ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1029/2018JD029150

Key Points:
- Extreme heat events are increasing and extreme cold events are decreasing across the United States and Canada
- Extreme temperature events relative to the time of the year are also changing in frequency

Supporting Information:
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Citation:
Sheridan, S. C., & Lee, C. C. (2018). Temporal trends in absolute and relative extreme temperature events across North America. *Journal of Geophysical Research: Atmospheres*, *123*, 11,889–11,898. https://doi.org/10.1029/2018JD029150

Received 20 JUN 2018
Accepted 21 OCT 2018
Accepted article online 24 OCT 2018
Published online 8 NOV 2018

Temporal Trends in Absolute and Relative Extreme Temperature Events Across North America

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Abstract In this research, we define extreme temperature events using a recently defined excess heat factor, based on the exceedance of apparent temperature beyond the 95th percentile along with an acclimatization factor, to define extreme heat events (EHE). We extend the calculation to assess cold and develop *relative* metrics to complement the absolute metrics, where extremeness is based on conditions relative to season. We thus examine extreme cold events (ECE), relative extreme heat events, and relative extreme cold events in addition to EHE. We present a climatology of these variables for North America, followed by analyses of trends from 1980 to 2016. While EHE and ECE are found in the core of summer and winter, respectively, relative events tend to have a broader seasonality. Trends in relative extreme heat events and EHE are upward, and relative extreme cold events and ECE are downward; the relative events are changing more rapidly than the absolute events.

Plain Language Summary One of the most critical ways in which weather conditions influence the environment is through extreme temperature events. While excessive heat and cold conditions have been amply studied, events that are extreme relative to the time of year have been less examined. These relative events may grab fewer headlines but can have important impacts on the environment, agriculture, and human health. In this research, we present a climatology of cold and heat events, both absolute and relative, for North America, followed by an analysis how they have changed from 1980 to 2016. Results show an increase in heat events and decrease in cold events across most of the United States and Canada. More interestingly, the relative events are changing slightly more rapidly than the absolute events.

1. Introduction

Global mean surface temperature is the most frequently cited indicator of climate change, with a steady upward trend since the 1970s (Rahmstorf et al., 2017). This indicator is useful for understanding the overall anthropogenic influence on the climate system and frequently is used as a shorthand benchmark for climate risks (e.g., Ebi et al., 2018). This said, there is a clear spatial variability in temperature trends, and while global mean temperature may correlate broadly with trends in many regions of the globe, the internal variability of the climate system yields considerable spatial variation in this trend (Sutton et al., 2015), even to the point of producing *warming holes* (e.g., Banerjee et al., 2017). Compounding the spatial variation is seasonal variability in trends, of which the high-amplitude autumn and winter warming in the Arctic is most well known (Cohen et al., 2014).

Beyond mean temperatures, there is also substantial interest in understanding trends in extreme temperature events (ETEs). Temperature extremes pose a greater ecological risk to many species than mean warming (Vasseur et al., 2014) and can alter natural community structure (Ma et al., 2015); they can also impact human systems through impacts on health (Sheridan & Allen, 2015) as well as energy consumption (Santamouris et al., 2015). In a warming world, it would generally be expected that extreme heat events (EHEs) would increase and cold events would decrease, and this has generally been the case, although it is not unambiguous, and there is evidence of increasing cold events in places (Kug et al., 2015).

One of the most complex aspects of studying ETEs is that there is no formal definition of what an ETE is; indeed, in one recent paper 16 different definitions of heat indices were evaluated for the United States with differing spatial patterns of mean and, to a lesser extent, trends, based on the metric used (Smith et al., 2013). For human impacts, the metric typically incorporates some form of apparent temperature, which includes wind and humidity in addition to temperature, in order to account properly for human thermoregulation (Steadman, 1984); selecting an ideal metric for ETEs, in particular heat, generally involves assessment relative to human health outcomes (e.g., Hajat & Kosatsky, 2010). Further, these metrics are typically defined in *relative*, not *absolute* terms (e.g., the 95th percentile of the local temperature distribution) to account for the variability in human response across different climate zones (Sheridan & Allen, 2015).

Less frequently explored is the seasonal variability in a threshold. There is some evidence that early-season heat events are more hazardous to humans than heat events later in the season (Anderson & Bell, 2010; Ng et al., 2014), something that has been attributed to acclimatization as well as the number of susceptible persons in a population. In terms of acclimatization, one must account for actual thermal conditions, as well as preceding conditions, evaluating how *oppressive* current atmospheric conditions are relative to recent weeks (Nairn & Fawcett, 2014).

It is with this concept that Nairn and Fawcett (2014) developed the excess heat factor (EHF), originally created for Australia. The EHF is a product of the number of degrees the mean temperature of the last 3 days exceeds the 95th percentile for a given location, and the difference in temperature between those 3 days and the preceding 30. Thus, warm conditions following relatively cool weather would yield the highest EHF. In several studies this has been shown to be an effective predictor of temperature-related human mortality (e.g., Hatvani-Kovacs et al., 2016; Sheridan & Dixon, 2017).

The EHF is defined to identify what could be termed absolute heat events, using a 95th percentile for year-round data, generally identifying events in the core of summer. This definition would likely not identify many early-season heat events, which, while extreme for the time of year, would not exceed the 95th percentile of the annual distribution. To this end, in this paper, we develop a relative extreme temperature metric to complement the absolute metric, based on Nairn and Fawcett's initial definition, and evaluate the EHF and an analogous excess cold factor (ECF), as well as a relative EHF (REHF) and ECF (RECF). Occurrences of these factors are then used to define events; we first present a climatology of EHEs, extreme cold events (ECE), relative extreme heat events (REHEs), and relative extreme cold events (RECEs) for North America, followed by an analysis of temporal trends from 1979 to 2016.

2. Data and Methods

2.1. Data and Calculation of Apparent Temperature

Three-hourly values of 2-m temperature, 2-m dew point, and 10-m wind speed (from *u*- and *v*-wind components) were obtained from the North American Regional Reanalysis (Mesinger et al., 2006) for all available land points over North America between 23°–84°N and 178°–46°W for the period 1979–2016.

For each 3-hourly period, an apparent temperature was then calculated based on the Steadman (1984) formula for outdoor shade conditions, where $AT = -2.7 + 1.04\,T + 2.0P - 0.65u$, where T and AT are in degrees Celsius, P is vapor pressure in kilopascals (calculated from dew point), and u is wind speed in meters per second. The Steadman AT was chosen over other apparent temperature metrics as it has typically been used in year-round analyses such as this study, where a standard single metric is needed across multiple seasons. Daily mean apparent temperature (AT) was then calculated based on the average of the eight 3-hourly values.

2.2. Calculation of Extreme Events

The extreme events in this paper are all based on the initial definition of EHF (Nairn & Fawcett, 2014), with the exception that apparent temperature is used instead of temperature. EHF is calculated as a product of the magnitude of the heat event, and an acclimatization term. First, excess heat (EH) is calculated:

$$EH = \left(\Sigma_{i=1}^{3} AT_i\right)/3 - AT95,$$

where AT_i is the apparent temperature on day i, averaged over a 3-day period, and AT_{95} is the overall 95th percentile of apparent temperature for a particular location (based on the 1981–2010 normal period). If the 3-day mean apparent temperature is not above the 95th percentile, there is no excess heat.

The acclimatization term is defined as follows:

$$EHaccl = \left(\Sigma_{i=1}^{3} AT_i\right)/3 - \left(\Sigma_{i=-30}^{0} AT_i\right)/30,$$

the difference between the 3-day mean apparent temperature and the 30 days prior.

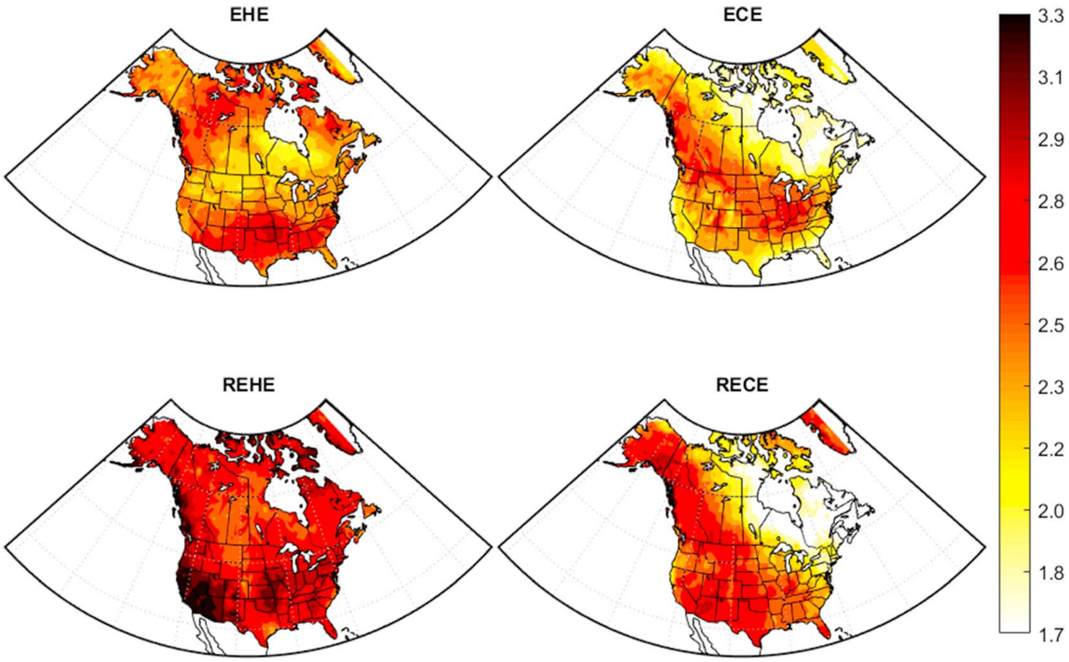


Figure 1. Mean number of extreme temperature events in days per year. EHE = excess heat event; ECE = excess cold event; REHE = relative excess heat event; RECE = relative excess cold event.

EHF then is defined as

$$EHF = \max(0, \ EH) \text{x} \max(1, \ EHaccl),$$

in units of Kelvins squared. The magnitude of *EHF* varies substantially from place to place, being larger in locations with greater climate variability. Hence, in the definition of a heat event, using the Nairn and Fawcett (2014) definition, an extreme heat *event* day is identified when the *EHF* exceeds the 85th percentile of all positive *EHF* values for a location over the climatological period.

ECFs and ECEs are defined similarly except with the 5th percentile (AT_5) instead of the 95th percentile (and the 15th percentile threshold for ECE days):

$$EC = \left(\sum_{i=1}^{3} AT_i\right)/3 \ - \ AT_5,$$

and *ECF* is defined as follows:$ECF = -1 \times \min(0, EC) \times \min(-1, EC_{\text{accl}})$.

EHF and ECF, by virtue of their use of percentiles defined over the entire year, have their highest values in the core of summer and winter, respectively. However, one may also define ETEs relative to time of year. Thus, two additional values are calculated for each location: the REHF and RECF. Conceptually, these are similar to the EHF and ECF above, except that for each day of the year, the threshold is calculated as the 92.5th (REHF)/7.5th (RECF) percentile over the climatological period for the 15 days centered on the day being evaluated. It is noted that in using the 92.5th and 7.5th percentiles, approximately the same number of events occur for the relative events as the absolute events.

Annual totals of EHE and REHE are based on the calendar year; for ECE and RECE, a year runs from July to the following June. Trends in the annual counts of these variables were calculated for each grid point, using bootstrapped estimates of the Thiel-Sen slope estimator, a nonparametric test that accounts well for outliers and the nonnormal distribution of ETE frequencies (Perkins & Alexander, 2013). Statistical significance is determined when the 95% confidence intervals of the bootstrapped slopes do not cross 0.

In order to quantify spatial variability in the results, a regionalization was performed upon the 37 year-over-year counts of EHE, REHE, ECE, and RECE days at each grid point. These 148 variables were then subjected to a principal components analysis, and all principal component scores with eigenvalues >1 were retained for a

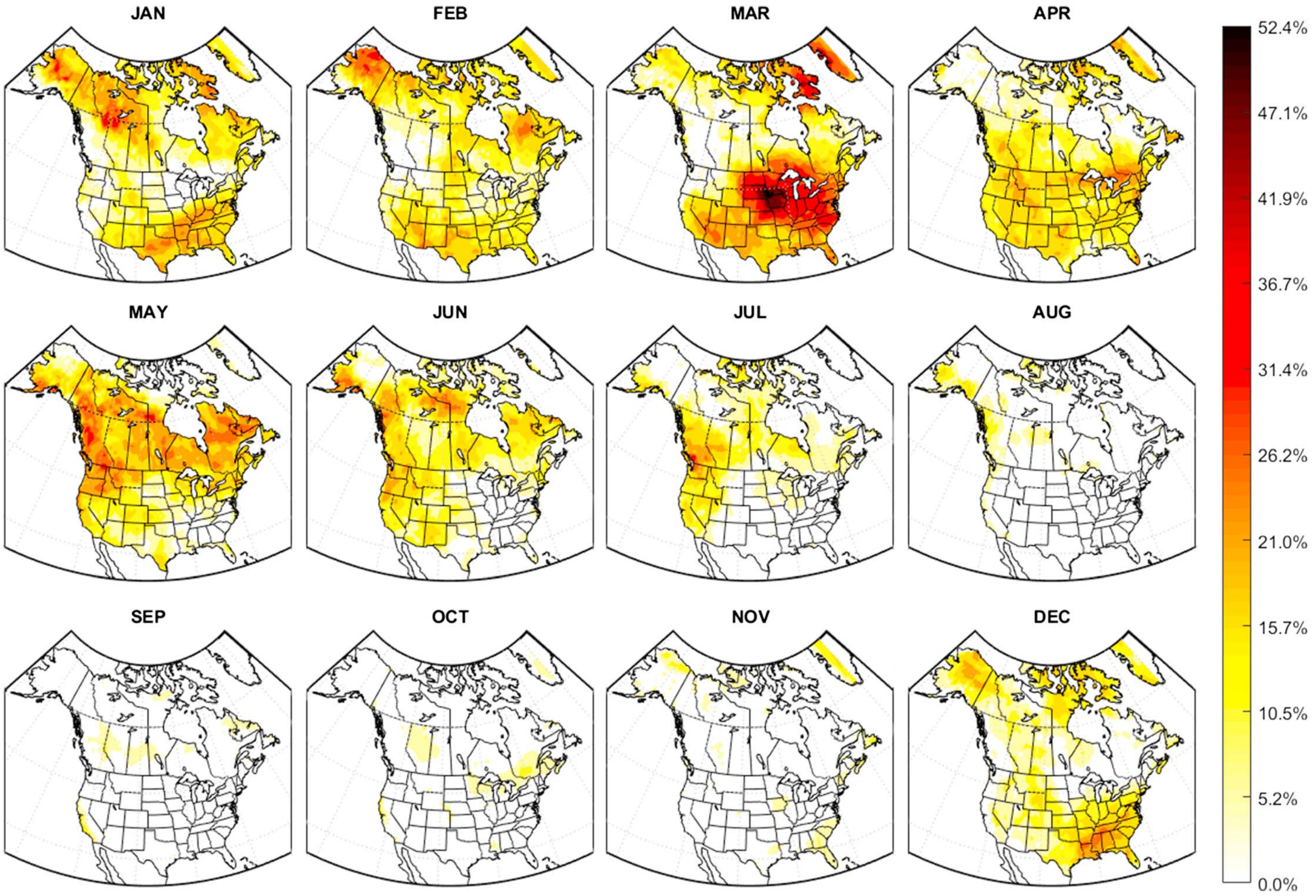


Figure 2. Mean frequency of relative extreme heat event (REHE) days by month.

subsequent *k*-means cluster analysis. This process resulted in each grid point being categorized into one of 12 regions. Multiple numbers of regions (between $k = 5$ and $k = 15$) were examined, and ultimately 12 were chosen based upon qualitative assessment as well as 12 regions having the best variability skill score (Lee, 2014). These statistically derived regions were then used to inform a customized drawing of the final regions in ArcMap.

3. Results

3.1. Climatology

The spatial patterns of the annual climatological means of the ETE variables are shown in Figure 1. Similar to Australia (Nairn & Fawcett, 2014), much of the continent experiences at least 2 days/year in which EHE criteria are met, with a continental mean of 2.4 days/year. Maximum mean frequencies are in the southern U.S. Plains with approximately 3 days/year, decreasing to roughly 2.5 days/year in the Rockies and parts of the southeastern United States, with the fewest along the southern coast of Hudson Bay (2 days/year). The seasonality of EHE (supporting information Figure S1) is broadly similar throughout the country, with a sharp peak in July, during which approximately 55% of all EHE occur in the study area, with some locations in the western United States experiencing over 90% of their EHE days; most of the remainder are in June and August. The only departures from this pattern are in northwestern Canada, Alaska, and western Texas, where some locations have June peaks, while eastern Texas and other parts of the Gulf coast states have August peaks, and in parts of coastal California EHEs last into September.

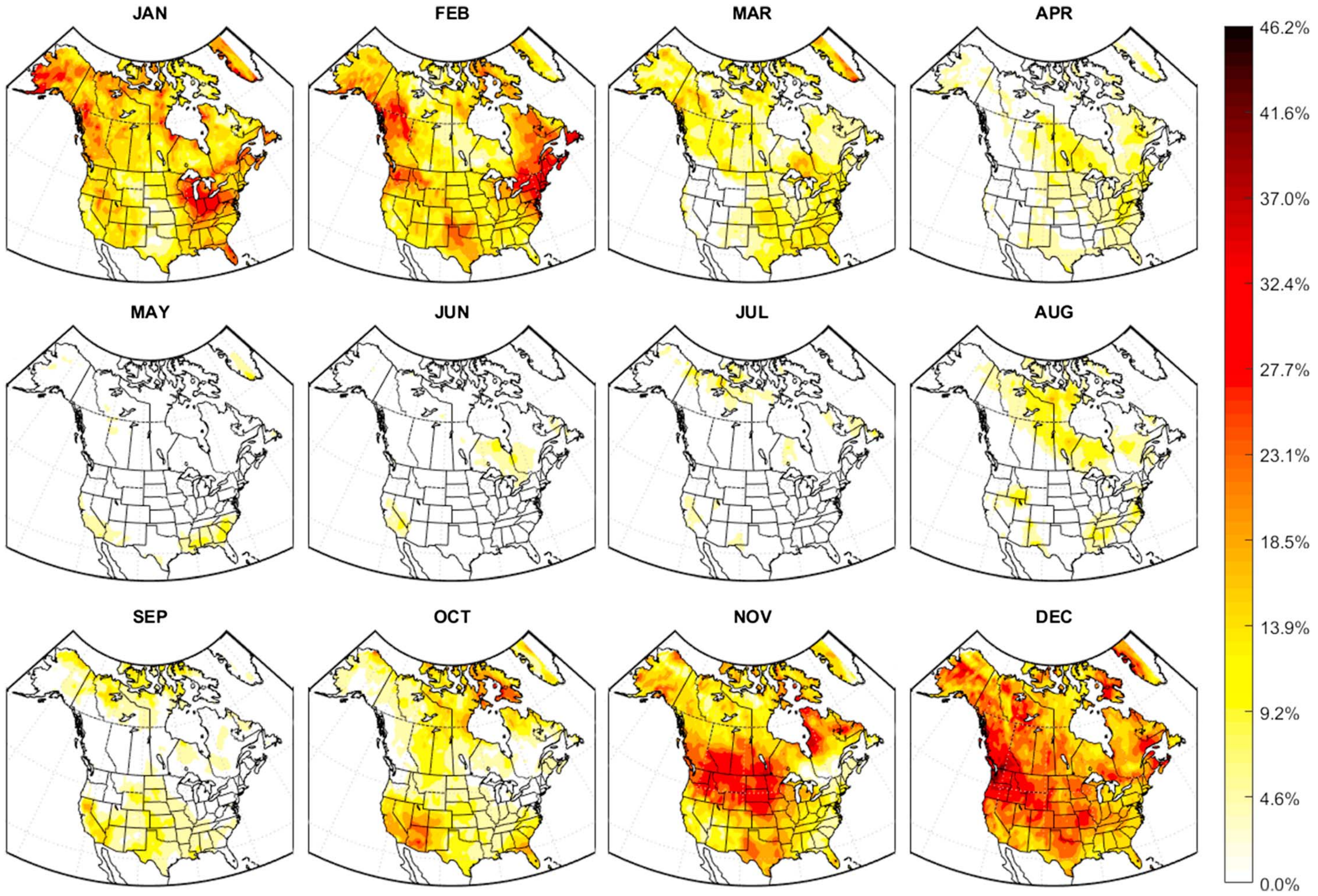
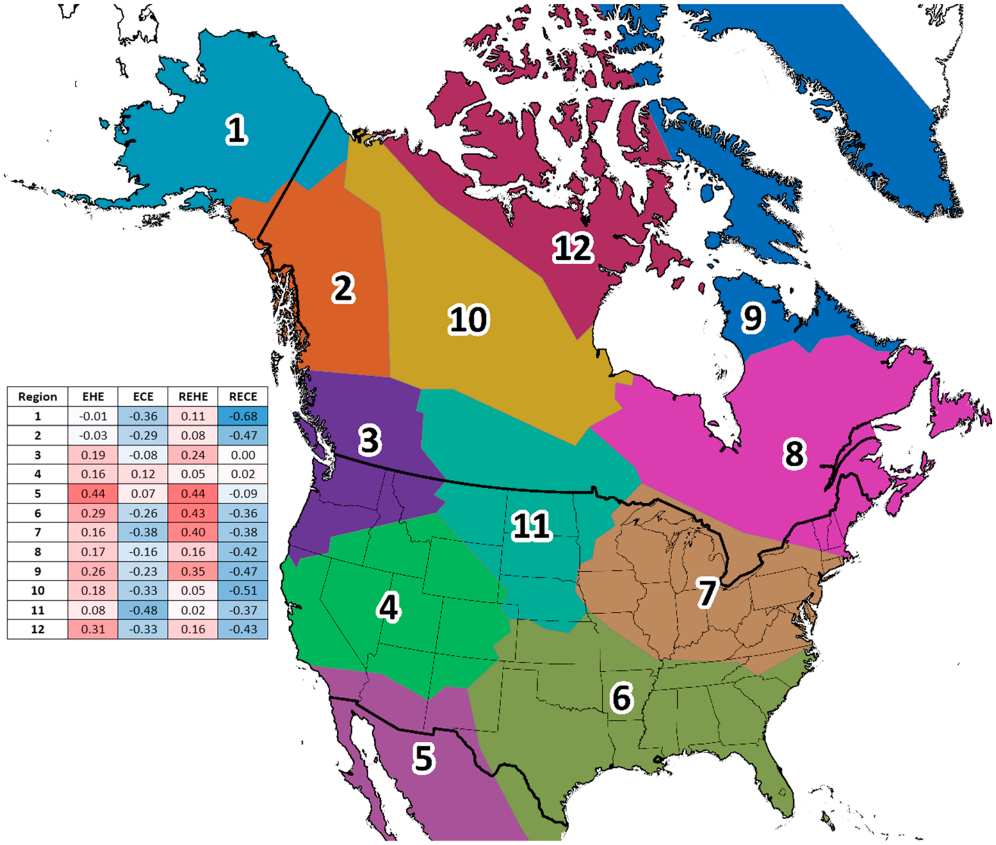


Figure 3. Mean frequency of relative extreme cold event (RECE) days by month.

Mean ECE frequencies overall are slightly lower than EHE, averaging 2.2 days/year across the United States and Canada. The highest frequencies, around 2.5 days/year or higher, are located in an arc from the Canadian Rockies to the Appalachians, with lowest values found in a swath from northern Alaska, across Hudson Bay, and through the Maritimes of Canada, where some locations average <2 days/year. Over 44% of all ECE occur in January (Figure S2), the peak month for many locations in the eastern third of the United States and the eastern half of Canada. Across the western two thirds of the United States a broader seasonality is noted, with this region experiencing the greatest number of ECE in December. Peak ECE frequency at several Arctic locations occurs in February.

More complex spatiotemporal patterns emerge with the relative variables REHE and RECE. For REHE, the annual mean number of events is 2.8 days/year, with peaks occurring in the desert Southwest and along the Pacific coast, as well as a broad swath of the midwestern United States. Relative minima are found in the lee of the northern Rockies as well as some maritime locations. In contrast to the absolute events (EHE), the majority of relative heat events (REHE; Figure 2) occur outside summer, with a mean frequency across the United States and Canada peaking in March, and continent-wide mean frequencies above 12% from January to May. In addition to the broader peak, seasonality varies much more spatially than with EHE. In the eastern half of the continent, peak REHE activity migrates north as winter and spring progress. There is an initial peak along the Gulf Coast and areas of the southeastern United States in December and January, which migrates north to the midwestern United States in March and southern Ontario and Quebec in April, before spreading westward across Canada in May. The spatial pattern is more varied across the west, with a later start to the REHE season; activity centers on the Sonoran Desert and California in March,



Region	EHE	ECE	REHE	RECE
1	-0.01	-0.36	0.11	-0.68
2	-0.03	-0.29	0.08	-0.47
3	0.19	-0.08	0.24	0.00
4	0.16	0.12	0.05	0.02
5	0.44	0.07	0.44	-0.09
6	0.29	-0.26	0.43	-0.36
7	0.16	-0.38	0.40	-0.38
8	0.17	-0.16	0.16	-0.42
9	0.26	-0.23	0.35	-0.47
10	0.18	-0.33	0.05	-0.51
11	0.08	-0.48	0.02	-0.37
12	0.31	-0.33	0.16	-0.43

Figure 4. Regionalization of stations and regionally averaged trends in days per decade for each ETE variable. EHE = excess heat event; ECE = excess cold event; REHE = relative excess heat event; RECE = relative excess cold event; ETE = extreme temperature event.

migrating to the Pacific coast for May and June, and declining in extent to encompass mostly around Puget Sound in July. REHEs become very infrequent in late summer through autumn, before reemerging in December across the southeastern United States.

While the seasonality of REHE is broader than EHE, RECE and ECE have more similar seasonalities, with nearly 65% of all RECE days between November and February (Figure 3). The spatiotemporal pattern generally has two main features, the peak time of occurrence and the length of season. Initial peak frequency of RECE in November stretches across southwestern Canada and the northwestern United States, before spreading considerably throughout the continent in December (the peak month of occurrence at 19.5%). By January and February RECEs become more isolated to specific regions, like the Great Lakes (in January) and coastal pockets (in February). A broader season extends across much of the Arctic, where September, October, and March RECE days are not uncommon, and parts of the Desert Southwest, where October is the peak month.

3.2. Trends

For EHE, there is an increase across the United States and Canada as a whole (Figures 4 and 5), averaging to +0.19 day/decade, with about 79% of locations showing an upward trend. This trend is greatest across the southern United States—especially in the Ozarks and southern Arizona—and extreme northern Quebec, where trends exceed 1 day/decade. Year-to-year changes (Figure S3) show some of these regions (e.g., region 9) with steady upward trends, with others (regions 5 and 6, along the southern extreme of the study region) depicting an extended period of greater EHE since 2010. In some cases, there is considerable interannual variability with several extreme outliers, such as 2004 in regions 1 and 2, coinciding with several all-time record high temperatures in British Columbia and Yukon, and the drought of 1988 across the eastern United States (region 7).

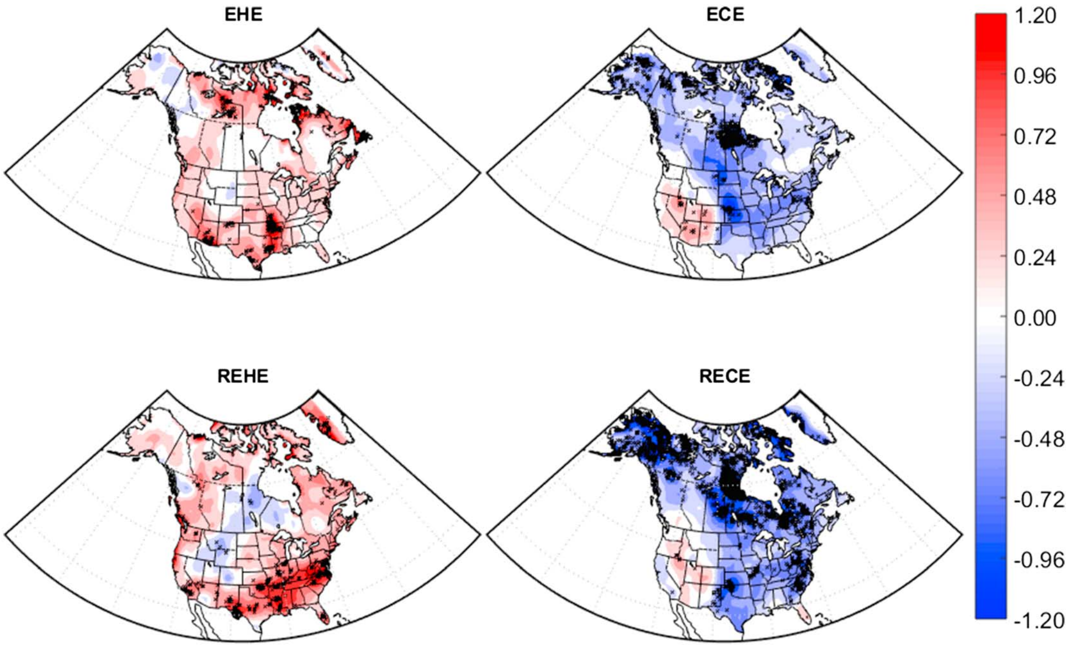


Figure 5. Trends in extreme temperature events in days per decade, 1980–2016. Shaded areas indicate grid cells in which the trend is statistically significant ($p < 0.05$). EHE = excess heat event; ECE = excess cold event; REHE = relative excess heat event; RECE = relative excess cold event.

In contrast, ECEs have decreased overall across the study region (in 86% of locations) and to a greater extent than the increase in EHE (−0.23 day/decade). This ECE decrease is most pronounced over northern Manitoba southward to the High Plains, as well as parts of the Canadian archipelago, where trends approach −0.88 day/decade. Most of the years with the greatest number of ECEs are in the earlier part of the record (Figure S4), and, when averaged across the continent, the top eight ECE years all occurred prior to the 1997–1998 winter. Across northern Canada and Alaska (regions 1, 9, 10, and 12) there are substantive declines in the era of Arctic amplification to where ECEs have largely disappeared most years since 2003. In other regions, there have been fewer years with substantial numbers of cold outbreaks than in previous decades, although in some cases very substantial ECE occurrences have also been noted more recently, such as the cold winters of 2012–2013 and 2013–2014 across the northeastern United States (region 7). In cases where downward trends are largely absent (such as the Pacific regions of 3, 4, and 5), there have been several substantial cold events in recent years at similar frequency to the earlier parts of the record.

REHEs have also increased significantly across much of the continent (77% of locations have positive slopes) and at a greater rate than EHE (+0.22 day/decade), with trends of 0.8–1 day/decade over most of the southern United States, much larger than with EHE. Interannual variability (Figure S5) is greater with REHE than with EHE, and the upward trend in some regions is affected by an increase in outlier years. Due to the greater seasonality of REHE, outlier years manifest themselves at different times. The single most substantial REHE event is associated with the anomalously hot month of March 2012 in the eastern and midwestern United States (regions 6, 7, and 11), while other extreme years were associated with early thaws in mild winters, such as February 2010 throughout much of eastern Canada (regions 8, 9, and 12), midwinter thaws in 2013–2014 in Alaska (region 1), and anomalous warmups in early winter, such as Decembers 2015 and 2016 in parts of the southern United States (regions 5 and 6).

By virtue of their overlapping seasonalities, RECEs show broadly similar patterns to ECEs, since many extreme events get classified as both. This said, RECEs overall have decreased in frequency at a greater rate than the ECE over the United States and Canada (−0.36 day/decade), with over 88% of locations showing a decreasing trend. The largest changes are seen in Alaska and Northern Canada, along with patches along the U.S. Atlantic coast, all of which have trends approaching −1.0 day/decade. Interannually (Figure S6), several different patterns emerge. Areas very heavily influenced by the Arctic (regions 1, 9, and 12) show a substantial decline since the early 2000s, where, similar to ECEs, RECEs have become rare. Where divergence between RECE and ECE have manifested, these typically arise as early cold snaps, such as November 1985 in regions 3 and 11. Across most of the rest of the United States and Canada, years with substantial RECEs have become fewer with further between, yet still occur. The best example of this can be seen in region 7, where, for example, in 2014–2015 a large early season cold air outbreak in November 2014 preceded the ECEs later on in the core of winter.

4. Discussion and Conclusions

The trends in EHEs and ECEs are similar to other published research on trends of ETEs. For instance, the peak area of EHE increase along the southern Mississippi Delta is similar to what has been observed in some of the metrics evaluated in Smith et al. (2013). The increase in northern Canada is similar to the results shown by Perkins et al. (2012) using the EHF; while they do not show a similar increase in the southern United States, the fact that this present study incorporates humidity may explain the difference, as high dew points have increased in frequency in recent years (Brown & DeGaetano, 2013; Sandstrom et al., 2004). Trends in ECE have been less well studied in the literature, but the broad decline does mirror other studies in examining coldest temperatures or general trends (e.g., Deser et al., 2016; Vincent & Mekis, 2006), though not necessarily cold outbreaks (Cohen et al., 2018). Specific extreme years are generally in alignment, though the magnitude of some years in our study varies from others; most particularly the summer of 1980 does not stand out as much as it does in other work (e.g., Russo et al., 2014), possibly due to lower dew points.

In contrast, there is little in the way of systematic study of relative ETE in the literature, despite their potential importance. These events are harder to classify since REHEs and RECEs occur through a greater portion of the year. Trends for these relative events are more pronounced than the absolute events in a number of regions in North America. Increases in REHE are greatest across the eastern half of the United States, in an area where they climatologically occur from midwinter into early spring. A number of substantial REHE have occurred in recent years to influence this trend. Most notable is the highly anomalous warm event in March 2012 (Grumm et al., 2014; Karl et al., 2012), which included persistent midsummer warmth in a number of locations and had many phenological repercussions by producing a *false spring* in which vegetation prematurely left dormancy and was subsequently negatively affected by subsequent frosts, leading to large agricultural losses in certain areas (Ault et al., 2013). With earlier starts to spring, these false spring *phenological mismatches* may substantially negatively affect a number of ecological systems moving forward (Allstadt et al., 2015).

RECE results show more interesting patterns, with an overall decrease except for Florida and the U.S. Great Basin. In some areas, these changes have been roughly linear, while in areas heavily influenced by the Arctic there is a significant drop in cold events associated with the period of Arctic amplification (Screen & Simmonds, 2010). While cold events are in decline, substantial ECE and RECE still occur, as some of the most extreme winters have been in the last few years of the study. Research suggests that with Arctic amplification, midlatitude weather may see an increase in extreme weather (Cohen et al., 2014), including cold extremes (Kug et al., 2015), which aligns with the observations of this study, particularly across the northeastern and midwestern United States.

We have conducted some preliminary comparisons between station observations from several airports and the nearest North American Regional Reanalysis data point. In cases with relatively homogeneous terrain (e.g., Columbus, OH), approximately 74% of events matched between the two data sets, and all trend lines were only negligibly different. In other examples, similarity was much weaker, including coastal stations (Astoria, OR, and Miami, FL) and a station with a substantial heat island influence (Phoenix, AZ). Further, at most stations we explored, cold events were in greater alignment than heat events. As this current study is based on reanalysis data alone, while it may represent anomalies and events at a regional level relatively well, there needs to be further assessment of how well extreme events are modeled at the station level. In particular, as many environmental system impacts will respond to local surface conditions, understanding model (e.g., reanalysis) ability to simulate observed extreme events is a planned avenue for future investigation.

Beyond model ability, there are other directions for this research moving forward. While there is ample evidence of the impact of EHE and ECE, there is less research assessing the impacts of REHE and RECE, aside from some notable events such as the March 2012 event (Grumm et al., 2014). As relative events are increasing at a pace slightly more quickly than absolute events, systematically understanding their prospective influence on humans and the environment is critical for understanding possible changes in these systems moving forward.

Acknowledgments

This research was supported by federal award NA17OAR4310159, entitled "Developing extreme event climate change indicators related to human thermal comfort" from the National Oceanic and Atmospheric Administration's Climate Program Office. The data sets used in this research are available on the lead-author's research page (http://sheridan.geog.kent.edu/research.html).

References

Allstadt, A. J., Vavrus, S. J., Heglund, P. J., Pidgeon, A. M., Thogmartin, W. E., & Radeloff, V. C. (2015). Spring plant phenology and false springs in the conterminous US during the 21st century. *Environmental Research Letters*, *10*(10), 104008. https://doi.org/10.1088/1748-9326/10/10/104008

Anderson, B. G., & Bell, M. L. (2010). Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental Health Perspectives*, *119*(2), 210–218. https://doi.org/10.1289/ehp.1002313

Ault, T. R., Henebry, G. M., De Beurs, K. M., Schwartz, M. D., Betancourt, J. L., & Moore, D. (2013). The false spring of 2012, earliest in North American record. *Eos, Transactions American Geophysical Union*, *94*(20), 181–182. https://doi.org/10.1002/2013EO200001

Banerjee, A., Polvani, L. M., & Fyfe, J. C. (2017). The United States "warming hole": Quantifying the forced aerosol response given large internal variability. *Geophysical Research Letters*, *44*, 1928–1937. https://doi.org/10.1002/2016GL071567

Brown, P. J., & DeGaetano, A. T. (2013). Trends in US surface humidity, 1930–2010. *Journal of Applied Meteorology and Climatology*, *52*(1), 147–163. https://doi.org/10.1175/JAMC-D-12-035.1

Cohen, J., Pfeiffer, K., & Francis, J. A. (2018). Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, *9*(1), 869. https://doi.org/10.1038/s41467-018-02992-9

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., et al. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, *7*(9), 627–637. https://doi.org/10.1038/ngeo2234

Deser, C., Terray, L., & Phillips, A. S. (2016). Forced and internal components of winter air temperature trends over North America during the past 50 years: Mechanisms and implications. *Journal of Climate*, *29*(6), 2237–2258. https://doi.org/10.1175/JCLI-D-15-0304.1

Ebi, K. L., Hasegawa, T., Hayes, K., Monaghan, A., Paz, S., & Berry, P. (2018). Health risks of warming of 1.5° C, 2° C, and higher, above pre-industrial temperatures. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326

Grumm, R., Arnott, J. M., & Halblaub, J. (2014). The epic eastern North American warm episode of March 2012. *Journal of Operational Meteorology*, *2*(4), 36–50. https://doi.org/10.15191/nwajom.2014.0204

Hajat, S., & Kosatsky, T. (2010). Heat-related mortality: A review and exploration of heterogeneity. *Journal of Epidemiology & Community Health*, *64*(9), 753–760. https://doi.org/10.1136/jech.2009.087999

Hatvani-Kovacs, G., Belusko, M., Pockett, J., & Boland, J. (2016). Can the excess heat factor indicate heatwave-related morbidity? A case study in Adelaide, South Australia. *EcoHealth*, *13*(1), 100–110. https://doi.org/10.1007/s10393-015-1085-5

Karl, T. R., Gleason, B. E., Menne, M. J., McMahon, J. R., Heim, R. R., Brewer, M. J., et al. (2012). US temperature and drought: Recent anomalies and trends. *Eos, Transactions American Geophysical Union*, *93*(47), 473–474. https://doi.org/10.1029/2012EO470001

Kug, J. S., Jeong, J. H., Jang, Y. S., Kim, B. M., Folland, C. K., Min, S. K., & Son, S. W. (2015). Two distinct influences of Arctic warming on cold winters over North America and East Asia. *Nature Geoscience*, *8*(10), 759–762. https://doi.org/10.1038/ngeo2517

Lee, C. C. (2014). The development of a gridded weather typing classification scheme. *International Journal of Climatology*, *35*(5), 641–659. https://doi.org/10.1002/joc.4010

Ma, G., Rudolf, V. H., & Ma, C. S. (2015). Extreme temperature events alter demographic rates, relative fitness, and community structure. *Global Change Biology*, *21*(5), 1794–1808. https://doi.org/10.1111/gcb.12654

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., Jović, D., et al. (2006). North American regional reanalysis. *Bulletin of the American Meteorological Society*, *87*(3), 343–360. https://doi.org/10.1175/BAMS-87-3-343

Nairn, J. R., & Fawcett, R. J. (2014). The excess heat factor: A metric for heatwave intensity and its use in classifying heatwave severity. *International Journal of Environmental Research and Public Health*, *12*(1), 227–253. https://doi.org/10.3390/ijerph120100227

Ng, C. F. S., Ueda, K., Ono, M., Nitta, H., & Takami, A. (2014). Characterizing the effect of summer temperature on heatstroke-related emergency ambulance dispatches in the Kanto area of Japan. *International Journal of Biometeorology*, *58*(5), 941–948. https://doi.org/10.1007/s00484-013-0677-4

Perkins, S. E., & Alexander, L. V. (2013). On the measurement of heat waves. *Journal of Climate*, *26*(13), 4500–4517. https://doi.org/10.1175/JCLI-D-12-00383.1

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, *39*, L20714. https://doi.org/10.1029/2012GL053361

Rahmstorf, S., Foster, G., & Cahill, N. (2017). Global temperature evolution: Recent trends and some pitfalls. *Environmental Research Letters*, *12*(5), 054001. https://doi.org/10.1088/1748-9326/aa6825

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrao, H., Dunbar, M. B., Singleton, A., et al. (2014). Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research: Atmospheres*, *119*, 12,500–12,512. https://doi.org/10.1002/2014JD022098

Sandstrom, M. A., Lauritsen, R. G., & Changnon, D. (2004). A central-US summer extreme dew-point climatology (1949–2000). *Physical Geography*, *25*(3), 191–207. https://doi.org/10.2747/0272-3646.25.3.191

Santamouris, M., Cartalis, C., Synnefa, A., & Kolokotsa, D. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and Buildings*, *98*, 119–124. https://doi.org/10.1016/j.enbuild.2014.09.052

Screen, J. A., & Simmonds, I. (2010). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, *464*(7293), 1334–1337. https://doi.org/10.1038/nature09051

Sheridan, S. C., & Allen, M. J. (2015). Changes in the frequency and intensity of extreme temperature events and human health concerns. *Current Climate Change Reports*, *1*(3), 155–162. https://doi.org/10.1007/s40641-015-0017-3

Sheridan, S. C., & Dixon, P. G. (2017). Spatiotemporal trends in human vulnerability and adaptation to heat across the United States. *Anthropocene*, *20*, 61–73. https://doi.org/10.1016/j.ancene.2016.10.001

Smith, T. T., Zaitchik, B. F., & Gohlke, J. M. (2013). Heat waves in the United States: Definitions, patterns and trends. *Climatic Change*, *118*(3–4), 811–825. https://doi.org/10.1007/s10584-012-0659-2

Steadman, R. G. (1984). A universal scale of apparent temperature. *Journal of Climate and Applied Meteorology*, *23*(12), 1674–1687. https://doi.org/10.1175/1520-0450(1984)023<1674:AUSOAT>2.0.CO;2

Sutton, R., Suckling, E., & Hawkins, E. (2015). What does global mean temperature tell us about local climate? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *373*(2054), 20140426. https://doi.org/10.1098/rsta.2014.0426

Vasseur, D. A., DeLong, J. P., Gilbert, B., Greig, H. S., Harley, C. D. G., McCann, K. S., Savage, V., et al. (2014). Increased temperature variation poses a greater risk to species than climate warming. *Proceedings of the Royal Society of London B: Biological Sciences*, *281*(1779), 20132612. https://doi.org/10.1098/rspb.2013.2612

Vincent, L. A., & Mekis, E. (2006). Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmosphere-Ocean*, *44*(2), 177–193. https://doi.org/10.3137/ao.440205