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Global, Regional, and Megacity Trends in the Highest Temperature of the Year: Diagnostics and Evidence for Accelerating Trends

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Key Points:
- The highest temperature of the year increased faster than the mean annual temperature over the past 30 years
- Most megacities show accelerated warming and a large region in Eurasia shows alarming warming trends
- Exceedance probabilities of observed 50- and 30-year warming trends are, in most cases, highly unlikely under natural climate variability

Supporting Information:
- Supporting Information S1.
- Movie S1.

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Abstract Trends in short-lived high-temperature extremes record a different dimension of change than the extensively studied annual and seasonal mean daily temperatures. They also have important socioeconomic, environmental, and human health implications. Here, we present analysis of the highest temperature of the year for approximately 9000 stations globally, focusing on quantifying spatially explicit exceedance probabilities during the recent 50- and 30-year periods. A global increase of 0.19°C per decade during the past 50 years (through 2015) accelerated to 0.25°C per decade during the last 30 years, a faster increase than in the mean annual temperature. Strong positive 30-year trends are detected in large regions of Eurasia and Australia with rates higher than 0.60°C per decade. In cities with more than 5 million inhabitants, where most heat-related fatalities occur, the average change is 0.33°C per decade, while some east Asia cities, Paris, Moscow, and Houston have experienced changes higher than 0.60°C per decade.

Plain Language Summary Short-term heatwaves can cause substantial health, economic, and social impacts. They adversely affect animals and plants, and increase the risk of wildfire while inadequate air conditioning may cause human fatalities. Most short-term heatwaves are associated with a strong anticyclone, and often with dry conditions, but they are clearly exacerbated by global warming from human-induced climate change. Other effects, such as intensified urbanization can also add to the risks. This paper analyzes the observed highest temperatures that occur every year at nearly 9000 stations, and how they are changing over time and especially over the past 50 and 30 years. We find these short-term heatwaves to be increasing in most places, especially Eurasia and Australia, and also in megacities.

1. Introduction

High temperatures cause detrimental health, economic, and social impacts (Mazdiyasni et al., 2017). The European 2003 and the Russian 2010 heatwaves caused, respectively, almost 70,000 and 55,000 deaths (Barriopedro et al., 2011; Robine et al., 2008; Stott et al., 2004), while an average of 658 deaths were reported annually during 1999–2009 in the United States alone due to excessive heat (Kochanek et al., 2011). Extreme high temperatures cause human casualties in large cities (Anderson & Bell, 2009; Ellis & Nelson, 1978; Hondula et al., 2012; Poumadere et al., 2005; Son et al., 2012), although air conditioning may alleviate impacts (Bobb et al., 2014), and have profound effects on farms due to reduced crop productivity and adverse effects on animals, including mortality (Ciais et al., 2005; Fuquay, 1981). Temperature extremes stress infrastructure, transportation, water supply, and electricity demand (Smoyer-Tomic et al., 2003); severely affect ecosystems and forests (Allen et al., 2010), and increase wildfire activity (Westerling et al., 2006). The effects of single-day temperature extremes have been reported as comparable to the increase in morbidity and mortality risk from prolonged extremes (Anderson & Bell, 2009; Gasparrini & Armstrong, 2011; Oudin Åström et al., 2011, 2013). Heat strokes—the most lethal condition of hyperthermia—can be caused by exposure to high ambient environmental temperatures (Bouchama & Knochel, 2002). We note that although there is no single definition of a heatwave or temperature-related mortality (Barnett et al., 2010; Robinson, 2001), the U.S. National Weather Service (NWS) issues "excessive heat warnings" when the heat index (accounting also for humidity) exceeds 115°F (46.1°C) for any period of time.

The global annual-mean surface air temperature (GMST), based on land data only, increased by 0.21 and 0.20°C per decade, respectively, during the past 50 (1966–2015) and 30 years (1986–2015) (Hansen et al., 2010), while the combined land–ocean increase was 0.17°C per decade for both periods (see https://data.giss.nasa.gov/gistemp/). Also a 0.14°C per decade increase is reported for the mean daily maximum temperature (Vose et al., 2005) over 1950–2004. Yet these trends capture annual averages and do not reflect the heat stress caused by short-term high temperature peaks. To the extent that the probability density function does not change, changes in extremes will tend to follow those of the mean, but in general this is unlikely, as discussed below. The highest temperature of the year (HTY) as well as heatwaves (Robinson, 2001) are short-term phenomena, with the latter triggered mainly by regional high pressure weather patterns and potentially intensified by land–atmosphere feedbacks (Miralles et al., 2014). Heatwaves will likely become more frequent and longer-lasting in the future (Meehl & Tebaldi, 2004; Mora et al., 2017; Panda et al., 2017; Sun et al., 2017) owing to global warming (Rahmstorf & Coumou, 2011; Trenberth & Fasullo, 2012), and significant increases in the number of hot days and nights have already been reported in many urban areas (Mishra et al., 2015; Panda et al., 2017).

Previous global studies using gridded data (e.g., Alexander et al., 2006; Donat et al., 2013) have analyzed extreme temperatures as part of the 27 extreme indices proposed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI; http://www.climdex.org/indices.html); however, they do not focus specifically on the HTY. Other studies investigating extreme warm days attempted to partition the observed changes into anthropogenic and natural components (Christidis et al., 2011). While trends in hot extremes (and precipitation extremes) at local scales are often found not significant, when spatially aggregated, they differ markedly from those expected under natural variability (Fischer & Knutti, 2014). Additionally, it was shown that global warming increased the severity of the hottest month and day of the year (Diffenbaugh et al., 2017). Here we use ground-based observations to analyze and compare changes in HTY over the recent 50- and 30-year periods globally, regionally and in megacities. We further provide spatially explicit exceedance probabilities of the observed trends in order to quantify trends higher that those expected under natural climate variability.

2. Data and Methods

Daily maximum temperature records from the Global Historical Climatology Network (GHCN)-Daily database have been used to investigate changes (global, hemispheric, zonal and in megacities) in the HTY, that is, the hottest daytime of the year, over the most recent half-century (1966–2015) and 30 years (1986–2015). We analyzed 8848 stations from all over the globe, distilled down from a total of 16,831 stations by applying a rigorous protocol for data quality control (see Text S1 and Figure S1 in Supporting Information S1). Stations were not stratified as urban and nonurban because localized changes occurring due to urbanization (heat island effect) have minimal effect on averaged anomalies over large areas compared to natural variability and climate change (Peterson & Owen, 2005; Vose et al., 2005). Because increases in extreme high temperatures impose high risk for human societies irrespective of their causes, the contribution of urbanization should be included in assessments. Changes in the HTY are quantified by the fitted trends in °C per decade and have been interpreted as the average increase or decrease rate over the studied periods (we made no inference for the past or the future of these trends, because intrinsic natural variability may alter their rates [Deser et al., 2012, 2013; Trenberth, 2015]).

As in many other studies (Easterling et al., 1997; Jones et al., 2012; Jones & Moberg, 2003; Vose et al., 2005), changes in the anomaly time series have been investigated to reduce station-to-station variability, especially over large areas, and render trend estimation and regional comparisons more accurate. The HTY anomaly time series were estimated in $5° \times 5°$ cells and in geographical zones according to the following steps: (1) for every HTY record the mean value from the 20-year baseline period (1970–1989) was calculated and subtracted from every HTY value; (2) the globe was divided in geographical cells of $5° \times 5°$ and the mean anomaly time series was estimated in each cell by averaging all available time series within it; (3) global, hemispheric, or zonal anomaly time series were estimated by averaging the corresponding cell time series weighted by the area of each cell (similar to other studies [Easterling et al., 1997; Vose et al., 2005]

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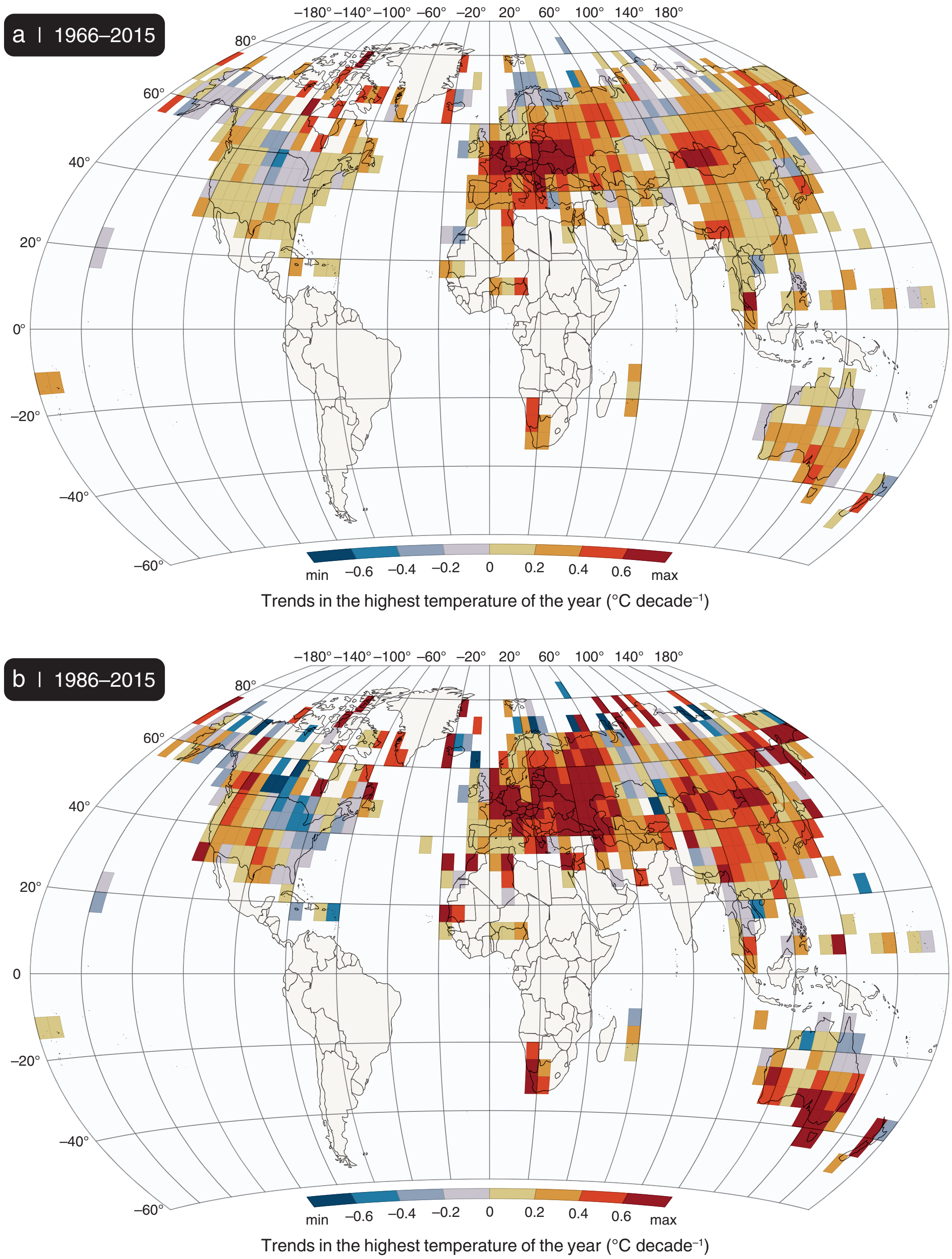

Figure 1. Observed temperature trends in °C per decade in the HTY. Results are shown in 5°×5° grid boxes (baseline period: 1970–1989) and for the 50 years (a) and 30 years (b) ending in 2015.

that provide global or zonal mean anomaly time series); and (4) long-term changes in geographical zones were assessed by estimating trends in the most recent 50 and 30 years. Note that trends were estimated only in cells having at least five values per decade during the 1966–2015 and 1986–2015 periods, a quality control fulfilled by 487 and 498 cells for the two periods, respectively (Figure 1).

To investigate changes in HTY in large cities we used absolute temperature values instead of anomaly values. This is because most cities have one station (see Table S1 in Supporting Information S1) or the few stations within a 30-km radius from the city center are climatically homogeneous. Similar to the method previously described, daily maximum temperature records have been used to extract the HTY values and to calculate the 50- and 30-year trends in cities that have at least five reliable values in each decade from 1966–2015 to 1986–2015. Finally, in cities where more stations are available, the mean trend was estimated by averaging the individual trends of each station. Table S1 in Supporting Information S1 provides detailed results for the cities studied (ranked by population size), the number of stations within a 30-km radius from the city center, and the estimated trends and their statistical significance for the afore-mentioned periods.

We evaluated the statistical significance of the observed trends (either in large zones, in grid cells, or in cities) by calculating the exceedance probability of the observed slope (rate of temperature change) based on Monte Carlo simulations. The null hypothesis is that there is no trend and thus the process can be assumed stationary. For each 50- and 30-year time series in zones, grid cells, or cities: (1) we estimated the sample lag-1 autocorrelation $\hat{\rho}_1$, the mean $\hat{\mu}$ and the standard deviation $\hat{\sigma}$, (2) 5000 samples were generated from an autoregressive model AR1 preserving the estimated characteristics, (3) a linear regression line was fitted in each random sample and the corresponding slope estimated, (4) a normal distribution was fitted to the 5000 estimated slopes, and (5) the exceedance probability $\overline{\mathrm{Pr}}$ of the observed slope was calculated using the fitted normal distribution. For maximum precision in the test, we took into account missing values (i.e., some of the 50- and 30-year time series have some years missing). In these cases, from the generated times series, we deleted the corresponding years with missing values before computing the statistics. The results for zonal and cities' trends are given, respectively, in Tables S1 and S2 in Supporting Information S1. Note that a number of tests have been applied and the results are robust to assumptions about the probabilistic and correlation structure of the analyzed series (see Text S1 and Figure S2 in Supporting Information S1).

Finally, we note that the estimated exceedance probability $\overline{\mathrm{Pr}}$ indicates the level at which the null hypothesis can be rejected, for example, the exceedance probability of the observed global trend is 0.2% (see Table S2) and thus this trend is highly unlikely to be observed under the stationarity assumption. It is also emphasized that larger exceedance probabilities (e.g., >10%) than those commonly used to assess statistical significance for a region or city do not necessarily indicate the absence of a causative trend.

3. Regional Changes

The spatiotemporal variation of the HTY anomaly in 5° × 5° cells is presented in a series of 50 annual maps starting in 1966 (see Movie S1). Well-known heatwaves, which caused thousands of fatalities, coincide with the positive HTY anomalies, providing evidence that temperature changes in the HTY offer also valuable information on heatwaves. Some characteristic heatwaves displayed in the corresponding annual maps of the HTY anomalies include the following: European (2003 and 2007), Russian (2010), UK (1976), United States (1980 and 1988), and Greek (1987) heatwaves, among others.

The 50-year trends (Figure 1a) show that approximately 80% of the land area studied has positive trends in the HTY, and 49.3% of the area has values greater than 0.20°C per decade (i.e., the GMST value), while spatial patterns reveal large differences between regions. Two major regions have experienced high rates of change during the past half century: the first and most intense starts at the Mediterranean Sea, extends diagonally covering Europe and ends to the west and north-west regions of Russia. The second region starts from Nepal and north Myanmar, extends to central China and Mongolia and covers east Russia. A large region between these two "hot" zones shows mild decreasing trends, starting from central-north Kazakhstan to central Russia. Large regions show trends in excess of 0.20°C per decade, including south Australia and most of its east coast, a large part of Japan, and South Africa and Namibia (note that data coverage in Africa is limited).

All available cells in a large area in the northernmost territory of Canada, known as Nunavut, have positive trends, with some indicating high increasing rates of more than 0.60°C per decade. Modest positive trends in HTY occur over most of the United States (typically less than 0.20°C per decade), and slightly decreasing trends occur in parts of the Midwest and south Canada. Other regions that exhibit slightly decreasing trends in the HTY include Alaska, parts of northern Norway, Sweden and Finland, as well as parts of north-east Australia.

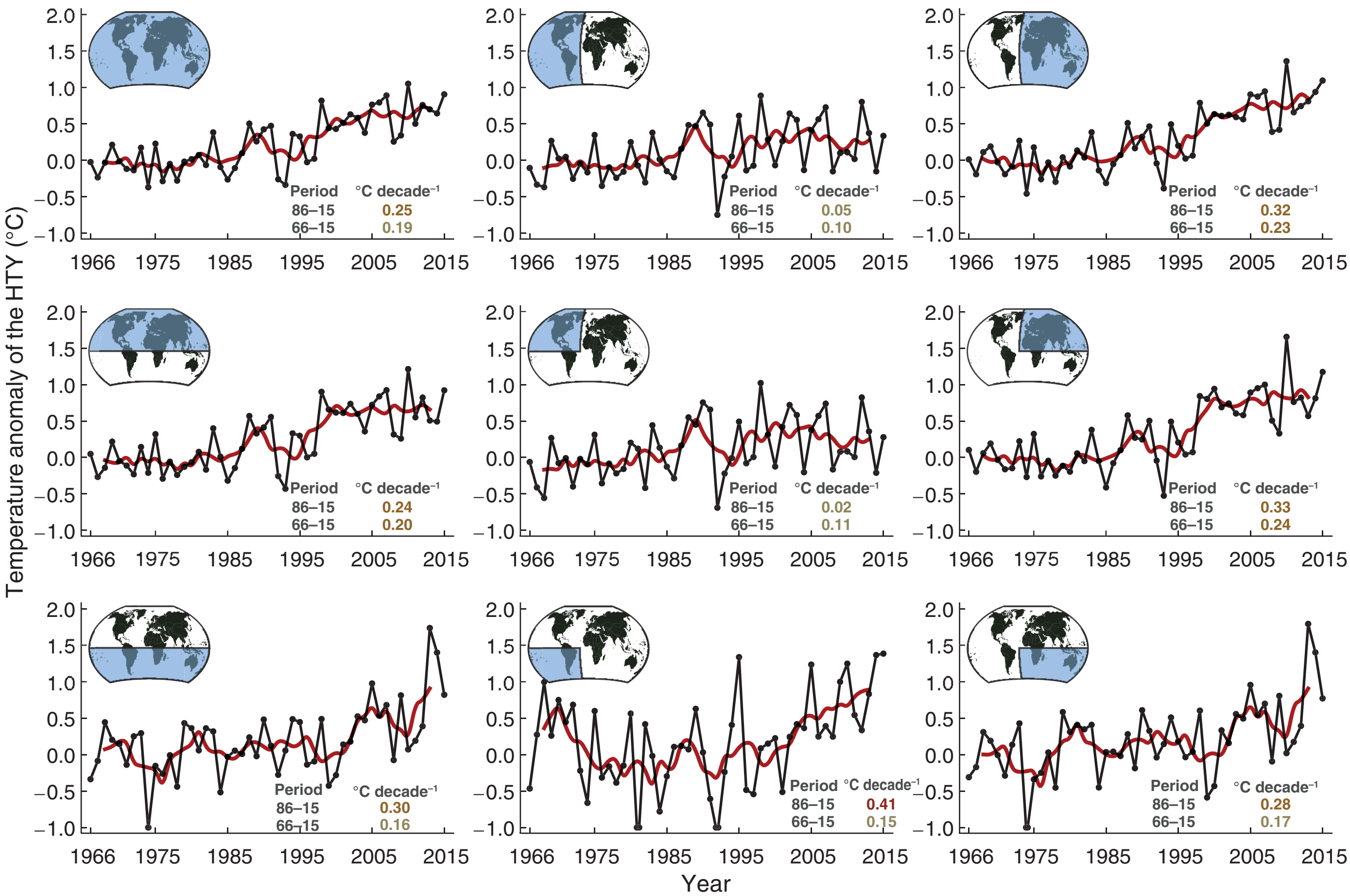

Figure 2. Temperature anomaly (baseline period: 1970–1989) of the HTY over 1966–2015 in major geographical zones. The red line indicates the 5-year moving average; the estimated 1966–2015 and 1986–2015 trends (°C per decade) are shown in boxes.

The spatial patterns of temperature trends during 1986–2015 (Figure 1b), are similar to those during 1966–2015, yet an acceleration of positive temperature trends is apparent in most cells. The overall percentage of cells with positive trends in the most recent three decades is 3% smaller than in the past five decades, yet 50% of the cells have trends higher than 0.27°C per decade and 59% higher than 0.19°C (the GMST of this period), while 60% of cells have more intense 30-year trends compared to the 50-year trends (Figure 1). Of the cells with high 50-year trends (larger than 0.30°C per decade), a further acceleration over the last 30 years occurs in 92%, especially in parts of Europe and in the west and north-west of Russia, with values larger than 0.60°C per decade. The statistical significance of the estimated 50- and 30-year trends is assessed by computing their exceedance probabilities based on Monte Carlo simulations (see Figure S3).

4. Global, Hemispheric and Zonal Changes

The temperature anomalies of the HTY in major geographical zones (Figure 2) show a 50-year average trend of 0.19°C per decade globally, while the corresponding Northern and Southern Hemispheres trends are 0.20 and 0.16°C per decade, respectively. Figure 2 shows that the observed rate of change in HTY (0.25°C per decade) in the past 30 years over the globe has been faster than the change in mean annual temperature over the same period (~0.20°C per decade). Most of these trends are significant at the 1% level—see Table S2. Different increasing rates are observed between the Western (west of the Atlantic Ocean, i.e., North and South America) and the Eastern (east of the Atlantic Ocean, i.e., Eurasia, Africa, Australia) Hemispheres having trends of 0.10 and 0.23°C per decade, respectively. This difference is more apparent over the last 30 years where the Western-Hemisphere trend decreased at 0.05°C per decade and the Eastern-Hemisphere accelerated at 0.32°C per decade. It may be tempting to interpret the slow, positive 30-year trend in the

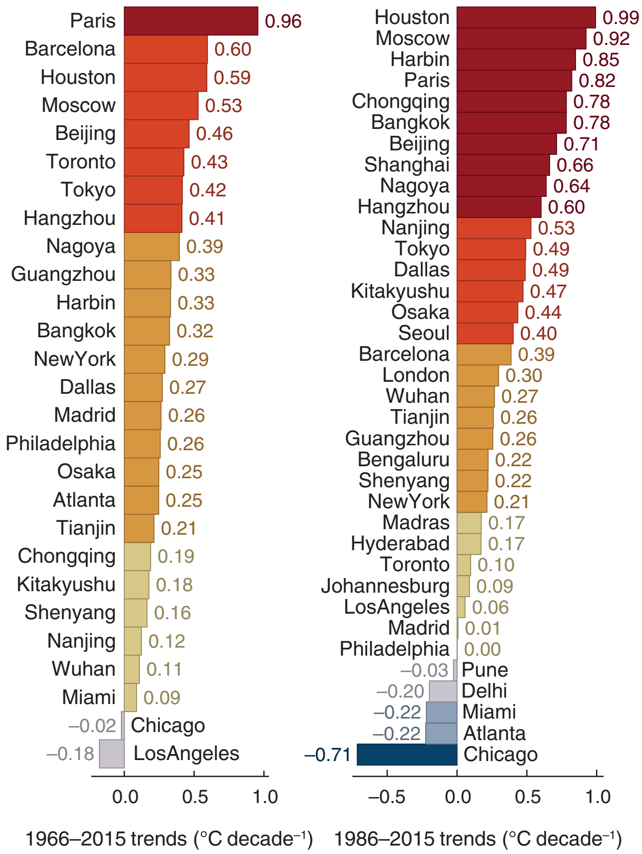

Figure 3. Observed temperature trends (°C per decade) in the HTY in large (5–10 million) and mega (>10 million) cities for the periods 1966–2015 (27 cities) and 1986–2015 (36 cities).

Northwestern Hemisphere (which affects the entire Western Hemisphere) as a "hiatus" but it could result from the striking regional spatial variability (Figure 1; e.g., see cooling in the Midwest) and spatial averaging of opposite trends. Internal climate variability can mask climate-warming trends, while the main cooling over the Pacific Ocean (Trenberth et al., 2014) suggests a Pacific origin for the 1998–2012 global warming hiatus (Trenberth, 2015). However, this does not necessarily imply a hiatus in extreme events over land (Seneviratne et al., 2014).

The largest warming in HTY is in Eurasia, where the 50-year trend of 0.24°C per decade increased in the last 30 years to 0.33°C per decade. All nine major geographical zones studied show positive 50-year trends, ranging from 0.10 to 0.24°C per decade (Figure 2). These trends have further accelerated during the most recent 30-year period in seven of the nine zones. The Tropics (25°S to 25°N), north (25°N to 65°N) and south (25°S to 65°S) temperate zones, north polar zone (65°N to 90°N), as well as east and west of the Atlantic Ocean exhibit positive 50- and 30-year trends (Figure S4), but the trend uncertainties are large in some zones (north polar, south temperate, and tropical) due to limited station coverage (see Movie S1 for the annual areal coverage).

5. Changes in Megacities

The United Nations study, "World Urbanization Prospects" (United Nations, 2015), reports that 54% of the 2014 population lived in urban areas, a value projected to rise to 66%, or more than 2.5 billion more people will be added to the population of urban areas by 2050. In 2016 the top 600 cities comprised 20% of the world's population. The number of large cities and megacities—those with 5 to 10 million and more than 10 million inhabitants, respectively—doubled over the last two decades (UN-Habitat, 2016). As of July 2014 there were 71 cities with more than 5 million inhabitants, including 28 megacities. The latter group is projected to reach 41 by 2030 (United Nations, 2015). This dramatic urbanization, which has occurred more rapidly in the least-developed parts of the world, will aggravate the impacts of extreme weather events and increase the risk of heat-related fatalities in the future.

Among the 71 large or megacities, 27 and 36, respectively, had available data and passed our quality control criteria for the recent 50- and 30-year periods. The mean 50-year HTY trend for cities with temperature stations within a 30-km radius from their center is 0.30°C per decade (Figure 3; see also Figure S5 for a global map showing megacities and Table S1 in Supporting Information S1 for statistical significance). Positive 50-year trends occur in 93% of cities, while trends larger than the GMST trend (0.20°C per decade over 1966–2015) occur in 70% of the cities. The trends are alarming in many cases, for example, 0.96°C per decade in Paris, and with Barcelona, Houston, Moscow, and Beijing following closely. Positive recent 30-year trends (Figure 3 - right panel) are observed in 86% of the cities analyzed (31 out of 36), and 66% of them have trends larger than 0.20°C per decade. Ten cities show alarming trends larger than 0.60°C per decade, with Houston, Moscow, Harbin, Paris, and Chongqing being the top five (Figure 3 - right panel). Individual extreme events like the 2003 and 2015 heatwaves in Paris contribute to large positive trends, or alternatively, the Chicago heatwaves in the 1980s and 1990s influence the recent 30-year negative trend. Yet, an evaluation of the significance of the trends probabilistically, shows how unlikely these trends are under natural variability and the assumption of stationarity. Hence, particular single extremes do not affect the general conclusions.

The comparison of the 50- and 30-year trends in the 27 cities where data are available for both periods reveals that trends increased in 17 out of the 27 cities, while the 27-city average trend accelerated from 0.30 to 0.38°C per decade. The spatial pattern of temperature trends in cities (Figure S5) is consistent with the regional trends (Figure 1). Some characteristic examples are: (1) the acceleration of regional trends over the last 30 years in east China and Japan, which is also detected in the 16 cities studied in east China, Thailand, South Korea, and Japan; (2) the "cooling zone" in the Midwestern United States that extends toward Florida is also in agreement with changes observed in Miami, Atlanta, and Chicago; and (3) the European cities and Moscow follow the observed regional trends. However, cities, in most cases, have larger trends than their corresponding cells, that is, 22 of 27 cities and 20 of 31 cities for the 50- and 30-year periods, respectively (Figure 1 and Figure S5). More localized analysis is needed to quantify possible climate-urbanization amplifications. The urban heat island effect is a well-studied phenomenon (see e.g., Arnfield, 2003; Zhao et al., 2014) and is likely to have contributed to the observed alarming changes. Understanding the predominant amplifiers of local temperature increase in an urban setting can inform mitigation strategies that could treat or ameliorate the heat-island component of urban warming (see e.g., Li et al., 2014; Rosenfeld et al., 1998).

6. Discussion

Increasing trends in annual mean temperature (e.g., Easterling et al., 1997; Hansen et al., 2010) are expected to modulate trends in the HTY. This study offers a comprehensive overview of trends and patterns of the HTY from city- to global scales. We report accelerated warming in the past 30 years, particularly in most megacities and a large region in Eurasia. We show that the exceedance probabilities of observed 50- and 30-years warming rates in HTY are highly unlikely under natural climate variability in most regions around the world. A comparison of trends in the HTY, presented here, with trends in the annual mean temperatures of previous studies (e.g., Hartmann et al., 2013) reveals common patterns of change but also highlights some important regional and local differences in the rates of warming. For example, in the Midwestern U.S., northern Australia, and central Russia the mean temperatures have increased, while the HTY shows a decreasing trend. In the Midwest, the cooling of summer temperature extremes (the same area where we show decreasing rates in the HTY) has been linked to cropland intensification (Mueller et al., 2016).

A negative correlation between summer monthly mean precipitation and temperature (Trenberth & Shea, 2005) over land, indicates that less sunshine and more evaporative cooling observed in wet conditions could lead to cooler summers. A comparison of trend patterns between HTY and annual precipitation (Hartmann et al., 2013) (for a slightly different period, i.e., 1951–2010) suggests this as a factor for the negative HTY trends in specific regions such as the Midwestern U.S. and parts of Australia. Likewise, negative trends in annual precipitation (less than the 50th percentile) (Wen et al., 2016) over 1961–2010 help explain the hot zones in HTY in Eurasia. Other possible factors for the warming HTY zones include persistent anticyclones formed by elevated sensible surface heating (Liu et al., 2001), and ocean–land–atmosphere interactions (Black et al., 2004). Arctic amplification has recently been linked to extreme weather in mid-latitudes (Francis & Vavrus, 2012), although this attribution has been challenged (Barnes, 2013). Clearly, natural variability in temperature depends also on large-scale atmospheric circulation patterns that cause regional variations and uncertainty in long-term trends (Deser et al., 2012). However, while many processes can affect trends, global warming is changing the odds of extreme high temperatures.

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