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Key Points:
- Increases in absolute record highs and decreases in record lows since 1980
- Lack of absolute coolest records since 2000 exceeded most climate simulations
- Projected increase in novel absolute warmest records for coming decades

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

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Observed and projected changes in absolute temperature records across the contiguous United States

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Abstract Changes in the extent of absolute, all-time, daily temperature records across the contiguous United States were examined using observations and climate model simulations. Observations from station data and reanalysis from 1980 to 2013 show increased extent of absolute highest temperature records and decreased extent of absolute lowest temperature records. Conversely, station data from 1920 to 2013 showed decreased extent of absolute highest records with nearly half of such records occurring in the 1930s during exceptional widespread drought. Simulated changes in the extent of absolute temperature records from climate model experiments were in general agreement with observed changes for recent decades. However, fewer lowest temperature records and highest temperature records were observed since 2000 than simulated by most models. Climate models project a continued increase in the occurrence of highest temperature records and decline in lowest temperature records through the mid-21st century.

1. Introduction

There is much interest in characterizing climate change in the observational record. While analyses have typically characterized changes in mean conditions such as annual or seasonal temperature, changes are evident across a spectrum of statistical moments including changes in the frequency and magnitude of temperature extremes [e.g., *Donat and Alexander*, 2012]. Extremes can be defined through a variety of means, thereby complicating the matter of examining changes thereof. *Meehl et al*. [2009] examined daily temperature records (i.e., all-time highest and lowest temperature for a calendar day) and found that the number of record daily high temperatures outpaced the number of record daily low temperatures in recent decades across the contiguous United States (U.S.). Over the past decade, several heat wave events resulting in absolute highest daily maximum temperature records (i.e., highest all-time daily high temperature for any day of the year) have been seen globally, including in Greece in 2007 [*Founda and Giannakopoulos*, 2009] and Australia in 2013 [*Lewis and Karoly*, 2013]. Events like these have heightened interest in examining changes in climatic extremes, the degree to which they can be attributed to anthropogenic forcing [e.g., *Morak et al*., 2013; *Christidis et al*., 2011; *Duffy and Tebaldi*, 2012] and how they may change over the 21st century [e.g., *Kharin et al*., 2013; *Sillmann et al*., 2013; *Wuebbles et al*., 2014].

Whereas temperature extremes have been examined through a variety of approaches, no known study has examined changes in absolute temperature records. Absolute temperature records generally coincide with exceptional synoptic dynamics (e.g., large-amplitude Rossby wave patterns) [*Screen and Simmonds*, 2014], but further enabled by antecedent conditions via midlatitude land-surface interactions that modify the surface energy budget [*Mueller and Seneviratne*, 2012]. For example, absolute low minimum temperature records occur favorably in the wake of a large-scale equatorward intrusion of an Arctic or Polar Continental airmass, with radiative cooling further enhanced by the presence of widespread ample snow cover. By contrast, absolute high maximum temperature records are exacerbated by persistent upper level ridging and dry surface conditions [e.g., *Miralles et al*., 2014]. In addition to their significance from a purely statistical measure, absolute temperature records help define the geographic range of ecosystems. Changes in absolute temperature records are reasoned to pose challenges for thermally sensitive species through physiological intolerance [e.g., *Parmesan*, 2006]. These records are also of societal relevance, as extreme temperatures pose impacts to transportation, energy demand and human health. Finally, the occurrence, or lack thereof, of absolute temperature records are often conveyed through media coverage and may be publicly perceived as emblematic of climate change, whether justified or not.

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This work builds on previous studies that have analyzed changes in daily temperature records [*Meehl et al.*, 2009] and the magnitude of return periods for temperature extremes [e.g., *Kharin et al.*, 2013] by focusing on observed and model simulated changes in absolute temperature records. We analyze the chronology of absolute highest and lowest temperature records for both maximum temperature and minimum temperature across the contiguous U.S. using station data from 1920 to 2013 and reanalysis data from 1980 to 2013 and compare observed changes with changes derived from climate model experiments. Finally, we examine the evolution of absolute temperature records through the mid-21st century under enhanced greenhouse forcing scenarios.

2. Data and Methods

Whereas numerous studies have examined temperature extremes, we focus on four measures that define daily absolute temperature records from a given time series: absolute highest maximum temperature (highest T_{MAX}), absolute highest minimum temperature (highest T_{MIN}), absolute lowest maximum temperature (lowest T_{MAX}), and absolute lowest minimum temperature (lowest T_{MIN}). The year during which records occurred was documented for each time series. Tied records were weighted accordingly (e.g., records set in 1936 and 1998 were each assigned a weight of 0.5).

Daily data from 1218 stations in the U.S. Historical Climate Network (USHCN) were acquired from the Global Historical Climate Network (GHCN) Daily database [*Menne et al.*, 2012]. USHCN stations generally have long-term, high-quality records that minimize influences of land use and land cover change and represent the best long-term climate record for the U.S. Despite potential observational challenges in validating absolute temperature records, efforts have been taken to improve their integrity [e.g., *Shein et al.*, 2013]. Daily GHCN data are not free of climate inhomogeneities associated with changes in observation practices and station relocations. However, the focus on absolute temperature records minimizes potential biases arising from well-documented time of observation bias. Changes in instrumentation from liquid-in-glass thermometers in Cotton Region Shelters to electronic systems for a majority of USHCN stations in the 1980s appear to have resulted in a slight reduction in T_{MAX} and slight increase in T_{MIN} [e.g., *Quayle et al.*, 1991], but it is unclear whether these biases are applicable to the extremes of the distribution. Data flagged as failing any GHCN quality assurance check were discarded. While some legitimate records may be flagged for failing the climatological outlier check, defined as being more than 6 standard deviations from the mean, we found that less than 1% of records for highest T_{MAX}, lowest T_{MAX} and lowest T_{MIN} would be altered using a more liberal filter. A larger percent of highest T_{MIN} would be affected by ignoring the climatological outlier flag. However, a majority of flagged highest T_{MIN} failed other quality control measures (e.g., T_{MIN} exceeding T_{MAX} or time of observation temperature).

Although some observations extend back into the 19th century, we restricted our focus to the time period 1920–2013. Stations missing more than 10% of daily T_{MAX} or T_{MIN} records over the 94 year period were eliminated leaving a total of 755 stations. We address the nonuniform station distribution across the U.S. that may otherwise lead to potential geographic biases in subsequent analyses by aggregating the count of station-based records to a 1° spatial horizontal resolution grid that gives equal weight to stations within each voxel. Acknowledging the complexities in observational practices arising from data inhomogeneities in station observations and spatial scaling issues, we repeated the analysis using complementary and independent daily T_{MAX} and T_{MIN} temperature from ERA-Interim reanalysis (1980–2013) regridded to the common 1° spatial grid.

There are statistical challenges in estimating trends in absolute records at local scales given their restricted sample size and spatial autocorrelation. Instead, we examined trends in the spatial extent of absolute records for all voxels over the contiguous U.S. Trends from station data were estimated for three time periods: 1920–2013, 1950–2013, and 1980–2013, and trends from ERA-Interim were estimated for 1980–2013. We assessed the statistical significance of trends using bootstrap resampling of the annual absolute temperature extrema (i.e., highest and lowest in T_{MIN} and T_{MAX} per year) with replacement ($n = 1000$), assuming approximate independence of such time series. Resampling using block bootstrapping with lengths of 1–5 years to account for potential serial correlation in annual temperature extrema time series did not alter our results. Trends are hereafter referred to as significant when the 95% confidence interval of resampled trends excluded no change.

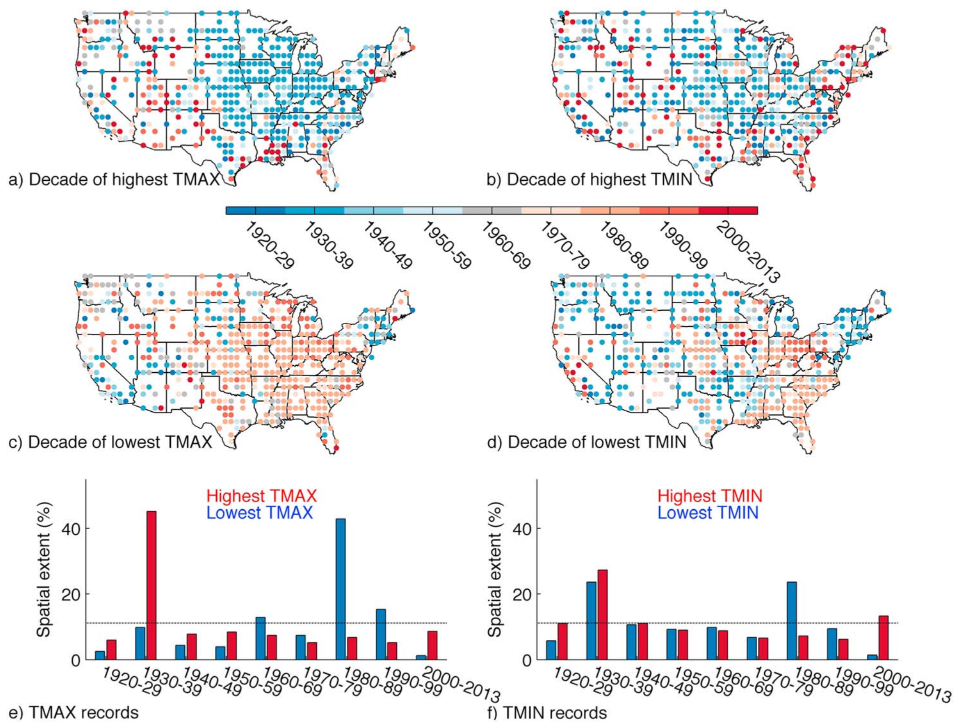

Figure 1. Decade during which absolute records of (a) highest daily maximum, (b) highest daily minimum, (c) lowest daily maximum, and (d) lowest daily minimum temperature occurred aggregated to a 1° spatial horizontal resolution from Global Historical Climate Network data from 1920 to 2013. Empty regions had insufficient station data over the period of record (see text). (e, f) Decadal variability in the percent of the mapped domain with absolute temperature records. The dashed horizontal line represents the expected distribution for a uniform distribution of records for reference. The extent of records for 2000–2013 was divided by 1.4 for compatibility with previous decades.

Daily T_{MAX} and T_{MIN} from 20 global climate models (GCMs) participating in the Coupled Model Intercomparison Project Phase 5 were acquired for model runs forced by twentieth century historical experiments for 1950–2005 and extended through 2049 using output from model runs forced by the Representative Concentration Pathway 8.5 experiment. Output from climate models was regridded to the common 1° spatial resolution grid and restricted to voxels over the conterminous U.S. Observed changes in absolute records from observations and climate models were compared for two time periods: 1950–2013 and 1980–2013. A comparison between in situ station data and gridded fields from models is problematic, particularly for extremes that are subject to subgrid scale land-surface feedbacks and local-to-regional diabatic and adiabatic processes. However, comparisons between model simulations and ERA-Interim reanalysis facilitate a more appropriate comparison by overcoming several of these limitations.

3. Results

Nearly half of highest T_{MAX} and over a quarter of highest T_{MIN} for the 1920–2013 period occurred during the 1930s (Figure 1), similar to results from prior studies examining temperature extremes and heat waves in the U.S. [e.g., *DeGaetano and Allen*, 2002; *Peterson et al*., 2013]. Conversely, a large number of lowest T_{MAX} and lowest T_{MIN} in the 1980s were associated with a series of cold air outbreaks [e.g., *Schmidlin*, 1993]. The period 2000–2013 was remarkable for its lack of lowest records (1%) with a moderate number of highest records (10%).

The stochastic nature of temperature records and their strong spatial coherence is apparent in Figure 1 and alludes to the important role played by exceptional large-scale climatic and synoptic factors. For example, nearly 25% of highest T_{MAX} were set in 1936, primarily across the Great Plains and Midwestern U.S. (Figure S1c in the supporting information) concomitant with anomalously low summer soil moisture with the majority of these records occurring between 5 and 16 July 1936 coinciding with broad-scale ridging over

Table 1. Linear Trends in the Observed Annual Spatial Extent of the United States with Absolute Temperature Records Expressed as a Percent of Total Area[a]

	Highest T_{MAX}	Lowest T_{MAX}	Highest T_{MIN}	Lowest T_{MIN}
GHCN 1920–2013	−1.89[b]	1.01	−0.77	−0.70
GHCN 1950–2013	−0.40	0.35	1.81[b]	−0.75
GHCN 1980–2013	0.75	−6.49[b]	2.36[b]	−5.99[b]
ERA-Interim 1980–2013	4.92[b]	−5.54[b]	5.30[b]	−4.80[b]

[a]Trends are expressed as the difference between the last and the first values from the least square line.
[b]The trend observed is significant according to a Monte Carlo test, that is, more than 95% of the simulated trends agree on the sign of the trend.

the central U.S. and Canada. Similarly, over 8% of lowest T_{MAX} occurred from 20 to 22 January, 1985 coinciding with a cold air outbreak that brought record low temperatures to the southeastern U.S. (Figure S1d) and widespread impacts to the Florida citrus crop [*Miller and Downton*, 1993]. Significant signals in both antecedent and synoptic conditions were found for temperature records. The mean Palmer Drought Severity Index concurrent with highest T_{MAX} was −3.0 (Figure S3, see supporting information for details) reinforcing the potential influence of antecedent conditions that enable enhanced sensible heat flux [e.g., *Mueller and Seneviratne*, 2012; *Miralles et al.*, 2014]. The mean standardized 500 hPa geopotential height anomaly coincident with lowest T_{MAX} and T_{MIN} exceeded -1.5σ, highlighting the influence of synoptic processes; standardized anomalies for highest T_{MAX} and T_{MIN} were significantly positive, albeit more subdued than for lowest T_{MAX} and T_{MIN} (Figure S4; see supporting information for details). Internal modes of climate variability may contribute to the occurrence of absolute temperature extremes at regional scales. However, relationships between records over the U.S. and the Multivariate El Nino Index (MEI) averaged from October to February [*Wolter and Timlin*, 1993] revealed only a weak increase ($p < 0.1$) in the occurrence of lowest T_{MAX} and lowest T_{MIN} during La Nina conditions (MEI < -1), suggesting that the primary mode of interannual climate variability cannot explain the variability in records through time.

A significant decrease in the extent of highest T_{MAX} was noted over 1920–2013 period, mainly due to the predominance of events during the 1930s. Observations commencing from 1950 failed to show a trend other than an increase in the occurrence of highest T_{MIN}, while observations commencing in 1980 show a significance increase in the extent of highest T_{MIN} and decrease in the extent of lowest T_{MAX} and T_{MIN} (Table 1). A more coherent signal was seen for T_{MIN} with increased extent of highest T_{MIN} and decreased extent of lowest T_{MIN} (significant at $p < 0.1$) over the last 64 years in contrast to the negligible signal for T_{MAX}, similar to diurnal asymmetry in temperature records reported in prior studies [*Rowe and Derry*, 2012]. Data from ERA-Interim reanalysis for the 1980–2013 period depicted significant increases in the extent of highest records (T_{MAX} and T_{MIN}) and significant decreases in the extent of lowest records (Table 1 and Figure 2). These trends were in general agreement to trends computed from station data from 1980 to 2013, but with a larger portion of highest records set in the last 10–15 years in reanalysis.

Nearly all models showed a significant increase in the extent of highest T_{MAX} (16 of the 20) and T_{MIN} (20 of 20) for 1950–2013 (Table S1). Moreover, all models had above normal extent of highest T_{MAX} and T_{MIN} for the 2000–2013 period with a multimodel mean of 150% above that expected from a uniform distribution of records. Lowest T_{MAX} and T_{MIN} exhibited more variability across time and models, with only a few models simulating a significant decrease over the 64 year period (Table S1 and Figure S2). However, models simulated a 40% reduction in the extent of lowest temperature records for 2000–2013 relative to a uniform distribution.

Models showed a larger increase in the extent of highest temperature records over the 1950–2013 period than did observations (Figure S2). The extent of observed highest T_{MAX} in the last 14 years was approximately equal to a uniform distribution, below that of any model simulation. By contrast, models generally underestimated the decline in lowest T_{MAX} and T_{MIN}, particularly since 2000. This comparison suggests that while observations and model simulations agree upon the direction of change from 1950 to 2013, more records were seen in simulations than in observations in recent decades. Conversely, observed increases in the extent of highest records from ERA-Interim were quantitatively similar to GCMs for 1980–2013, while observed decreases in the extent of lowest records surpassed those simulated by a majority of models

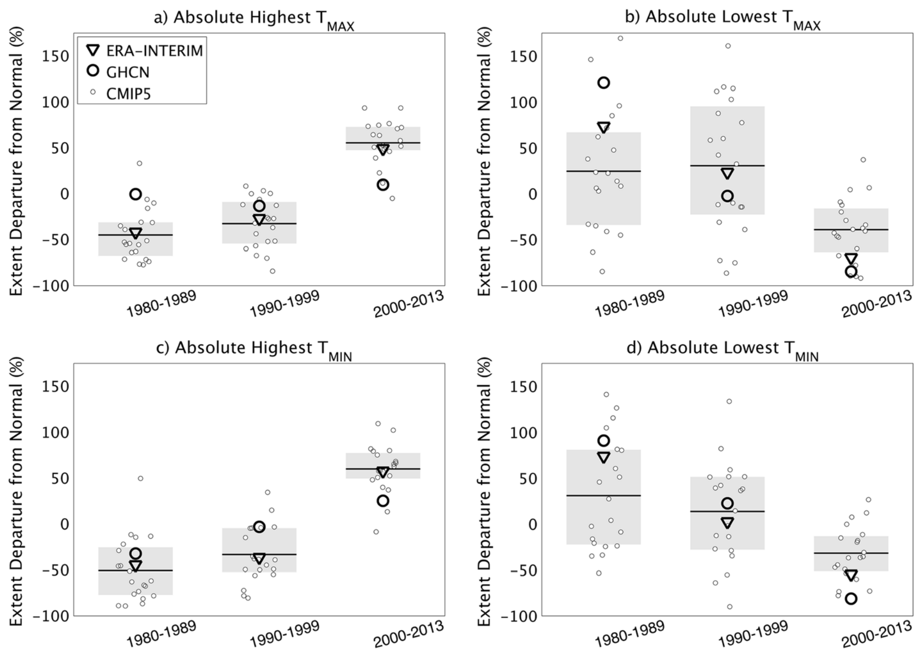

Figure 2. Decadal variability in the spatial extent of absolute records for (a) highest maximum temperatures, (b) lowest maximum temperatures, (c) highest minimum temperatures, and (d) lowest minimum temperatures for GHCN, ERA-Interim, and 20 different climate models from 1980 to 2013. Data are expressed as a departure from an assumed uniform distribution of records. Climate model results are depicted by the box plots where the interquartile range is shown by the grey envelope, the 20-model mean is shown by the black horizontal line and individual model results shown by small circles.

(Figure 2). Trends using GHCN data for 1980–2013 showed a more subdued increase in the extent of highest records and more exaggerated decline in the extent of lowest records.

Differences in the trends of records between observations and models may arise due to inherent differences in the signal-to-noise ratio. We examined annual absolute temperature extrema in GCMs and observations, and calculated both linear least squares trends (signal) and standard deviations (noise) for the 1950–2013 period. The standard deviation of annual absolute temperature extrema was similar between observations and models, with the magnitude of variability for annual lowest temperature nearly twice that of annual highest temperature (not shown). By contrast, inconsistencies were found between trends in annual absolute temperature extrema with lesser warming of highest daily T_{MAX} seen in observations than for models and larger warming of lowest daily T_{MIN} seen in observations than for models, similar to those reported globally by *Fischer and Knutti* [2014]. Discrepancies were largely minimized when comparing trends from ERA-Interim and GCM output for the 1980–2013 period. The similar modeled trends in annual absolute temperature extrema, with larger variability in annual lowest temperature explain the strong model agreement of increased extent of highest records relative to the weaker signal of decreased extent of lowest records.

Climate projections show a continued increase in the prevalence of highest T_{MAX} and T_{MIN} through the mid-21st century (Figure 3). Approximately half of all highest records for the 100 year period through 2049 occurred in the last decade of model simulations. However, climate models do not exclude the potential for highest records accrued from 1950 to 2013 to remain as records through 2049, with a multimodel average of 9% of records for the time period 1950–2049 occurring through 2013. By contrast, the occurrence of lowest records decays in the 21st century with approximately 2% of such records occurring in the last decade of the period analyzed and 88% of absolute cold extremes accrued from 1950 to 2013 remaining through 2049. These results not only suggest that lowest records are projected to occur with diminishing frequency under enhanced greenhouse forcing but also suggest the occurrence of novel lowest records under future climate due to the stochastic nature of atmospheric circulation and increased sampling opportunities.

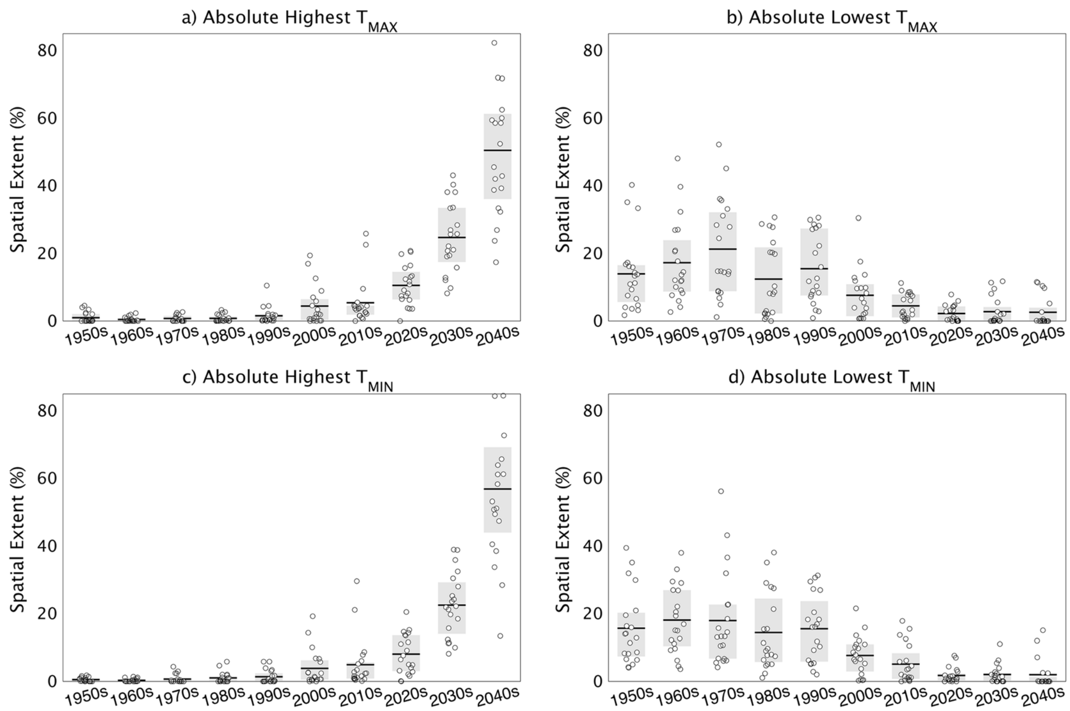

Figure 3. Decadal variability in the spatial extent of absolute records for (a) highest maximum temperatures, (b) lowest maximum temperatures, (c) highest minimum temperatures, and (d) lowest minimum temperatures across the United States from 20 different climate models from 1950 to 2049. Climate model results are depicted by the box plots where the interquartile range is shown by the grey envelope, the 20-model mean shown by the black horizontal line and individual model results shown by small circles.

4. Discussion and Conclusions

Many of the absolute highest temperature records across the U.S. were set during the 1930s, during the most widespread severe drought of the twentieth century [*Andreadis and Lettenmaier*, 2006] consistent with several previous studies that examined the occurrence of moderate extremes over the past century [e.g., *Peterson et al*., 2013]. Nearly 75% of stations with highest T_{MAX} in the 1930s had PDSI values less than -3, nearly twice the number seen for other time periods. Excluding the 1930s, the only significant observed trend for 1950–2013 was an increase in the extent of highest T_{MIN}. Conversely, climate models depicted increases in the occurrence of highest records and decreases in the occurrence of lowest records over the 1950–2013 period. These discrepancies were largely reduced when restricting observations from 1980 to 2013 and incorporating reanalysis data. While our analysis was confined to the contiguous U.S., these findings are consistent with the observed increase in daily temperature records in the Northern Hemisphere since 2001 [*Christiansen*, 2013] and hot extremes over global landmasses over the past three decades [*Seneviratne et al*., 2014].

The near-absence of lowest records observed since 2000 concurs with prior studies that have noted a decrease in cold waves in the U.S. [*Peterson et al*., 2013]. The over four-to-one ratio in highest to lowest records for 2000–2013 from reanalysis is consistent with results from climate models. The larger ratio in station data was due to a sharper decline in the presence of lowest records similar to daily records as reported by *Meehl et al*. [2009]. Asymmetric trends in annual temperature extrema that include significant warming of the coldest night each winter and lack of significant warming of the warmest day each summer have been observed over parts of the U.S. [e.g., *Abatzoglou et al*., 2014]. Conversely, climate models simulate relatively proportional increases in annual temperatures extrema, overestimating the increase in hot extremes and underestimating the decrease in cold extremes relative to observations for the 1950–2013 period.

While there is solid agreement between changes in temperature records observed with reanalysis and models from 1980 to 2013, we fail to show a clear signal for the longer time periods considered.

Irrespective of changing environmental conditions, the aforementioned changes in station instrumentation in the 1980s may have contributed to a reduction in extent of highest T_{MAX} and lowest T_{MIN} and increase in extent of highest T_{MIN} and lowest T_{MAX} over the past three decades. Discrepancies between observed and modeled trends may be associated with numerous factors including natural climate variability and GCMs inability to capture mesoscale and land-surface processes that contribute to all-time records. Given the strong linkages between drought and the occurrence of highest T_{MAX} (Figure S3), the lack of agreement in longer-term trends in highest T_{MAX} between observations and models may be due to differences in the manifestation of internal climate variability pertaining to the occurrence of severe droughts [*Ault et al.*, 2014]. It has also been suggested that the anthropogenic influence on temperature extremes may not yet sufficiently exceed background natural variability, particularly for singular events such as absolute records [*Brown et al.*, 2008; *Hegerl et al.*, 2004].

Changes in absolute temperature records may arise through changes in mean temperature (e.g., a symmetric shift) in addition to changes in variance. Observational studies show negligible changes in daily temperature variability over the past 50 years in North America, with the exception of decreased T_{MIN} variance arising through a warming of the coldest days [*Bonsal et al.*, 2001]. Trends in absolute temperature records should differ from changes in mean conditions due to both of the stochastic nature of exceptional events and the underlying processes that favor record setting temperatures such as land-surface feedbacks and the amplitude of large-scale atmospheric waves. The coldest air masses in North American source regions have warmed over the past six decades [e.g., *Hankes and Walsh*, 2011], while changes in the amplitude and persistence of midlatitude Rossby waves with warming are more ambiguous [*Barnes*, 2013]. Whereas warmer temperatures have played a contributing role in reducing snow depth during late winter and spring, nominal changes in snow depth have been observed during midwinter that would generally coincide with the lowest T_{MIN} or T_{MAX} in regions where snow cover feedback plays an important role [*Dyer and Mote*, 2006]. Overall increases in twentieth century precipitation have resulted in increased soil moisture [*Andreadis and Lettenmaier*, 2006] and decreased climatic water deficit [*Dobrowski et al.*, 2013] across much of the central U.S. Widespread changes in land cover including increases in irrigable land over the 1920–2013 period may further contribute to the longer-term signal, particularly during the summer months when irrigation augments soil moisture [e.g., *Cook et al.*, 2014]. These changes would otherwise reduce the Bowen-Ratio and limit land-surface feedbacks for novel highest T_{MAX} records. Additional insight into land-surface feedbacks as well as synoptic and mesoscale processes responsible for such records is needed to better resolve such factors.

Absolute temperature records are projected to evolve into the 21st century with an increase in highest records and decay in lowest records. Climate projections do not exclude potential future novel lowest records [e.g., *Kodra et al.*, 2011], or for present-day highest records to remain as such through the mid-21st century due to the stochastic nature of combined synoptic factors and land-atmosphere interactions that foster records. Changes viewed through the lens of coarse-resolution GCM output may be augmented or diminished via land-surface feedbacks. Future analyses that consider projected changes in favorable antecedent conditions for absolute records including midwinter snow cover, or midsummer soil moisture may resolve such changes. Novel temperature records will have implications for summer peak-energy demand and heat-related health impacts that may necessitate adaptation measures to reduce societal risk, and pose acute risks to ecosystems that are not thermally adaptive and lack migration options [e.g., *Beever et al.*, 2010]. Decreasing proclivity for novel cold records may bring benefits (e.g., reduced cold mortality for ecosystems, reduced peak winter-energy demand). However, the lack of novel cold records may also have ecological consequences as reduced cold mortality of species may be conducive to biological invasions and ecosystem change [*Walther et al.*, 2009].

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