030948.

Meehl, G. A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel (2009), Relative increase of record high maximum temperatures compared to record low minimum temperatures in the US, *Geophys. Res. Lett.*, *36*, L23701, doi:10.1029/2009GL040736.

Meehl, G. A., J. M. Arblaster, and G. Branstator (2012), Mechanism contributing to the warming hole and the consequent U.S. east–west differential of heat extremes, *J. Clim.*, *25*, 6394–6408.

Melillo, J. M., T. C. Richmond, and G. W. Yohe (Eds.) (2014), *Climate Change Impacts in the United States: The Third National Climate Assessment*, 841 pp., U.S. Global Change Research Program, Washington, D. C., doi:10.7930/J0Z31WJ2.

Menne, M. J., and C. N. Williams Jr. (2009), Homogenization of temperature series via pairwise comparisons, *J. Clim.*, *22*, 1700–1717, doi:10.1175/2008JCLI2263.1.

Menzel, A., et al. (2006), European phenological response to climate change matches the warming pattern, *Global Change Biol.*, *12*, 1969–1976, doi:10.1111/j.1365-2486.2006.01193.x.

National Climate Assessment and Development Advisory Committee (2013), Federal Advisory Committee Draft Climate Assessment, Draft for the Third National Climate Assessment Report. [Available at http://ncadac.globalchange.gov.]

NOAA (2012), National Climatic Data Center, State of the Climate: Synoptic Discussion for May. [Available at http://www.ncdc.noaa.gov/sotc/synoptic/2012/5.]

Pan, Z. T., R. W. Arritt, E. S. Takle, W. J. Gutowski, C. J. Anderson, and M. Segal (2004), Altered hydrologic feedback in a warming climate introduces a "warming hole", *Geophys. Res. Lett.*, *31*, L17109, doi:10.1029/2004GL020528.

Peterson, T. C., C. Folland, G. Gruza, W. Hogg, A. Mokssit, and N. Plummer (2001), Report on the activities of the Working Group on Climate Change Detection and related rapporteurs 1998–2001, World Meteorol. Organ. Rep. WCDMP- 47, WMO-TD 1071, 143 pp.

Peterson, T. C., X. Zhang, M. Brunet-India, and J. L. Vázquez-Aguirre (2008), Changes in North American extremes derived from daily weather data, *J. Geophys. Res.*, *113*, D07113, doi:10.1029/2007JD009453.

Peterson, T. C., et al. (2013a), Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge, *Bull. Am. Meteorol. Soc.*, *94*, 821–834.

Peterson, T. C., M. P. Hoerling, P. A. Stott, and S. Herring (2013b), Explaining extreme events of 2012 from a climate perspective, *Bull. Am. Meteorol. Soc.*, *94*, S1–74.

Portmann, R. W., S. Solomon, and G. C. Hegerl (2009), Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States, *Proc. Natl. Acad. Sci. U.S.A.*, *106*, 7324–7329, doi:10.1073/pnas.0808533106.

Rupp, D. E., S. Li, N. Massey, S. N. Sparrow, P. W. Mote, and M. Allen (2015), Anthropogenic influence on the changing likelihood of an exceptionally warm summer in Texas, 2011, *Geophys. Res. Lett.*, *42*, 2392–2400, doi:10.1002/2014GL062683.

Schwartz, M. D., and B. E. Reiter (2000), Changes in North America spring, *Int. J. Climatol.*, *20*(8), 929–932.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300, doi:10.1029/98GL00950.

Trenberth, K. E. (1990), Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Am. Meteorol. Soc.*, *71*, 988–993.

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere–ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303–319.

Wake, C. P., P. Frumhoff, J. McCarthy, J. Melillo, S. Moser, and D. Wuebbles (Eds.) (2008), Special issue: Assessment of climate change, impacts, and solutions in the Northeast United States, *Mitigation Adapt. Strategies Global Change*, *13*(5–6), 419–660.

Wallace, J. M., and D. S. Gutzler (1981), Teleconnections in the geopotential height field during the Northern Hemisphere Winter, *Mon. Weather Rev.*, *109*, 784–812.

Wallace, J. M., Q. Fu, B. V. Smoliak, P. Lin, and C. M. Johanson (2012), Simulated versus observed patterns of warming over the extratropical Northern Hemisphere continents during the cold season, *Proc. Natl. Acad. Sci. U.S.A.*, *109*, 14,332–14,337.

Weaver, S. J. (2012), Factors associated with decadal variability in Great Plains summertime surface temperatures, *J. Clim.*, *26*, 343–350.

Westerling, L., G. Hidalgo, R. Cayan, and W. Swetnam (2006), Warming and earlier spring increase western U.S. Forest wildfire activity, *Science*, *313*(5789), 940–943.

Wolfe, D. W., L. Ziska, C. H. Petzoldt, A. J. Seaman, L. E. Chase, and K. Hayhoe (2008), Projected change in climate thresholds in the Northeastern U.S.: Implications for crops, pests, livestock, and farmers, *Mitigation Adapt. Strategies Global Change*, *13*, 555–557.

Wolter, K., and M. S. Timlin (1993), Monitoring ENSO in COADS with a seasonally adjusted principal component index, in *Proceedings of the 17th Climate Diagnostics Workshop*, pp. 52–57, NOAA/NMC/CAC, NSSL, Oklahoma Clim. Surv., CIMMS and the School of Meteor., Univ. of Oklahoma, Norman, Okla.

Zhang, X., and F. Yang (2004), *RClimDex (1.0) User Manual*, Climate Research Branch Environment Canada, Downsview, Ontario Canada.

Zhang, X., L. A. Vincent, W. D. Hogg, and A. Niitsoo (2000), Temperature and precipitation trends in Canada during the 20th century, *Atmos. Ocean*, *38*, 395–429.

Zhang, X., G. Hegerl, F. W. Zwiers, and J. Kenyon (2005), Avoiding inhomogeneity in percentile-based indices of temperature extremes, *J. Clim.*, *18*, 1641–1651.

Zhang, X., L. Alexander, G. C. Hegerl, P. D. Jones, A. K. Tank, T. C. Peterson, B. Trewin, and F. W. Zwiers (2011), Indices for monitoring changes in extremes based on daily temperature and precipitation data, *WIREs Clim. Change*, *2*(6), 851–870.