The SSC: A Decade of Climate-Health Research and Future Directions

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The SSC: a decade of climate–health research and future directions

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Abstract This year marks the tenth anniversary of the development of the revised Spatial Synoptic Classification, the "SSC", by Scott Sheridan. This daily weather-type classification scheme has become one of the key analytical tools implemented in a diverse range of climatological investigations, including analysis of air quality variability, human health, vegetation growth, precipitation and snowfall trends, and broader analyses of historical and future climatic variability and trends. The continued and expanding use of the SSC motivates a review and comparison of the system's research and geographic foci to date, with the goal of identifying promising areas for future efforts, particularly within the context of human health and climate change. This review also assesses how the SSC has complemented and compares with other current environmental epidemiological studies in weather and health.

Keywords Spatial synoptic classification · Human health · Climate change · Warning systems · Weather type · Biometeorology · Epidemiology

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SSC overview

The SSC represents the most recent iteration in a line of synoptic research initiated by Muller, Kalkstein, and others in the late 1970s to develop an automated daily weather type classification scheme for individual locations the United States. The goal was to facilitate the identification of daily weather types analogous to the classic Bergeron air masses based on polar, tropical, continental, and maritime source regions (Bergeron 1930). As shown in Table 1, the SSC's origins can be traced as far back as a subjective weather typing system developed by Muller (1977) that relied on manual organization of 12-hour weather maps. However, this technique was very cumbersome and impractical for wide-scale environmental analysis as it focused on only one site. The direct methodological ancestor of the SSC is the Temporal Synoptic Index (TSI) (Kalkstein and Webber 1990). The TSI overcame scaling limitations with a completely automated algorithm that used principal components analysis and clustering techniques. In the subsequent decade, the system continued to evolve and re-incorporated some subjectivity (Kalkstein et al. 1996), leading to the present "hybrid" method in use today.

The current and most recent manifestation of this methodology is the 'SSC2', developed by Sheridan (2002). For any station at which the SSC2 (henceforth, simply the 'SSC') has been developed, a calendar is available that categorizes the daily surface weather into one of six types (Dry Polar [DP], Dry Moderate [DM], Dry Tropical [DT], Moist Polar [MP], Moist Moderate [MM], Moist Tropical [MT]), or an additional Transition category (TR), that identifies days best characterized as a shift from one weather type to another. Subsets of the weather types have also been developed to identify extreme days that may be especially dangerous for human health,

Table 1 Published literature related to the development of the Spatial Synoptic Classification

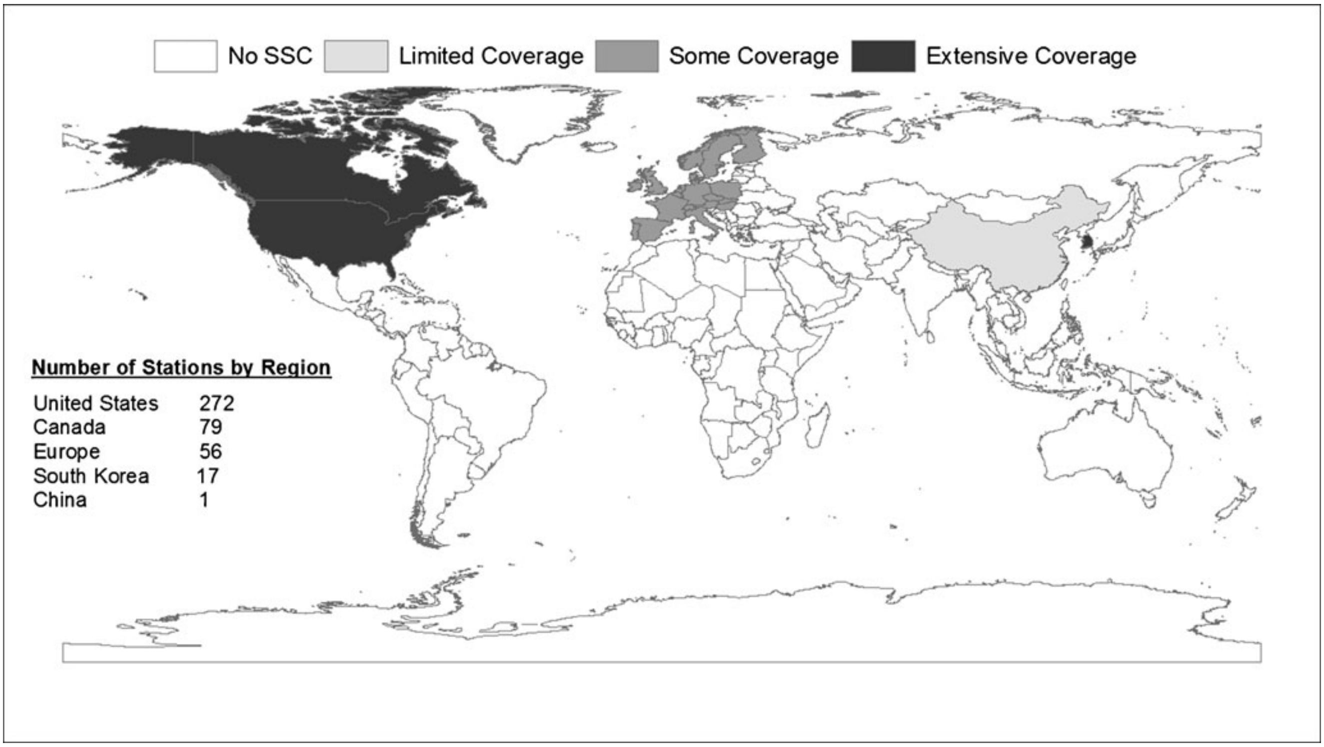
Location(s)	Authors	Year	Goals and classification method(s)
New Orleans, United States	Muller	1977	Developed subjective methodology to identify differing air masses using synoptic climatology; applied to environmental baseline analysis in New Orleans
United States	Mather et al.	1980	First notion of the Temporal Synoptic Index (TSI); provoked climatologists to increase their understanding of the synergistic relationships among climatic processes, surface features, and human actions
Delaware, United States	Kalkstein and Corrigan	1986	First paper applying the TSI. Created an objective system using principal components and clustering in order to assess SO_2 variability across different air masses
Alabama, United States	Kalkstein et al.	1987	Used the TSI to evaluate different clustering techniques for air mass identification; objective air mass evaluation of the northern Gulf Coast
North American Arctic: Anchorage, Gulkana, Fairbanks, Mayo	Kalkstein et al.	1990	Applied the automated TSI to four locations in the Arctic to assess long-term trends in various air masses; first article to study the Arctic with the TSI
United States	Davis and Kalkstein	1990	Developed the first SSC. Applied to 141 stations in the U.S. as a synoptic index using principal components and clustering
Northern Arizona, United States	Kalkstein and Webber	1990	First three dimensional model of the TSI. Also applied the TSI to assess air pollution variables
Philadelphia, United States	Cheng et al.	1992	Applied the SSC to assess air pollution variability in Philadelphia
Middle Atlantic Region, United States	Vose	1993	To account for both spatial and temporal continuity of synoptic conditions, the Regional Synoptic Index (RSI) was developed for seven stations using six variables. Created regional maps that showed the synoptic categories simultaneously
Phoenix, United States	Cheng and Kalkstein	1993	Used the SSC to evaluate climate change; first study to establish the linkages between synoptic climatology and long-term climate change trends
United States	Kalkstein et al.	1996	First proposal of the SSC using "sliding seed days" as a new method of analysis to identify resident air masses at hundreds of weather stations on a national scale. This update of the SSC (SSC1) classified winter and summer days
New Orleans, Memphis, and Chicago, United States	Greene and Kalkstein	1996	Calculated air mass modification rates with SSC1 and used system to identify air masses associated with high mortality
Utah Valley, United States	Pope and Kalkstein	1996	First study to use the SSC1 to assess the linkages between synoptic climatology, air pollution and human mortality
New York, United States	Jamason et al.	1997	Linked synoptic weather conditions to hospital admissions due to asthma and respiratory effects; first SSC1 study using morbidity (rather than mortality) data
Grand Canyon, United States	Schreiber	2002	Assessment of visibility and pollutant source locations using the SSC1
United States	Sheridan	2002	Redeveloped the SSC1 to facilitate year-round classification, improved spatial cohesiveness, expanded geographically from 48 American States to Canada, Alaska and Hawaii, being updated daily. Designated as the SSC2
Shanghai, China	Tan et al.	2004	Extended the SSC2 to China, created the first operational Heat-Health Watch-Warning System (HHWS) in Shanghai
Western Europe	Bower et al.	2007	Successfully developed and extended the SSC2 to Western Europe; named the 'spatial synoptic classification for western Europe' (SSCWE)—48 locations
Republic of Korea: Seoul, Busan, Incheon, Daegu, Daejeon Gwangju, Ulsan, Suwon	Kalkstein et al.	2008b	Extended SSC2 to Republic of Korea; also developed HHWS and Cold-Health Watch-Warning Systems for Seoul and Busan

including Moist Tropical Plus (MT+, the combined warmest and most humid conditions) and Dry Tropical Plus (DT+, the combined warmest and driest conditions). A suite of six-hourly meteorological parameters (air temperature, dew point, wind velocity, pressure, and cloud cover) is used to classify each day. The classification derives from an algorithm that compares the listed surface observations to days that are most representative of the various weather types at each station. These "seed days" are derived from actual days in the meteorological record that are identified as representative of the various air masses for a given time of year and location. One of the major advancements that led to the current iteration of the SSC (Sheridan 2002) was the adoption of "sliding" seed days. Selection of the seed days, while grounded in theoretical climatology, is a subjective process. Seed days are only selected during four two-week periods of the year, between which a linear smoother is used to establish the expected characteristics of each air mass time on each day of the year. Thus there is an expected value for each of the meteorological variables on every day of the year for each of the SSC weather types. An automated z-scoring procedure is used to determine the SSC type that most closely matches any day's meteorological observations across the entire period of record—this is the objective component of the system. Because the seed day characteristics vary seasonally and from place to place, the SSC is a *relative* (rather than absolute) classification system. To ensure regional consistency in the SSC climatologies, a chaining procedure is used to link nearby stations such that the initial selection of seed days is not needed for each individual station in the network. Complete details of the classification procedure can be found in Sheridan (2002).

To date, the SSC has been developed for approximately 400 stations spanning the United States, Canada, and Europe, and select cities in Asia (Sheridan 2002; Tan et al. 2004; Bower et al. 2007) (Fig. 1). At most stations, the SSC archive spans several decades, resulting in a total of over eight million classified days (Sheridan 2011). This archive is freely available to the research community and openly accessible on the Internet (http://sheridan.geog.kent.edu/ssc.html). The automated and accessible nature of the system has led to its adaptation and use by a growing number of researchers. Since its first publication in 2002, the SSC has been integrated into a wide range of research studies, particularly in the areas of climate change and health (Table 2 and Fig. 2). The system has also gained recognition in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Chapter 14 of Working Group II: Impacts, Adaptation and Vulnerability for North America) (Field et al. 2007). Particularly, there has been a heightened interest of research into air mass impacts on human health outcomes, as many environmental variables synergistically affect human health and comfort (Greene et al. 1999; Davis et al. 2003).

The SSC and human health

A re-emerging discipline within the field of biometeorology focuses on the impacts of weather and atmospheric processes on human health (International Society of Biometeorology 2011). Extreme warm and cold conditions have significant physiological impacts, although the precise nature of the relationship between weather and health varies geographically (Kalkstein and Davis 1989; Díaz et al. 2005; Gosling et al. 2007; Hajat et al. 2010). The SSC is well-suited for such research because it enables analysis across varying locations.



Number of Stations by Region

United States	272
Canada	79
Europe	56
South Korea	17
China	1

Fig. 1 Distribution of the Spatial Synoptic Classification system across the globe. The coverage categories reflect the number of stations relative to total land area and population in the various regions served by the SSC

Table 2 Published literature using the Spatial Synoptic Classification (SSC) to evaluate human health and/or climate change relevant to human health

Study Number	Location(s)	Sublocation(s) (none listed if study uses many stations)	Authors	Year published	SSC usage	Major conclusions
1	United States		Sheridan et al.	2000	Urban climate, climate change	The magnitude of the urban heat island varies across SSC types
2	Canada	Toronto	Rainham et al.	2001; 2005	Health study	Mortality risk is generally not sensitive to air pollution concentration within air mass types; air pollution varies across air mass types
3	United States	Ohio	Sheridan and Dolney	2003	Health study	No difference in heat-related mortality risk between residents of urban and rural counties on oppressive air mass days
4	Italy	Rome	Kirchmayer et al.	2004	HHWS implementation and evaluation	Describes a national effort to prevent heat-related illness and mortality in Italy; mortality found to be slightly underpredicted during 2003 European heat waves
5	International	Several U.S. cities, three Italian cities, Shanghai, Toronto	Sheridan and Kalkstein	2004a	HHWS implementation	Air mass subsets DT+, MT+, MT++ developed and useful predictors of mortality for many locations
6	United States	Philadelphia	Ebi et al.	2004	HHWS evaluation	SSC-based warning system has likely saved lives and is very cost-effective
7	China	Shanghai	Tan et al.	2004	HHWS evaluation	HHWS successfully predicted mortality during experimental run in summer 2001 and was deployed for operational use
8	United States	Chicago, Cincinnati, Memphis, New Orleans, Phoenix, Rome, St Louis, Shanghai, Toronto	Sheridan and Kalkstein	2004b	Health study	Air mass type has a greater influence on mortality than pollutant concentrations during oppressive conditions
9	Italy	Rome	de'Donato et al.	2004	HHWS evaluation	System captured major spikes in mortality but underpredicted the number of heat wave days and related mortality, incorporation of temperature-based component for warning system recommended
10	United States		Merrill et al.	2005	Health study	People in locations with more frequent DM air masses have higher daily activity, MT lower
11	United States	Phoenix	Brazel et al.	2007	Urban climate, climate change	SSC used to identify days with significant urban heat island effects
12	Republic of Korea	Seoul	Kalkstein et al.	2008a	HHWS implementation	Mortality in Seoul increases with DT, MT + by approximately 7 %
13	United States		Knight et al.	2008	Climate change	Increase in MT air masses and decrease in DP at many stations over multidecadal period of record
14	United States	Detroit, New York, Philadelphia, St. Louis, Washington D.C.	Kalkstein et al.	2008b	Health study	Developed meteorological analogues using SSC air mass calendars of the Paris 2003 heat wave (EHE) for the five cities. Large impact found, yet not as large as Paris; results varied by city
15	United States	29 metropolitan areas	Sheridan et al.	2009	Health study	Overall decline in heat-related mortality over 30 years, less of a decline on oppressive days, number of oppressive days steady or increasing
16	Canada	Toronto	Bassil et al.	2009	Health study	Identified specific high-risk areas using ambulance callout data from days when synoptic HHWS was activated
17	Italy	34 major cities	Michelozzi et al.	2010	HHWS evaluation	Rapid mortality surveillance system enables the timely estimation of the impact of heat in Italy
18	Republic of Korea	Seoul	Kysely and Huth	2010	Health study	Oppressive air masses associated with high summertime mortality, effect varies based on classification system used
19	United States	29 metropolitan areas	Sheridan and Kalkstein	2010	Health study	Relative mortality increases in spring can equal those of mid-summer, risk lower in late summer and fall in most areas

Table 2 (continued)

Study Number	Location(s)	Sublocation(s) (none listed if study uses many stations)	Authors	Year published	SSC usage	Major conclusions
20	United States	Chicago	Hayhoe et al.	2010	Health study, climate change	Increase in heat waves and related mortality expected for Chicago, USA
21	United States	New York City	Metzger et al.	2010	Health study	SSC types used as one of several metrics to evaluate heat-related mortality in NYC for setting warning criteria guidance
22	Republic of Korea	Seoul, Busan, Incheaon, Daegu, Daejeon, Gwangju, Suwon	Lee et al.	2010	HHWS implementation	Created SSC for 1982 to 2007; DT and MT + identified as high mortality air masses; real-time operational HHWS developed
23	United States	Phoenix	Svoma and Brazel	2010	Urban climate	Interaction effect between SSC type and urbanization in temperature diurnality
24	United States		Greene et al.	2011	Health study, climate change	Increase in extreme heat events and heat-related deaths by 2100 projected using SSC combined with downscaled model output
25	United States		Kalkstein et al.	2011b	Health study	Overall reduction in extreme heat events since 1996, significant health burden remains
26	United States	North Carolina	Hanna et al.	2011	Health study	Some circulation patterns combined with high ozone levels lead to higher asthma and myocardial infarction admissions
27	United States		Hondula and Davis	2011	Climate change	Decline in SSC transition frequencies linked to increasing low dew point temperatures
28	Republic of Korea		Lee et al.	2011	HHWS implementation	Geographic variability in heat sensitivity, HHWS provides more specific information for public officials
29	Republic of Korea	Seoul, Busan	Kalkstein and Sheridan	2011a	CHWS implementation	Cold-health systems proposed for Korean cities using analogous methods to HHWS (report to Korean Meteorological Association)
30	United States	New York City	Davis et al.	2012	Health study	Certain air masses associated with higher flu mortality events at particular lags time
31	United States	California	Sheridan et al.	2012a	Health study, climate change	Future heat-related mortality could increase dramatically by 2090s, large uncertainties related to model projections, population growth
32	United States	Virginia	Hondula et al.	2012	Health study	SSC one of a suite of variables used in a predictive model for respiratory-related hospital admissions
33	United States	California	Sheridan et al.	2012b	Climate change	Projected future significant increase in heat events, oppressive types more than double in frequency in many locations

Similarly, environmental health outcomes are seasonally dependent, and hence studies using the SSC have been completed in both warm and cold seasons (e.g., Rainham et al. 2005; Kyselý and Huth 2010; Lee et al. 2011; Kalkstein and Sheridan 2011). The impact of atmospheric conditions on human health is also expected to change with shifts in the frequency and intensity of air masses that negatively impact human health ("oppressive air masses") as the climate changes (e.g., Kalkstein and Greene 1997; Sheridan and Kalkstein 2004a, b; Knight et al. 2008; Kalkstein et al. 2011a; Greene et al. 2011).

Heat, particularly when combined with high humidity, causes excess weather-related mortality and morbidity. These negative health effects arise because high temperatures and humidity stress the human thermoregulatory system (Vanos et al. 2010). Heat is often considered an acute health problem, as negative health effects are evident within the first few days after the onset of adverse conditions (Anderson and Bell 2009; Sheridan and Kalkstein 2010). These negative health outcomes include heat syncope, cramps, exhaustion, heat stroke, and death (McGeehin and Mirabelli 2001). Those with pre-existing cardiovascular and respiratory ailments and the elderly are commonly found to be at greatest risk (Diaz et al. 2002a, b). Negative health impacts have been associated with the oppressive weather types of MT+ and DT (Sheridan and Kalkstein 2004b; Sheridan et al. 2009). Consecutive days of such conditions increase the debilitating health effects, sometimes up to tenfold with five persistent days of oppressive conditions (Sheridan and Kalkstein 2004a). Elevated

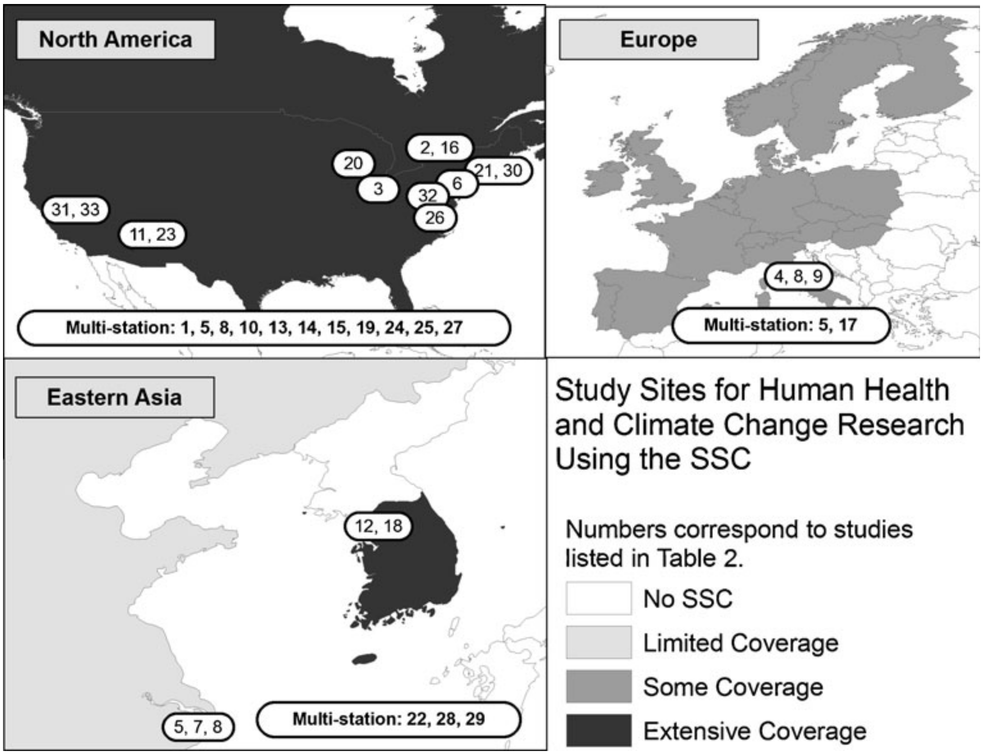


Fig. 2 Locations that are the subjects of published research using the Spatial Synoptic Classification to analyze climate–health relationships or climate change that is relevant to human health. Study authors and conclusions can be found in Table 2

nighttime temperatures also inhibit relief from the daytime heat and/or humidity (Meehl and Tebaldi 2004).

Exposure to low temperatures also gives rise to direct cardiovascular stress (Keatinge and Donaldson 1995; Huynen et al. 2001). The effect of cold weather on mortality occurs over longer time scales than the acute response to heat; mortality is highest 1–2 weeks after a cold spell occurs (Huynen et al. 2001; Anderson and Bell 2009; Martin et al. 2012). Less health research with the SSC has been completed on cold effects, however the coldest weather type, DP, has been found by both Rainham et al. (2005) in Toronto, Canada and by Kalkstein and Sheridan (2011) in Republic of Korea, to be associated with significantly *lower* mortality than other types. This is surprising as DP is commonly associated with the most stressful cold and dry conditions. In Korea, higher air pollution days under MP coincided with the highest mortality (Kalkstein and Sheridan 2011). In mid-latitude areas that experience large seasonal variability in climate, some models have shown that overall yearly mortality burden may decrease due to higher winter temperatures (Martin et al. 2012), as polar weather types (DP and MP) are replaced by moderate (DM and MM) (Knight et al. 2008).

Although the individualized health response to environmental conditions varies (e.g., Koppe and Jendritzky 2005; Vanos et al. 2010), research has consistently documented an association between certain SSC weather types and an increase in human mortality at many locations around the world (Fig. 2, Table 2). The consistency in this relationship has led to the development of synoptically-based heat-health warning systems (HHWS) in select cities, many of which are based on the SSC (Fig. 3; Sheridan and Kalkstein 2004b). Each city has a customized predictive mortality algorithm based on historical data linking weather type with mortality and select meteorological variables. The first SSC-based HHWS was implemented in Philadelphia, USA in the 1990s. Subsequent research has evaluated its effectiveness, with potentially hundreds of lives saved since the system has been in operation (Ebi et al. 2004). Subsequently, the use of other city-specific HHWS's have been found to be effective at communicating risks and reducing deaths when accompanied by specific health interventions (Tan et al. 2004; Kovats and Ebi 2006). The World Health Organization and World Meteorological Organization have both recognized the potential health improvements associated with the use of heat-health warning systems (including those based on the SSC) by providing guidance on warning system development (McGregor et al. 2010). More recently, cold-health warning systems are being piloted and implemented (Kalkstein and Sheridan 2011).

In spite of longstanding work on the potential impact that changing *temperatures* may have on human health with future climate change (Dessai 2003; Gosling et al. 2009a, b, 2012), there has been very little application of the SSC to aid understanding of how more general changes in *weather* may affect human health with future climate change. Recent work is beginning to address this knowledge gap. For instance, the SSC has been applied to show that climate change could be associated with approximately a tenfold

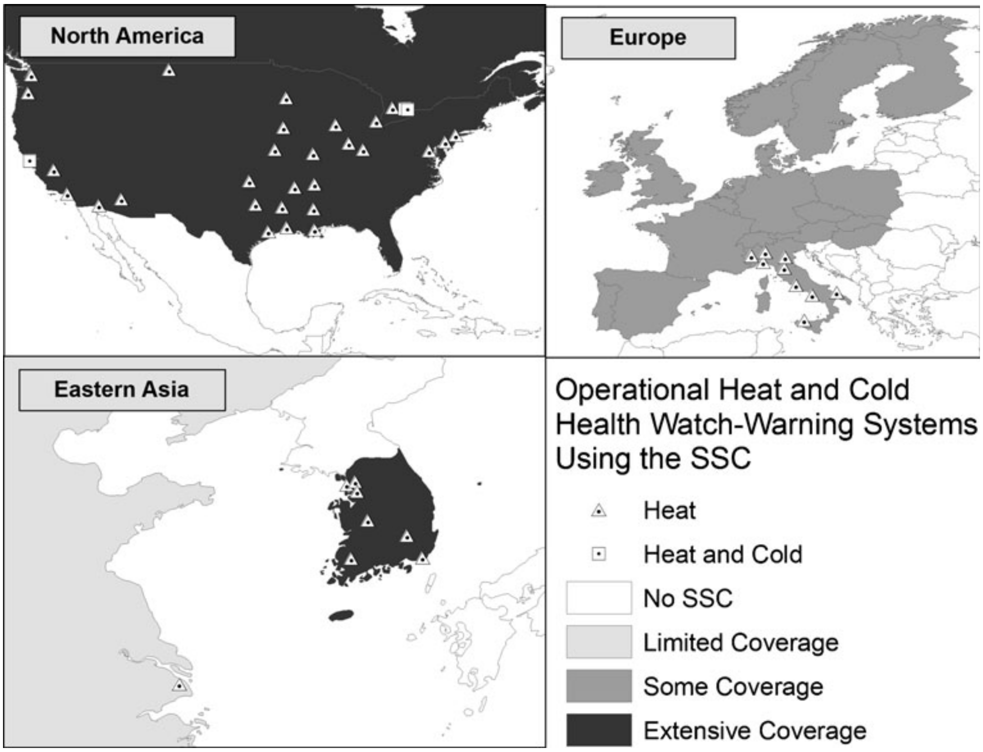


Fig. 3 Locations of currently operational Heat- and Cold-Health Watching-Warning Systems (HHWS and CHWS) based on the Spatial Synoptic Classification

increase in heat-related mortality by the end of the century, both in California (Sheridan et al. 2012a, b) and Chicago (Hayhoe et al. 2010). The SSC has also been used in retrospective analysis of long-term trends in heat-related mortality, with one study identifying significant reductions in 40 U.S. cities since the mid 1990s (Greene et al. 2011).

Comparison with other approaches

As research into weather and health has grown rapidly in the past two decades, a wide range of approaches to modeling have been implemented (Gosling et al. 2009b). These techniques can be grouped into several broad categories, including synoptic classification methods (e.g., SSC, TSI), direct comparisons of temperature and mortality, biometeorological or physiological indices based on combinations of meteorological variables (e.g., Apparent Temperature or Humidex combining temperature and humidity) or human energy balance models (Gosling et al. 2009b; Hajat et al. 2010). A common epidemiological approach associates health effects with a single variable (e.g., mean daily air temperature) using a generalized additive model (GAM) or a generalized linear model (GLM) to control for confounding variables such as day of week, air pollutants, season, and long-term time trends (e.g., Schwartz and Dockery 1992, Braga et al. 2001; Anderson and Bell 2009). The SSC has also been applied using a GLM with the SSC acting as a health-effect modifier (Rainham et al. 2005). Additional layers of model complexity include incorporation of exposure timeframes, age- and cause-specific stratification, lag structures, and displacement effects (e.g., Anderson and Bell 2009).

Although differing methods are employed in weather–health studies, similar findings and conclusions are commonly found (e.g., overall health impacts, relative risks, hot and cold lag times, consistent spatial and temporal variability). Although the SSC has now been used in a number of weather–health studies and active public health warning systems (Figs. 2 and 3), a great deal of research in the realm of environmental epidemiology has been successfully completed using more traditional methods prior to its invention. The synoptic approach posits that weather tends to affect people's health in its entirety, i.e. high temperatures *combined* with factors of humidity, wind speed, and/or radiation/cloud cover. While temperature may be the dominant factor, the computation of various indices, such as the Humidex and Wind Chill (Environment Canada 2012), Apparent Temperature (Steadman 1979), WBGT (Budd 2008), and the Universal Thermal Climate Index (UTCI) (Bröde et al. 2012a, b; Jendritzky et al. 2012) have in the past acknowledged that additional weather elements are important factors in contributing to human thermal comfort. The SSC and other synoptic weather-typing schemes offer a different and complementary framework for analysis that embraces this idea of synergistic mechanisms behind the physiological response to weather. Most notably, the SSC provides a discrete exposure metric (daily weather types) that is location- and time-specific, rather than a continuous variable (e.g., temperature).

The simultaneous consideration of several weather variables, along with spatiotemporal variability, highlights theoretical advantages of the SSC over a simple temperature threshold model. However, all variables needed for synoptic classification are not always readily available, which may preclude the computation of a SSC for a given location. This is an issue that will be more prominent for developing countries, where meteorological data availability can be quite limited. Thus, in practice, a simple threshold model is more straightforward to define and thus implement. Moreover, forecasts of wind speed, cloud cover, and humidity tend to be less accurate than forecasts of temperature alone, therefore a warning system that is based upon temperature alone may be more accurate. This contention is speculative, however, and only additional research can confirm this.

Although a large number of studies employing different methodologies have identified significant links between meteorological factors and human health, much less work has been completed to evaluate the relative success of one versus another. A more thorough examination of differences between the methodologies could contribute towards an improved understanding of weather-related risks, and could also provide practical benefits from targeted intervention measures to reduce the public health and societal impacts of adverse weather. In some cases, researchers have explored different temperature metrics (e.g., minimum, mean, maximum) and differences between temperature and temperature-humidity indices (e.g., Barnett et al. 2010; Vaneckova et al. 2011), yet there is a dearth of research comparing the synoptic weather typing approach to other techniques. As the SSC is a multivariate tool incorporating many different weather variables, it would be instructive to learn how the SSC predictability of human health related to extreme heat and cold, such as mortality or morbidity, compares to a single-variable approach. Such a study would compare the accuracy and reliability of heat and cold warnings derived from a SSC-based warning system with those from a temperature-threshold system using forecast weather data, being completed in several cities located in various climate regimes. Both systems would need to be constructed from consistent historical weather data and tested operationally over several years.

Further, if the SSC is found to give improved model performance or predictability, how does this improvement compare to the added model complexity? It should also be noted that the development of an SSC for a specific location requires subjective decisions related to seed day weather type characteristics, adding additional complexity to the design of a predictive variable for health risk. This subjectivity is true also for the use of GAMs or GLMs to identify temperature-mortality relationships, as subjective decisions are required, such as the specific shape and flexibility of the exposure–response curve, lag structure, and specific temperature metric (Anderson and Bell 2009).

In a recent comparison of the major methodological approaches linking hot weather and human health, Hajat et al. (2010) examined four different metrics across four countries and cities (Chicago, USA; London, UK; Madrid, Spain; and Montreal, Canada) encompassing various climates. The metrics chosen are among the most commonly employed in heat warning systems, all based on an activation "threshold" for specific health intervention activities. The metrics tested include the SSC, mean daily temperature, Humidex, and the environmental stress index (ESI). The authors found little agreement amongst the methods in simply identifying those days that would be associated with warning system activation, and further differences in the ability of the different metrics to identify high mortality days. In general, the days identified as heat adverse based on air temperature and synoptic-based indicator methods had a greater association with increased mortality than the remaining two methods; however, the results varied by city and by the number of heat adverse days considered.

In Chicago, USA, for example, the most heat adverse day as predicted by the SSC was associated with a 23.9 % increase in mortality, yet that predicted by the absolute temperature method was an 8.5 % increase. However, when considering the top ten heat adverse days, the average mortality increase for the two methods was more comparable, with a 10.7 % increase for the SSC versus 12.8 % for the direct temperature method. In London, UK, the ESI and Humidex were associated with the highest increase of the four methods when considering a larger number of heat adverse days. From this analysis, it is not obvious which method is preferable for identifying those days on which the population it is at a higher risk of heat-related mortality. The optimal method might vary from place to place because of geographic differences in the population sensitivity to variables other than temperature (e.g., humidity, wind, solar radiation) (Barnett et al. 2010; Hajat et al. 2010).

The SSC framework is also applicable in studies examining modifiers of extreme heat vulnerability, such as location and socioeconomic status. The notion of differential responses in subpopulations was explored by Kalkstein and Davis (1989), who used the SSC to assess demographic and interregional responses in the United States. The SSC has been used in numerous health studies, where specific causes of death, such a cardiovascular, respiratory, or myocardial infarction, have been examined by weather type, or by an air pollution-weather type interaction (Pope and Kalkstein 1996; Smoyer et al. 2000; Rainham et al. 2005; Hanna et al. 2011). In the warm season, the entire population is susceptible to early season heat, hence leaving a smaller vulnerable population later on in the season. However, according to Naughton et al. (2002), a working air conditioner is the strongest protective factor against such death. Elderly and the sick are commonly kept indoors in controlled environments, where exposure to air pollution and environmental extremes would be at a minimum. When isolated, the risk of mortality due to weather has been shown to dramatically increase (Naughton et al. 2002).

Further socioeconomic indicators of vulnerability to weather-related death include age, living conditions, race, gender, psychiatric illness, isolation, minorities, immigrants or tourists, outside workers or physical labourers, elite athletes, and high-rise apartment dwellers (Semenza et al. 1996; Naughton et al. 2002; Harlan et al. 2006; Vanos et al. 2012). As urban neighborhoods are uniquely susceptible to extreme heat, they can benefit from tools and planning initiatives for reduction (Perera et al. 2012), such as bioclimatic urban design measures (e.g., increased vegetation and park abundance, open space, and prevalence of shade, reflective roofs and pavement), which have been cited to reduce hot and cold temperature extremes in urban areas, and modulate the human energy budget (Harlan et al. 2006; Vanos et al. 2012). Relating to synoptic air mass classification, the use of bioclimatic urban design to reduce urban heat islands may result in a weather type not reaching an 'offensive' category.

A variety of different methods including the SSC and other synoptic approaches applied to health, e.g., air mass-types (McGregor 1999) and synoptic weather typing (Cheng et al. 2007), should be considered in the design and implementation of future heat and cold warning systems and studies linking weather and health. Comparative reviews and active interchange of ideas and methods should be fully supported by the research community, as ultimately the goal is to find the optimal way to provide assessments and predictions to cope with the pressing global health issues related to weather and climate. It is vital to have a suite of complementary methods and tools that can be understood and applied by the various disciplines tackling these challenges.

Summary and future directions

The development of the current SSC a decade ago provided a new research tool for the study of weather impacts and climate change on human health. Since that time, the system has been incorporated in operational public health warning systems in more than 40 cities, and served as the framework for research studies in many more. However, there is very little published evaluation of the SSC alongside other methodological approaches in examining weather–health linkages. There is ample room for formal discussion and debate over the relative strengths and weaknesses of various approaches. In terms of health policy and decision-making, the use of well-recognized temperature metrics, such as the mean daily temperature, provides more easily interpreted results by the end-users for employing targeted heat-mortality prevention efforts (Anderson and Bell 2009). Simultaneously, it has been established that human health is sensitive to a larger suite of meteorological variables, and the SSC is one example of a system that attempts to capture these synergistic effects. If the ultimate goal in developing more rigorous methodologies to examine the weather–health relationship is to discover the best way to reduce the public health burden caused by adverse conditions, then more collaborative efforts like that of Hajat et al. (2010) are warranted.

The SSC's geographic extent mainly reaches developed countries to date, and thus applications are limited to those countries (see Fig. 1). This is in part due to the rigid input requirements for the current SSC that cannot be met at locations without long-term, continuous records of six-hourly meteorological data. Even within the areas where the SSC is available, gaps exist with respect to both research and application. For example, there is a lack of SSC application in Canada (although 77 SSC's are complete throughout the country) and in the southern Atlantic United States. In both of these locations, harmful air masses are found, but the negative health impacts are likely greater for a population un-acclimatized to the heat, such as that in Canada. There is also a lack of published studies using the SSC in the context of human health in central Europe. In some cases, these gaps might be related to the prevalence of other climate-health approaches, notably the energy balance methods more commonly used in German research, e.g. the PET (Hoppe 1999), the UTCI (Jendritzky et al. 2012; Havenith et al. 2012; Bröde et al. 2012a, b; Psikuta et al. 2012), and the preference for using the Humidex in Canada. The recent extensions of the SSC to Republic of Korea and Shanghai, China highlight the potential for additional geographic expansion, with collaboration from the host country facilitating system implementation and application.

Given that the direct and indirect human health impacts of climate change are expected to be most severe in many developing countries (e.g., Field et al. 2007; Wheeler 2011), we identify a significant opportunity for weather–health tools akin to the SSC to promote mitigation and adaptation activities through expansion into the developing world. There are many populated regions that are under-served by weather–health research. There could be practical benefits and improvements to our general understanding of associations between climate and health by employing an SSC in these regions. There are a suite of other synoptic classification approaches that have been developed over the past century, yet the SSC has the advantages of automated classification, accessible data, and a framework for climate-health impact studies that has proven successful in many locations. We encourage the SSC's development for locations where it does not exist, with a comparison of the relative performance of the SSC and other exposure metrics in assessing weather–health linkages. Future expansion of the SSC could be facilitated by training additional researchers on all aspects of system development. Additional study is also needed to address how future climate change may affect human health on a global scale. This can help guide targeted mitigation and management strategies, as well as resource allocation, to most effectively reduce the negative health impacts associated with extreme weather conditions and an evolving climate.

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