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Detecting synoptic warming trends across the US Midwest and implications to human health and heat-related mortality

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ABSTRACT: This paper highlights and expands on the extensive work concerning extreme heat events, and the environmental and societal factors that affect human health. Selections of this work were presented originally in a Union of Concerned Scientists public report ('*Heat in the Heartland*'). As humans respond concomitantly to a suite of meteorological variables, we accordingly aim to examine summertime frequencies and characteristics of select synoptic weather types in the Midwestern United States, particularly those associated with elevated health impacts risk. We analyse five major urban centres, paired with five nearby smaller cities, to investigate the potential relative differences due to urban form and size. In virtually all of these locales, the frequency of health-debilitating hot weather types has increased in the six most recent decades, with many of these also demonstrating statistically significant upward trends in air and dew point temperatures. This is most prevalent for overnight temperatures, where the hottest weather types display increasing overnight temperatures in both large and small cities, thus causing the diurnal temperature ranges to decrease. Furthermore, the prevalence of three or more consecutive runs of these days is on the rise, with all five large cities experiencing a higher number of heat waves today than in the late 1940s. We emphasize the importance of city-level efforts to assist in minimizing future climate-related health risks. Finally, we demonstrate the increasing human mortality response in one select city (Detroit, MI), which is estimated without the presence of city-level efforts, targeted interventions, adaptation strategies, or physiological acclimatization. This highlights the importance of providing accurate heat-health warnings to the public, and provides essential understanding of the Midwest US region's summertime climate trends.

KEY WORDS spatial synoptic classification; human health; synoptic weather type; urban heat island; Midwest; heat-related mortality; bioclimatology

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1. Introduction

There is a well-established connection between extreme heat and summer excess mortality in the United States (Kalkstein and Davis, 1989; Sheridan and Kalkstein, 2010; Greene *et al.*, 2011). In 2012, over 34 000 high-temperature records were broken at stations across the United States, with the full year identified as the hottest on record (National Climate Data Center, 2013). In past years, the Midwest has been affected by many heat-related tragedies, such as in St. Louis and Kansas City, MO (July 1980), Milwaukee (1980), and Chicago (July 1995). Such tragedies could be exacerbated by a changing climate (Wuebbles and Hayhoe, 2004) and become more common. Hence, more heat events akin to the 2003 European heat wave, which killed 70 000 people (Robine *et al.*, 2008), are possible. Climate models project that some regions will see more intense, more frequent, and longer-lasting extreme heat events in the second half of this century (Meehl and Tebaldi, 2004; O'Neill and Ebi, 2009). The International Panel on Climate Change (IPCC; Solomon *et al.*, 2007) is in general agreement with such projections, stating 'It is *very likely* that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent'.

Previous research has shown that 1500 heat-related deaths occur in the United States during an average summer (Harvard Medical School, 2005). High temperatures can lead to dehydration, heat exhaustion, deadly heatstroke, kidney problems, lethargy, and poor work and athletic performance (Epstein and Moran, 2006; Kjellstrom *et al.*, 2009; Vanos *et al.*, 2010). Very hot weather can also aggravate the existing medical conditions, such as diabetes, respiratory ailments, and kidney and heart diseases (Semenza *et al.*, 1999; Mastrangelo *et al.*, 2007; Basu, 2009). Urban residents, the elderly, children, outdoor workers, and people with impaired health and limited mobility are particularly susceptible to heat-related illness and death (Basu, 2009; O'Neill and Ebi, 2009). In addition, the effects of heat are cumulative, and a run of several days of oppressive heat has a greater negative impact on human health (Kalkstein *et al.*, 2011).

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Many predictive climate-health models commonly use only changes in mean air temperature (Parry *et al.*, 2007), disregarding the forecasting of important meteorological variables that work in concert with temperature, such as sunlight and vapour pressure (Kalkstein and Davis, 1989; Greene *et al.*, 1999; Davis *et al.*, 2003; Greene *et al.*, 2011). By accounting for the full atmospheric situation, we can holistically address the overall heat stress impact on the human energy balance and the resulting health impacts within populated urban areas (Vanos *et al.*, 2012, 2010). A well-tested synoptic weather typing scheme is the spatial synoptic classification (SSC) system (Sheridan, 2002), which has displayed strength in applications for the determination of those synoptic situations that lead to extreme heat events that are harmful to human health (Sheridan and Kalkstein, 2004; Greene *et al.*, 2011; Hondula *et al.*, 2013).

There is limited research in evaluating long-term temporal trends within synoptic weather situations, and no study has focused on the comparison of small and large city weather-type trends, particularly looking at temperature and moisture characteristics across a region. A study completed by Knight *et al.* (2008) for the contiguous United States found that from 1948 to 2005, statistically significant increases in the yearly number of warm and moist weather types, at the expense of cold and dry air, have been occurring. Similar trends were found for a large-scale study contiguously across Canada (30 cities, both large and small) by Vanos and Cakmak (2013), with a general increase in all warm weather types, particularly moist tropical, in both summer and winter seasons. Although a direct comparison is needed, the magnitudes of the trend changes in Canada seem to be stronger relative to those of the United States, particularly in the north. This enhanced strengthening in the more northerly stations, where urban heating effects are nonexistent in the very small cities/towns, aligns with the results of Kalkstein *et al.* (1990) from the Arctic.

As the effects of atmospheric conditions on human health are expected to change with increasing magnitudes and frequencies of extreme weather (Gosling *et al.*, 2007; O'Neill and Ebi, 2009), such weather-type frequency changes are also expected (Knight *et al.*, 2008; Hondula *et al.*, 2013). This study expands on our 2012 climate and health public report on extreme heat in the Midwest (Perera *et al.*, 2012). The research goal is to investigate the 60-year trends in frequency and thermal and moisture characteristics of dangerously hot summer days – as well as cool, dry summer days – in five large Midwestern US cities (Figure 1). We determine if, in fact, any frequency trends are most prevalent within those weather types that have historically been associated with negative health outcomes (DT and MT+), or if trends are limited to rather 'benign' weather types. If the answer is the latter, there is much less concern on human health outcomes than if it is the former. This is what renders a segregation of weather types significant; we cannot assume that changes in either meteorological frequency or character are uniform among all synoptic weather types.

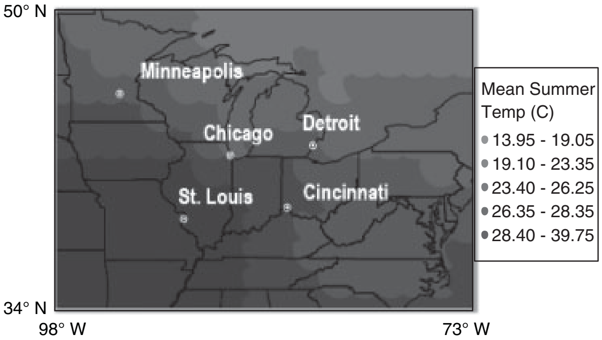

Figure 1. Locations of the five large Midwestern cities in this study. Grey shading depicts projected 20-year daily average (2040–2059) for summertime temperatures (Jun–Jul–Aug), in units of degrees celcius, as simulated under the SRES A2 scenario (high emissions) using the *Community Climate Systems Model* (National Center for Atmospheric Research GIS, 2012).

The study is focused on the Midwest due to its variable climate, many large population centres, predictions of future summertime warming (Nakicenovic *et al.* (2000); Figure 1), and the projections of increasing number and intensity of heat waves (Meehl and Tebaldi, 2004; O'Neill and Ebi, 2009). We also investigate whether 3-day or longer runs of hot and oppressive weather types associated with elevated health impacts [i.e. dry tropical (DT) and moist tropical plus (MT+)] have become more common through the period of record. The highly variable climate of the Midwest renders the area to be one of the most sensitive regions in terms of human health responses to heat (Sheridan *et al.*, 2009); hence, this study accounting for local weather via the SSC establishes more spatially accurate climate–health relationships.

Finally, we pair each larger city with a nearby smaller city to address differences in frequency and temperature characteristics of weather types for large and nearby relatively smaller cities. This allows for a full regional outlook of such trends, as the extent of each weather type usually will cover thousands of kilometres in land area. However, this analysis does not intend to attribute findings to the urban heat island (UHI) effect, although such an effect generally would be less important at an airport site associated with a smaller city, rather than a major city. In addition, this work does not seek to substantiate anthropogenic global climate change. Rather, this study attempts to quantify empirical long-term trends, and emphasizes the importance of accurately addressing the health risks of potential future climate change, and to motivate preparedness to extreme heat events.

A growing number of cities have developed and adopted the use of the SSC for city-specific heat/health warning systems (HHWSs), where advisories and warnings are activated when lives are threatened by extreme heat days and/or extended heat waves (Hondula *et al.*, 2013). With an established HHWS mortality algorithm, we further demonstrate the consequences of assuming that the population does not acclimate or adapt behaviourally and technologically to changing weather patterns. The established HHWSs have been shown to save lives and result in positive impacts on human health (Ebi *et al.*, 2004; Bassil and Cole, 2010; Greene *et al.*, 2011), and have validated existing intervention strategies for adaptation in changing climates. The use of HHWSs also demonstrates the benefits of implementing adaptation strategies locally, accounting for the sensitivity of the local population within cities that face a growing risk of dangerous heat events, but do not yet have plans in place.

2. Methods

2.1. City-specific SSC

Spatial synoptic classification is a hybrid, manual and automatic, climate classification scheme that classifies each day into one of eight distinct weather types (Sheridan, 2002; Sheridan and Dolney, 2003). See Hondula *et al.* (2013) and Sheridan (2002) for further detailed use of the SSC and information. The SSC allows for a more useful climate evaluation than traditional climate change analysis, which considers thermal and moisture variation regardless of synoptic type. Surface airport meteorological data are used four times a day (03:00, 09:00, 15:00, and 21:00 h), with necessary variables being air and dew point temperatures, air pressure, and cloud cover. We analysed summertime [June, July, August (JJA)] synoptic weather-type frequencies for the past six decades for five large Midwestern US cities, along with paired relatively smaller city counterparts (Table 1). The smaller cities were chosen based on being in relatively close proximity to the large cities, and also the presence of a first-order NOAA airport weather station from which the SSC is computed. All station data records were checked for movements in measurement location and/or instrument changes during the period of record (National Climate Data Center, 2009).

This study focuses on four synoptic weather types: hot and humid (moist tropical, MT), an extreme subset of MT (moist tropical+, MT+), hot and dry (dry tropical, DT), and cool and dry (dry polar, DP) (Sheridan, 2002). The DT and MT+ weather types contribute the greatest to negative health outcomes, as they are associated with an increased risk of heat-related deaths (Sheridan and Kalkstein, 2004).

The SSC assumes that the human population responds to all weather variables concomitantly (Sheridan and Kalkstein, 2004; Sheridan *et al.*, 2009; Sheridan and Kalkstein, 2010). Furthermore, as different populations have different levels of acclimatization, the SSC categories differ by time of season and location (Table 2) (Davis *et al.*, 2003; Sheridan and Kalkstein, 2010). This specificity results in the SSC being less likely to identify ‘false-positive’ extreme heat days or heat waves, accounts for early season heat waves, and the fact that human response differs by location (e.g. New York *vs* Arizona). In the US Midwest, the heat response was demonstrated by Sheridan and Kalkstein (2010) to peak in early in July, and decline thereafter.

Using the SSC and meteorological data, frequency and characteristic trends (air and dew point temperature) were investigated for potential differences due to city/population size (Table 1). The same weather type simultaneously affects both the large city and its smaller counterpart due to the macro-scale dimensions (1000 km) of a synoptic weather type. If differentials in both weather-type frequency and character response are minor between the paired cities, this would strengthen the argument that these differentials are regionally based rather than localized.

2.2. Trend analysis

The time series analysis of the Jun–Jul–Aug occurrence of each synoptic-scale weather type was carried out using standard ordinary least squares regression. In addition to the trends in frequency of each synoptic weather type, changes in the weather-type characteristics were investigated using air and dew point temperatures based on average 03:00 and 15:00 h values within the three examined weather types, DT, MT, MT+, and DP. The use of two times diurnally gives a consistent time of record (rather than only using one daily maximum or minimum value) providing vital knowledge of day-to-day and overnight conditions, as utilized by Curriero and Heiner, (2002) and Davis *et al.* (2003) to successfully predict mortality. Many studies will use one daily time for each given value (T_{min}, T_{max}, T_{mean}, etc.) as a prediction of how humans will respond to weather on a given day (e.g. Davis and

Table 1. Location, demographic, and select climatological information for each city and its corresponding airport.

City/small city pair	Latitude	Years of data	Distance to airport (km)	Distance/direction to paired large city	City population 2011[a]	Population growth rate (1940–2010)[a] (% per year)
Chicago	41.85°N	1948–2010	14.0	–	2 707 120	−2.6
Peoria	40.69°N	1948–2010	9.1	207 km SW	115 234	+2.0
Cincinnati	39.16°N	1948–2010	14.7	–	296 223	−4.8
Lexington	38.03°N	1948–2010	8.7	118 km S	301 569[b]	+20.3
Detroit	42.33°N	1959–2010	15.0	–	706 585	−14.4
Toledo	41.66°N	1956–2010	22.0	86 km SSW	287 206	+0.3
Minneapolis	44.98°N	1945–2010	11.7	–	387 753	−2.1
Rochester	44.02°N	1948–2010	13.0	113 km SE	107 890	+23.4
St. Louis	38.63°N	1946–2010	7.3	–	318 069	−10.7
Columbia	38.95°N	1945–2010	18.0	188 km W	110 438	+29.9

[a] US Census Bureau (2010, 2011). [b] City population of Lexington reached that of Cincinnati in 2010.

Table 2. Descriptive meteorological statistics for Jun–Jul–Aug in each of the five large cities for the three synoptic weather types examined in this study: two hot and oppressive air masses (MT+ and DT) and one cool and dry (DP).

City	Weather type	Frequency (%)	T_a 15:00 h (°C)	T_d 15:00 h (°C)	T_a 03:00 h (°C)	T_d 03:00 h (°C)	Cloud cover (10ths)	Sea-level pressure (mb)	Wind velocity (km h^{-1})
Chicago	DP	14.0	22.7	10.3	13.3	10.3	5.0	1019.0	13.0
	DT	3.8	34.3	16.0	21.0	16.0	4.0	1014.8	15.2
	MT+	7.5	32.3	22.0	24.3	21.0	5.3	1013.0	17.5
Cincinnati	DP	8.0	24.0	11.0	13.0	10.7	4.7	1018.2	10.7
	DT	1.2	35.0	15.3	21.0	16.3	3.3	1016.7	10.0
	MT+	3.4	33.3	22.3	23.7	22.0	5.3	1014.0	13.5
Detroit	DP	11.0	22.3	8.7	11.7	8.7	5.3	1019.2	13.3
	DT	3.2	33.3	15.0	19.7	15.3	4.0	1015.2	15.3
	MT+	6.1	32.0	21.7	22.7	20.3	5.3	1013.3	16.0
Minneapolis	DP	12.3	22.0	9.3	12.7	9.3	5.7	1018.7	14.2
	DT	5.8	33.3	15.3	21.3	15.0	3.3	1012.0	17.2
	MT+	4.4	32.0	21.7	24.0	20.3	6.0	1010.8	18.0
St. Louis	DP	6.2	25.0	12.3	15.3	13.0	6.0	1018.8	12.0
	DT	4.9	36.0	17.7	25.0	18.3	3.7	1013.8	13.3
	MT+	13.0	34.0	21.7	26.0	22.3	5.3	1013.3	14.2

Knappenberger, 2003; Anderson and Bell, 2009); however, this less accurately represents the heat stress experienced by a human diurnally. For instance, if night-time temperatures do not cool sufficiently to provide relief from the elevated daytime heat, this needs to be noted.

Furthermore, we examined the presence of temporal trends in the frequency of three consecutive day runs of very hot, humid (MT+) and/or hot, dry (DT) weather-type days, in any combination. Three or more consecutive days of such days with their characteristic high heat and humidity have been shown to elevate the levels of heat-related mortality (Basu and Samet, 2002; Kalkstein *et al.*, 2011). All trends were evaluated based on regression slopes at a level of statistical significance of $p < 0.05$ using the R Foundation for Statistical Computing 2.14.1 software package (2012). Normality testing was completed using the Shapiro–Wilk's test of normality, and interpretation with Q–Q plots.

The analysis of data extends back to the late 1940s when digital records first became available, and does not extend the past 2010. Thus, our analysis does not capture the warm decade of the 1930s, or the hot summers of 2011–2012, which may have influenced the trends. However, both the 1920s and 1940s were relatively cool and the decade of the 1930s likely represents an anomalous period of warmth in the longer trend of gradual warming (USGCRP, 2009). Therefore, extending the data set further back in time would likely not greatly affect the trends we present.

2.3. Heat-related mortality estimates

As described in Section 1, the growing risk of heat-related mortality is a serious consequence of the combined impacts of UHI and climate change projections. HHWSs are in full operation by the National Weather Service in 32 cities across the United States (Sheridan and Kalkstein, 2004; NWS, 2005; Sheridan *et al.*, 2009), including the five large cities examined in this study. On days of oppressive heat (DT and MT+), the relationships between the variation in standardized mortality with meteorological variables (e.g. air, dew point, and apparent temperatures), time of season, and consecutive days of extreme heat are assessed, where the strongest relationships become the predictive mortality algorithm for each specific city (Greene *et al.*, 2011).

As an example to be applied in this study, we calculate heat-related mortality estimates for Detroit, MI, using the following equation for both DT and MT+ synoptic weather types:

$$M = -4.753 + 0.6 \times \mathrm{DIS} + 0.12 \times T_3 + 0.11 \times \mathrm{AT}_{17}, \tag{1}$$

where M is the anomalous mortality (in deaths) predicted to occur, DIS refers to the day in sequence of an oppressive weather type, T_3 is the 03:00-h [local standard time (LST)] temperature (°C), AT_{17} is the 17:00-h LST apparent temperature (°C).

This predictive algorithm for Detroit is used to produce an estimate of M for an oppressive weather type, developed based on historical empirical relationships with observed mortality. The description of development can be found in Greene *et al.* (2011) and Sheridan and Kalkstein (2004), with the Detroit HHWS, along with all the 32 urban HHWS sites, documented here: http://sheridan.geog.kent.edu/hwws/. There is added value in using forecasted metrological data, as the mortality can also be predicted for up to 5 days in advance (Sheridan and Kalkstein, 2004; Hayhoe *et al.*, 2010).

3. Results and discussion

3.1. Trends in synoptic weather-type frequency

Comprehensive long-term trends of summer weather-type frequencies demonstrate generally decreasing frequencies of DP weather-type days and increasing frequencies of hot, tropical days. This is predominantly consistent among the cities, although regression slopes display some variation (Table 3). The MT and MT+ weather types are increasing most rapidly in frequency as compared with the DT weather type. All five large cities display statistically significant increasing trends of MT air. This increase is slightly greater than a 1 day per decade increase, on average, for the five cities, or six extra MT summer days for the 60-year time period. Three of the large cities (Cincinnati, Detroit, and St. Louis; Figure 2) demonstrate similar increasing trends and significance for the much less frequent yet more extreme MT+ weather type (see Table 2).

Trends in St. Louis display the most dramatic increase, with twice as many MT+ days occurring in 2010, on average, than in the late 1940s. All smaller cities also exhibit the strongest upward trend in frequency of the extreme hot and humid MT+ weather type. For example, in Lexington the number of MT+ days is now at 5 per summer (*vs* two in the 1940s). Similar increases are noted in Peoria and Toledo. The overall strengthened trends of the weather types MT and MT+ across the Midwest is of concern, as human mortality rates have been shown to be significantly higher on hot and humid days in Midwestern cities, as well as in northern US cities (Bridger *et al.*, 1976; Kalkstein and Davis, 1989; Kalkstein and Greene, 1997; Davis and Knappenberger, 2003).

The prevalence of the second extreme weather type, DT, is less throughout the Midwest in summertime as compared with that of MT, MT+, and DP (Table 2). This results in difficulty in detecting significant trends, and somewhat less consistent results among the cities. Results demonstrate an increase in the number of DT days

Table 3. Summary statistics for comparison of large and small cities. Shaded portions indicate agreement in trend between large and smaller city counterparts.

City Air mass	Weather-type frequency		15:00 h T_a		15:00 h T_d		03:00 h T_a		03:00 h T_d	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
Chicago										
DP	−0.119	0.135^{*}	−0.007	0.021	−0.031	0.014^{*}	0.027	0.144^{*}	0.007	0.008
DT	0.024	0.011	−0.005	0.002	−0.033	0.040	0.023	0.040	0.025	0.026
MT+	0.038	0.025	−0.002	0.001	−0.001	0.000	0.015	$0.060^{\wedge}$	0.007	0.009
Peoria										
DP	−0.069	0.065^{*}	0.011	0.042	0.016	0.028	0.023	0.106^{*}	0.030	0.125^{*}
DT	0.010	0.001	−0.004	0.002	−0.019	0.010	0.026	0.034	0.010	0.003
MT+	0.094	0.152^{*}	−0.007	0.012	0.021	$0.056^{\wedge}$	0.013	0.077^{*}	0.018	0.096^{*}
Detroit										
DP	−0.203	0.332^{*}	−0.020	0.088^{*}	−0.012	0.015	0.028	0.105^{*}	0.010	0.011
DT	0.065	$0.050^{\wedge}$	−0.028	$0.085^{\wedge}$	−0.054	$0.084^{\wedge}$	0.046	0.173^{*}	0.011	0.006
MT+	0.066	$0.059^{\wedge}$	0.002	0.000	0.007	0.007	0.023	0.098^{*}	0.027	0.110^{*}
Toledo										
DP	−0.167	0.344^{*}	0.000	0.000	−0.011	0.013	0.023	$0.054^{\wedge}$	0.006	0.004
DT	0.048	0.038	0.004	0.004	0.005	0.001	0.038	$0.057^{\wedge}$	0.050	0.092^{*}
MT+	0.063	$0.048^{\wedge}$	0.001	0.000	0.021	$0.069^{\wedge}$	0.014	0.043	0.021	$0.062^{\wedge}$
Minneapolis										
DP	−0.068	$0.057^{\wedge}$	−0.010	0.035	−0.016	0.034	0.009	0.017	−0.007	0.009
DT	0.045	0.022	−0.027	0.101^{*}	−0.014	0.008	−0.007	0.004	−0.012	0.007
MT+	0.025	0.016	−0.012	0.018	0.005	0.004	0.014	$0.050^{\wedge}$	0.019	0.071^{*}
Rochester										
DP	0.022	0.004	−0.003	0.006	0.038	0.211^{*}	0.022	0.148^{*}	0.019	0.085^{*}
DT	−0.058	0.067^{*}	−0.018	0.041	−0.052	0.067	0.001	0.000	−0.011	0.005
MT+	0.012	0.005	−0.016	$0.059^{\wedge}$	0.010	0.017	0.000	0.000	0.009	0.022
St. Louis										
DP	−0.06	0.098^{*}	−0.001	0.000	0.012	0.016	0.030	0.149^{*}	0.026	0.093^{*}
DT	0.000	0.000	−0.002	0.000	0.029	$0.060^{\wedge}$	0.038	0.132^{*}	0.066	0.181^{*}
MT+	0.152	0.243^{*}	−0.011	$0.052^{\wedge}$	0.009	0.028	0.018	0.176^{*}	0.005	0.014
Columbia										
DP	−0.118	0.135^{*}	0.021	0.137^{*}	0.047	0.165^{*}	0.026	0.166^{*}	0.037	0.187^{*}
DT	0.024	0.011	0.053	0.273^{*}	0.049	0.108^{*}	0.031	0.111^{*}	0.034	0.114^{*}
MT+	0.038	0.025	−0.008	0.02	0.015	$0.058^{\wedge}$	−0.003	0.008	0.011	0.088^{*}
Cincinnati										
DP	−0.033	0.019	0.002	0.001	0.013	0.016	−0.001	0.000	−0.003	0.001
DT	−0.029	0.013	−0.007	0.015	−0.018	0.023	0.005	0.008	−0.010	0.022
MT+	0.033	$0.054^{\wedge}$	−0.010	0.013	0.000	0.000	0.002	0.001	−0.006	0.008
Lexington										
DP	−0.035	0.023	0.000	0.000	0.020	$0.040^{\wedge}$	0.013	0.038	0.006	0.005
DT	−0.009	0.001	0.002	0.001	−0.002	0.000	0.019	0.031	0.000	0.000
MT+	0.038	0.068^{*}	−0.016	0.042	−0.003	0.003	0.009	0.021	−0.002	0.002

*Indicates statistical significance at the $p < 0.05$ level. $^{\wedge}$Indicates statistical significance at the $p < 0.10$ level.

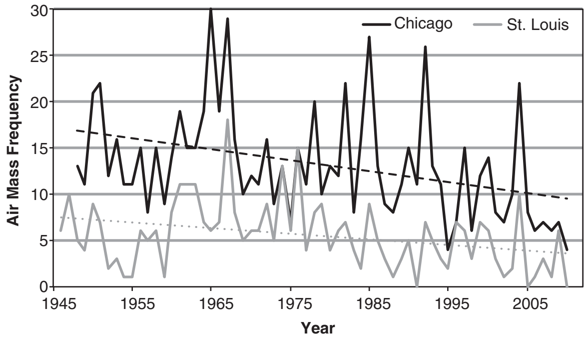

Figure 2. Linear regression results demonstrating statistically significant ($p < 0.05$) decreasing summertime frequencies of DP air for Chicago and St. Louis over the last six decades. DP weather-type frequencies in Detroit and Minneapolis (not shown) also decreased in similar fashions.

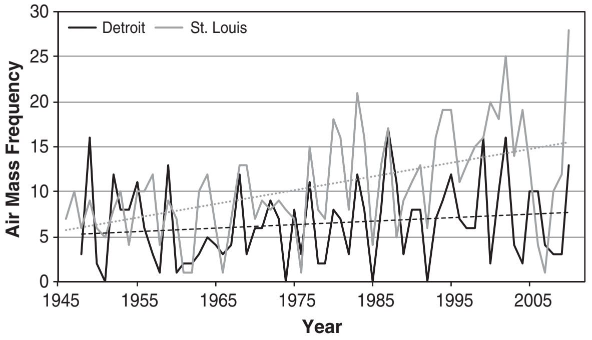

Figure 3. Regression results demonstrating the statistically significant ($p < 0.05$) increasing frequencies of the MT+ weather type for St. Louis and Detroit.

occurring each summer, on average, detected for 7 of the 10 cities, with Detroit approaching the statistical significance. Cincinnati and nearby Lexington demonstrate slight yet insignificant decreases in DT, and St. Louis demonstrates no change through its period of record. For St. Louis, this is largely due to the steep and statistically significant rise in the MT+ weather type (+2 per decade); hence, when the temperature of a weather type (either DM or MM) crossed the threshold temperature criteria to become 'tropical', the moisture was at a sufficient level to be classified as *moist* tropical, rather than dry. This is found to be occurring in most cities, and also agrees with results (found in Section 3.2) of rising dew point temperatures within these hot weather types. The statistically significant increases in MT/MT+ are consistently greater than DT weather-type trends, with a greater average magnitude of increase found in the larger cities *versus* the minor cities.

Much of the increases found in hot and moist weather types are occurring at the expense of the coolest summer days, those being DP air, which is decreasing in 9 of the 10 cities (exception: Rochester). Six cities display statistically significant frequency increases of the MT+ weather type, which coincides with the significant decreasing frequencies of the DP weather type. Hence, a decreasing number of cool summer days is occurring, which often bring relief from the oppressive heat. Across the Midwest, we now see five less days on average per summer today than 60 years ago, and to a greater extent in the larger cities. The most notable decline for DP is in Toledo, with nine less summer DP days, on average, in 2010 than in the 1950s. Reductions for Detroit, St. Louis, Chicago, Columbia, and Peoria also demonstrate statistically significant decreases. For Detroit, the city now experiences 10 fewer DP days per summer today than 50 years ago (Figure 3). Furthermore, in the 1940s, the DP weather type in the above-mentioned four cities was more prevalent than MT or MT+; now the reverse is true.

The greater increase in the MT+ frequency, as compared to DT, is due to the concomitantly increasing dew point temperatures (discussed in Section 3.2). Therefore, the MT+ weather type seems to be 'capturing' some of the DT days that are relatively humid for this hot, dry air. If DT air is becoming increasingly moist, as rising dew point temperatures suggest (Section 3.2), then MT+ days are expected to become more common. This finding is consistent with temperature and moisture changes across the United States, and agrees with North American studies by Kalkstein *et al.* (1990), Knight *et al.* (2008) and Vanos and Cakmak (2013), who all found increases in warm, moist weather types at the expense of cold and dry.

3.2. Temperature characteristic trends within weather type

As displayed in Table 3, we find statistically significant increases in the air and dew point temperatures within the hot weather types of MT+ and DT during the night-time hours, measured at 03:00 h. These trend increases are consistent across the majority of the cities, and are considerably more pronounced than the afternoon (15:00 h) trends. For Detroit (Figure 4) and St. Louis, significant upward trends for 03:00 h air temperature are present in all weather types, including an overnight warming of the coolest weather type of DP. All cities demonstrate increasing trends in the overnight

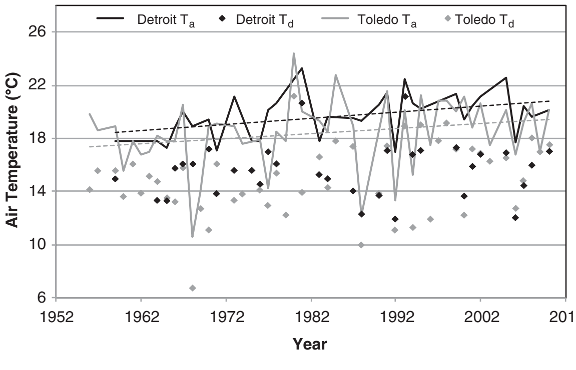

Figure 4. Linear regression results demonstrating overnight (03:00 h) air and dew point temperatures (T_a and T_d, respectively) for the DT weather type in both Detroit and Toledo. Air and dew point temperature increases were significant ($p < 0.05$) in Toledo, with air temperature significantly increasing in Detroit.

temperature in the MT+ weather type over the period of record, with the magnitudes in Detroit and St. Louis being the greatest (+1.8 °C), and Cincinnati the least (+0.1 °C). Night-time temperatures in the MT+, DT, and DP weather types warmed notably in the minor cities of Lexington, Peoria, and Toledo, agreeing with their larger city counterparts. However, the strength and progression of these temperature trends vary among the cities, and by the synoptic weather type being assessed. For example, 03:00 h dew point temperature trends are slightly negative in Minneapolis and Cincinnati.

Figure 4 displays the statistically significant increases for overnight air temperature in Detroit, and for both air and dew point temperatures in Toledo. For Toledo, this represents an increase of about 2.8 °C for the 55-year period of record. Rochester results tend to be muted for the hot weather types; however, significant increases in air temperature at 15:00 h, and both air and dew point temperatures at 03:00 h, for the cooler DP weather type are found. This demonstrates that the coldest summertime days have been warming, and to a greater extent overnight, with trends in 6 of the 10 cities demonstrating statistically significant increases in 03:00 h air temperature. On average, across the US Midwest, both night-time air and dew point temperatures even on the coolest nights (DP air) have increased by 1.2 °C.

An interesting feature is the strong dry weather type bias in slope trends for air temperature. In general, the largest temperature increases during the period are in the hot dry DT and cool dry DP weather types, rather than the MT+. However, frequency increases are most dramatic for MT+. These greater temperature increases in the DT weather type, *versus* the MT+, are most likely related to the lower specific heat of the hot, dry DT air. Thus, its thermal characteristics have the propensity to change more rapidly as compared with a more humid atmosphere that will display a lesser change in air temperature character.

The daytime (15:00 h) air temperature trends within each weather type display less agreement among the cities than overnight trends. The occurrence of flat or negative regression slopes in temperature trends of the hot weather types is due to a relatively cooler weather type (such as dry moderate) narrowly crossing the temperature criteria threshold to become ‘hot’ (DT); hence, the air temperature value in the DT weather type will be at the lower end of the temperature range to be classified as ‘tropical’. This then lowers the overall temperature averages on days with DT weather.

Even so, significant increases in temperatures are still present. The increasing temperature trends found here align with projections across the Midwest US by Wuebbles and Hayhoe (2004), who estimate annual average daily maximum temperatures to increase anywhere from 2 to 9 °C by century’s end. This projected increase is dependent on the specific city, climate sensitivity, and the emissions scenario followed (based on the Special Report on Emissions Scenarios (SRES); Nakicenovic *et al.*, 2000; See Figure 1).

Elevated overnight temperatures have long been suggested as a leading contributor to negative heat-related health outcomes (O’Neill and Ebi, 2009), and narrowing of diurnal temperature ranges is also a cause for concern, as the impact of longer periods of high temperatures on human health is cumulative (Basu and Samet, 2002). The increasing trends in night-time air and dew point temperatures, more so than those in the daytime, can cause adverse health effects due to less relief from high temperatures overnight, exacerbating any cumulative health effects due to heat (Poumadere *et al.*, 2005; O’Neill and Ebi, 2009; Bumbaco, 2013). The current evidence further corroborates a recent study by Bumbaco (2013) also reporting increasing night-time humidity (moist air) to be a primary cause for lack of cooling overnight, and similarly revealing mute trends in daytime temperature events. They also found the number of night-time heat events in the Pacific Northwest to be significantly increasing, quadrupling in numbers in the three decades after 1980 (Bumbaco, 2013).

The near-surface UHI in the boundary layer is less in the daytime due to turbulent mixing, and highest at night, more so in calm and clear conditions (Arnfield, 2003; Oke, 2003; McCarthy *et al.*, 2010); hence, the 03:00 h temperature trends may be the most important variable to address in this study. The high density of impervious building materials that possess high heat capacities (as compared to soil and vegetation) results in the storage of more heat during the daytime. This retained heat is slowly emitted as longwave radiation throughout the night, increasing night-time temperatures, and inhibiting relief from high daytime temperatures (Meehl and Tebaldi, 2004). This is found in the current study and the study by Bumbaco (2013) to be even more inhibiting with the higher moisture levels.

3.3. Consecutive day analysis

Consecutive day runs of oppressive weather types have a debilitating impact on human health, causing morbidity and mortality, which are affected to a greater extent when excessive heat is cumulative (e.g. Hajat *et al.*, 2006). Due to the empirical association of MT+ and DT weather types with negative health outcomes, we define an ‘SSC’ heat wave as the presence of DT or MT+ days on three or more consecutive days, and further address all the MT days as a separate and less extreme heat wave type when present consecutively. The analysis was completed for the large cities. The results demonstrated that four of the five cities have increasing frequencies in three consecutive day runs of MT+/DT weather types (Table 4), with Cincinnati showing no change. This zero trend in Cincinnati is expected based on low numbers of DT days encountered in each summer in recent years, resulting in less likelihood of a string of DT or MT+ days occurring.

For St. Louis (Figure 5), the frequency of DT/MT+ or MT consecutive day runs has increased at a statistically significant rate. For the DT/MT+ combination,

Table 4. Average increase in the number of three consecutive day runs per summer of MT+/DT weather types, or the MT air mass, over the period of record.

City	Trend change[a]		Percent change (%)[a]		Decadal trend change	
	MT+/DT	MT	MT+/MT	MT	MT+/MT	MT
Chicago	1.1	3.0	76	93	0.2	0.5
Cincinnati	0.0	6.7	0	106	0	1.1
Detroit	2.1	6.1	200	222	0.5	1.5
Minneapolis	1.0	3.7	57	230	0.2	0.6
St. Louis	4.0	9.0	230	65	0.7	1.5

[a] For the period of record for each city, as listed in Table 1.

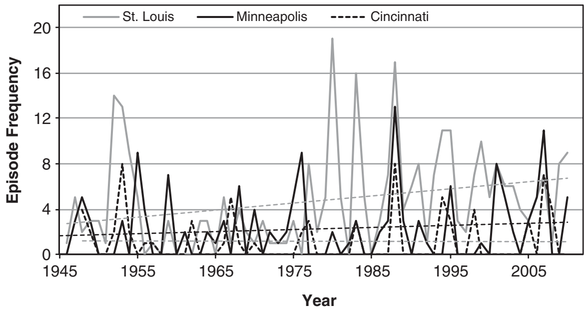

Figure 5. Frequency of three consecutive day episodes (DT/MT+) in St. Louis ($p < 0.05$), Minneapolis, and Cincinnati from 1946 to 2012.

on average there were three consecutive day runs in the 1940s; this has more than doubled to an average of seven such episodes today. St. Louis further displays four of the five summers from 2005 to 2010 having had five or more DT/MT+ extreme heat episodes that equalled or exceeded three consecutive days. Furthermore, in Detroit from 1959 to 1985, no three consecutive day runs of MT+/DT were experienced, yet in 18 of the following 25 summers (1985 through 2010) one or more of these 3-day events occurred. In addition to immediate effects of temperature on heat stress as would be seen on the first day of these heat waves, it has been established in the literature that a lag of 0–3 days in heat-health effects is present during a heat wave, increasing with continuous hot days (Basu and Samet, 2002; Anderson and Bell, 2009; Sheridan *et al.*, 2009). Future studies can address the lag effect of specific health outcomes (e.g. morbidity and/or mortality type) within select weather types.

The current results are intuitive based on the observations of increasing frequencies of the oppressive weather types, and fewer cool summer days (DP) that interrupt strings of consecutively hot days and bring relief from hot weather. One of the advantages of utilizing an synoptic-based approach is the means to define the excessive heat by weather type, and further predict mortality based on strong relationships with meteorological and time-related variables (e.g. consecutive days), rather than by arbitrary meteorological variables. Thus, the SSC is indispensable in identifying long protracted periods of health-debilitating weather. Although not frequently used in historical analyses, such results support an abundance of research studies and reports projecting more and longer-lasting heat events into the future (e.g. Meehl and Tebaldi, 2004; Tebaldi *et al.*, 2006; Meehl *et al.*, 2009; Sheridan *et al.*, 2012; Peterson *et al.*, 2013).

3.4. Heat-related mortality and building resilient communities

The UHI is an important topic in the literature regarding the establishment of heat resilient communities. According to Stewart and Oke (2012), the UHI is affected by two critical current environmental aspects: population growth and climate change. In order for cities to manage a growing risk of heat-health impacts, progress in developing the most sophisticated HHWSs, intervention measures, and other adaptive techniques must continue.

Mortality estimates in Detroit from Equation (1) were compared alongside the observed oppressive weather-type frequencies (DT, MT+) from 1959 through 2012 (Figure 6). This figure demonstrates that both variables have been increasing at statistically significant rates; however, these mortality estimates do not account for human acclimatization, or any adaptations that may be put in place to counteract the effect of increasingly hot weather during extreme heat events (e.g. increased air conditioning, cooling centres, behavioural adaptation, pubic awareness, and technological advancement; see Table 5). These listed adaptations have been found to cause reductions in heat-related mortality in recent decades, even with a higher prevalence of extreme weather types (Davis *et al.*, 2003; Ebi *et al.*, 2004; Sheridan *et al.*, 2009).

Accordingly, by assuming no heat intervention strategies were employed by the city of Detroit (such as those in Table 5), we would expect an increase in anomalous mortality of 11 lives per decade in the city (Figure 6). However, a nationwide heat-related mortality study conducted by Sheridan *et al.* (2009) reported the observed rate of anomalous mortality in Detroit to be declining by 0.3 per decade from 1975 to 2004. Hence, by using the predicted algorithm [Equation (1)] for Figure 6, we are over-estimating the heat-related mortality. In order to account for this rate change, the predicted slope from Figure 6 is adjusted (by −0.3 per year), to a rate of 0.8 per year. This results in an estimate of 402 lives that may have been saved from 1975 to 2012 using the new slope (from the 2811 anomalous deaths predicted). This reduction in heat-related mortality is most likely due to increases in air conditioning, heat awareness resulting in the implementation of heat-health programmes, and many adopted intervention strategies in Detroit in recent decades, such as the HHWS. These reasons have been shown to potentially save lives in Philadelphia (Ebi *et al.*, 2004). However, a complete study, such as that in Philadelphia, is warranted to make more accurate estimates for Detroit, as well as the four remaining large metropolitan areas in this analysis.

Although heat-related mortality has declined somewhat from the 1960s through the mid-1990s, this trend

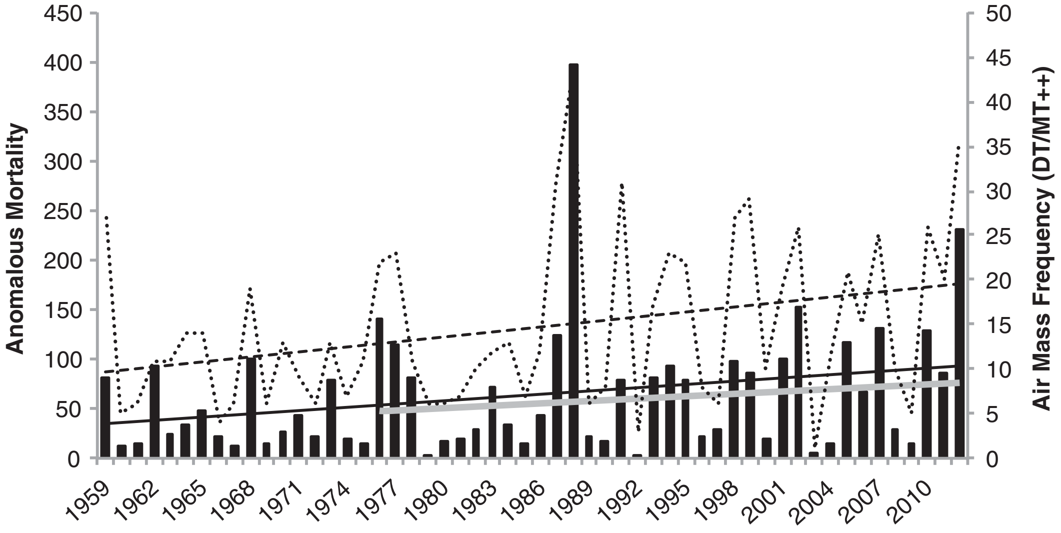

Figure 6. Trends in anomalous mortality (thick bars) predicted to occur based on Equation (1) for Detroit, coinciding with oppressive synoptic weather-type frequencies (dashed line) of DT/MT+ for warm/hot season (May–Sept). Thick grey line represents the estimated −0.3 magnitude decrease in the slope for Detroit (Sheridan *et al.*, 2009) adjusted in relation to the solid black regression line for predicted mortality.

Table 5. City-specific actions plans, resources, and initiatives adopted in recent years to reduce heat-related mortality and morbidity during extreme heat events.

City	Action plans and group, resources, and initiatives
Chicago	• 'Extreme Weather Operations Plan' • Opening 24-hour cooling centres (26 in Chicago) • Conducting police checks of seniors and at-risk individuals • Inspecting high-risk buildings (i.e. buildings with no air conditioning) to ensure that windows and ventilation systems are operating properly
Cincinnati	No official heat plan, although the city has taken steps to deal with heat waves: • The Cincinnati Health Department (CHD) monitors daily weather forecasts, issues heat alerts, and designates heat emergencies • The Cincinnati Drug and Poison Information Center issues health alerts during extreme heat • Recreation cooling centres open during heat waves
Detroit	Heat awareness plans and activities are divided between the Department of Health and Wellness Promotion, the Office of Homeland Security and Emergency Management, and the Recreation Department: • Opening of cooling centres by the Recreation Department during NWS extreme heat advisories/warnings. • Group Initiatives: Health Department's All Hazard Plan, Emergency Management's Emergency Operations Plan, Metro-Detroit Climate Justice Task Force, Detroit Climate Action Collaborative
Minneapolis	From the Extreme Weather Annex of its Emergency Operations Plan, when the NWS issues a heat advisory or heat warning: • Door-to-door wellness checks are completed; lists of public air-conditioned buildings are available • The local Department of Health and Family Support works closely with Regulatory Services and Emergency Preparedness • Minnesota Department of Health helps residents prepare for extreme heat events
St. Louis	St. Louis Health Department maintains an Extreme Temperature Plan from Operation Weather Survival and the United Way: • Email and telephone calls are used to alert members of heat warnings and advisories • Air conditioners are provided and installed for medically needy individuals The Missouri Department of Health and Senior Services also offers cooling centres across the state.

Adapted and condensed from Perera *et al.* (2012).

seems to have abated and there are signs that a reversal has commenced (Sheridan *et al.*, 2009). Two adaptations that have contributed to the decline are the health care advances of the mid-20th century, and the greater awareness of heat as a major health threat (O'Neill and Ebi, 2009; Greene *et al.*, 2011). In terms of excess mortality during heat events, it has been shown that cities taking more serious action regarding the heat/health issue, such as Chicago, have tended to experience dramatic improvements (Greene *et al.*, 2011). Understanding the heterogeneous social and environmental risk across a given city is also vital for saving the most vulnerable lives, with indices of vulnerability shown to adequately predict heat vulnerability (Reid *et al.*, 2009; Harlan *et al.*, 2013).

An additional and vital human adaptation response to heat is the use, or overuse, of air conditioning, as corroborated by O'Neill and Ebi (2009). This use has resulted in declining heat-attributable mortality in the United States (Davis *et al.*, 2002; Davis and Knappenberger, 2003; Davis *et al.*, 2003) and in London, UK (Carson and Hajat, 2006). This is of particular importance as we reach air conditioning saturation in many large cities (Davis *et al.*, 2003). The vulnerability of our main adaptive mechanism to heat, that being air conditioning, was demonstrated by wide-scale power outages in 2003 during a heat wave in the Northeast, negatively affecting many cities (e.g. Toronto and New York) (Anderson and Bell, 2012).

The demand for air conditioning is expected to increase; under a high emissions (A1F1) scenario, Midwestern US cities will likely experience at least 20–60 days over 90 °F (32 °C) and 20 days topping 100 °F (37.8 °C) (Hayhoe *et al.*, 2009). A shift in the mean temperature and broadening standard deviation (σ) of the summertime temperatures is also projected: for Chicago, historical (1960–1990) *versus* century's end (2070–2099) air temperatures are predicted to change from 25.9 °C ($\sigma = 5.52$) to 32.2 °C ($\sigma = 6.73$) under this higher emissions scenario (Hayhoe *et al.*, 2009). However, local adaption should be accounted for as each city is unique, and policy makers must be aware of local patterns of heat vulnerability (Grimmond *et al.*, 2010). The crucial findings from this study warrant such assessments, and highlight the fact that increasing rates of oppressive weather types *are* occurring, along with higher temperatures within these weather types, which represents an increasing public health risk.

3.5. Future directions

Although similar trends exist for the large and small city counterparts, with the current methods we cannot unequivocally determine the attribution of the cause of increasing warm weather types and associated temperatures – it can be merely hypothesized that a regional change is occurring based on the similar results in both large and small cities. From Table 1, we see that the population magnitudes are notably greater in the large cities, yet the urban growth rates from 1940 to 2010 of these cities are negative (mean = −6.9%; range: −14.4 to −2.6), whereas those of the small counterparts are positive (mean = +15.2%; range: +0.3 to +29.9). This indicates that the encroachment of urbanization to airports would potentially not exist, or could be dramatic depending on the direction of growth (e.g. towards or away from airport, or building upwards), which could potentially influence observations at weather stations if surface cover change occurs. Understanding land use land cover changes over the last 60+ years would be helpful in future analyses to make such a comparison, as they play a crucial role in the local and regional climate system (Mahmood *et al.*, 2013).

Future studies can address the potential impacts of land cover and the UHI on airport surface stations, and hence determine if weather-type classifications are also affected. Past and present urban forms can be assessed by utilizing a new framework, where the UHI magnitude is dependent on local climate zone (LCZ) temperature difference (e.g. $\Delta T_{\mathrm{LCZ1}} - \Delta T_{\mathrm{LCZ2}}$), not an 'urban–rural' difference ($\Delta T_{\mathrm{u-r}}$) (Stewart, 2011; Stewart and Oke, 2012). By differentiating all the LCZs from the downtown urban areas to the airport, the common surface and thermal characteristics can be accounted for through time, and relative warming contributions can be detected.

4. Conclusions

This research study achieved two important goals: it has highlighted the increasing summertime long-term trends of select synoptic weather types, particularly those that lead to negative heat-health outcomes. In addition, we have found increasing trends in the thermal and moisture characteristics in the select 10 Midwestern US cities within these weather types. Specifically findings include:

- Hot, humid weather types (MT, MT+) have increased most rapidly in frequency.
- Hot, dry weather types (DT) have increased most rapidly in air temperature.
- Cool, dry weather types (DP) have decreased in frequency.
- Hot synoptic weather types have become hotter and more humid overnight. This lack of night-time relief increases the risk of heat-related complications during heat waves.
- There is a greater prevalence of heat waves lasting 3 days or more in recent times compared with the beginning of the historical record.

Many of these changes are statistically significant, which is unusual in weather trend analyses. The recent surge in the literature of projects linking synoptic-scale oppressive weather to negative human health outcomes emphasizes the value in holistically assessing a whole weather-type situation, rather than one or two variables separately. Furthermore, there is an increased likelihood of heat-related mortality due to these increasingly hot and oppressive weather types, assuming no physiological acclimatization. This underscores the additional importance in the implementation of new and effective adaptation and response plans to extreme heat, as we find the risk to be increasing. Further advanced synoptic-based research approaches can be advantageous for extended climate-health analyses, heat-related mortality predictions, 'cool cities' technology evaluation, air pollution-weather synergies with health, and climate change trend detection.

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