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Perspectives on the Synoptic Climate Classification and its Role in Interdisciplinary Research

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Abstract

Synoptic climatology has a long history of research where weather data are aggregated and composited to gain a better understanding of atmospheric effects on non-atmospheric variables. This has resulted in an applied scientific discipline that yields methods and tools designed for applications across disciplinary boundaries. The spatial synoptic classification (SSC) is an example of such a tool that helps researchers bridge methodological gaps between disciplines, especially those studying weather effects on human health. The SSC has been applied in several multi-discipline projects, and it appears that there is ample opportunity for growth into new topical areas. Likewise, there is opportunity for the SSC network to be expanded across the globe, especially into mid-latitude locations in the Southern Hemisphere. There is some question of the utility of the SSC in tropical locations, but such decisions must be based on the actual weather data from individual locations. Despite all of the strengths and potential uses of the SSC, there are some research problems, some locations, and some datasets for which it is not suitable. Nevertheless, the success of the SSC as a cross-disciplinary method is noteworthy because it has become a catalyst for collaboration.

1. *Introduction*

One of the most comprehensive methods of air-mass categorization is the spatial synoptic classification (SSC) system (Sheridan 2002; Sheridan and Dolney 2003). The current SSC was developed by Sheridan (2002) and was referred to as “SSC2” because it stemmed from an extensive line of research initiated by Muller, Kalkstein, and others in the late 1970s (Kalkstein et al. 1996; Lamb 1972; Muller 1977) that eventually led to an initial version that is sometimes referred to as “SSC1” (see Hondula et al. 2014 for an in-depth history). A combination of weather variables (air temperature, dew-point depression, wind speed, mean cloud cover, mean sea-level pressure, diurnal temperature range, and diurnal dew-point range) 6is used to numerically characterize the state of the atmosphere; these quantities are subsequently differentiated into weather-type categories, encompassing variables that synergistically affect human health (Davis et al. 2003; Greene et al. 2011) and various ecological systems (e.g., Frank et al. 2008a,2008b).

The relative nature of the SSC daily weather-type classification scheme (i.e., weather-type definitions vary across space and time) is a strength cited in many studies. The SSC has become one of the key analytical tools implemented in a diverse range of climate and health research investigations that are location-specific and time-specific (Hondula et al. 2014). Other areas of the study that have benefited from analyses of SSC data include air-quality variability (Davis et al. 2010; Pope and Kalkstein 1996; Power et al. 2006; Rainham et al. 2005; Vanos et al. 2014), human health (Hajat et al. 2010; Vanos et al. 2014, 2015), the urban heat island (Dixon and Mote 2003), and climatological trend analyses (Hondula and Davis 2011; Knight et al. 2008; Vanos and Cakmak 2014). Through these studies, we see the SSC is applicable to various topics in cross-cutting disciplines and has a large geographical range, which includes approximately 400 stations (Figure 1) spanning the USA, Canada, and Europe, and select cities in Asia with data covering several decades (Bower et al. 2007; Hondula et al. 2014; Sheridan 2002; Tan et al. 2004).

There are numerous opportunities to expand the application of synoptic-scale impact analyses to new locations, contexts, and disciplines. In this article, we discuss the identified gaps in both the spatial nature of the system and the disciplinary applications, providing critical information to researchers outside of the area of climatology on where and how the SSC can be successfully applied. This review highlights synoptic climatology as a catalyst for cross-discipline research.

2. *Synoptic Climatology*

2.1. DISCIPLINE REVIEW

A goal of synoptic climatology is to understand the relationships between the surface environment and overlying atmospheric circulation (Yarnal 1993). With a horizontal scale of

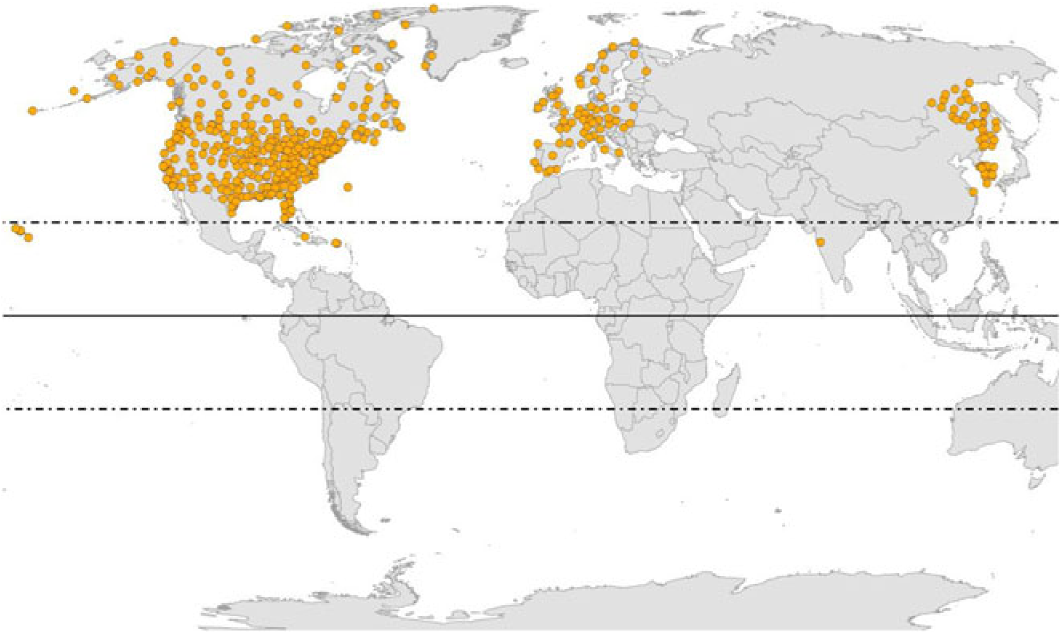

Fig. 1. Map of locations with SSC data available.

~1,000 km and a lifespan of ~5–7 days, cyclones and anticyclones, which are the main synoptic-scale features of the atmosphere, influence a wide range of environmental processes including water resources, severe-weather outbreaks, and health. Accordingly, local-scale analysis of weather often begins with a characterization of the synoptic-scale forcing processes. Such atmospheric "snapshots" provide simple, useful descriptions that are designed to aid understanding of our physical world.

In synoptic climatology, the classification scheme has been a primary focus of research efforts for many decades. Multiple variables have been used to classify atmospheric patterns including temperature, pressure, airflow, and derived properties such as vorticity (Barry 2005; Ledrew 1984). Additionally, these features are classified at multiple spatial (e.g., global or regional) and temporal (e.g., annual or daily) scales. Discrete classification of synoptic patterns allow synoptic climatologists to communicate with other disciplines so that environmental relationships may be analyzed (Carleton 1999). Only during the last two decades has the use of synoptic climatology accelerated significantly as a tool for applications rather than pure classification (Sheridan and Lee 2014; Yarnal et al. 2001).

Synoptic climatological classifications often involve one of two approaches. The circulation-to-environment approach emphasizes the atmospheric patterns. In this case, the overlying atmospheric scenario is classified *a priori* and then related to the surface variable of interest (e.g., air temperature). In contrast, the environment-to-circulation approach initially determines the environmental variable of study and then compares its condition to the circulation pattern(s) (Yarnal 1993).

Within the field of synoptic climatology, multiple classification approaches exist and may be subjective (manual), objective/computer-automated, or hybrid. Manual map comparisons began very early (Abercromby 1883; Lamb 1950; Van Bebber and Köppen 1895), yet this method was subjective and labor-intensive (Frakes and Yarnal 1997). In manual approaches, the analysis relies on professional expertise to define *a priori* classifications. While the majority of subjective catalogs (Baur et al. 1944; Lamb 1972) focus on regional analysis, some have been developed for larger-scale considerations (Girs 1948). Recently, automated and hybrid classification methods have been developed, and the discipline continues to evolve with the increased availability of weather data and more complex climate models. There is no standard classification scheme, but rather, synoptic climatology highlights the importance of interpreting map patterns and evaluating surface relationships. Huth et al. (2008) provide further discussion on synoptic climatological approaches.

Along with increased computing ability, more sophisticated, statistically robust techniques for classification have become increasingly common in synoptic climatology (Yarnal et al. 2001). In addition to understanding basic circulation controls, statistical and dynamic modeling techniques are used to uncover the patterns and near-surface processes related to a variety of environmental issues. Techniques such as cluster analysis (e.g., Esteban et al. 2005) and self-organizing maps (Hewitson and Crane 2002; Kohonen et al. 2001) have helped re-shape the discipline. Globally gridded reanalysis datasets (e.g., Dee et al. 2011; Ebita et al. 2011; Kalnay et al. 1996) have led to the inclusion of more complex, derived variables such as vorticity and moisture characteristics. Regional and global climate modeling now offer new approaches to examine the physical mechanisms linking surface conditions with atmospheric circulation (Giorgi and Mearns 1999).

2.2. SPATIAL SYNOPTIC CLASSIFICATION

The Spatial Synoptic Classification (SSC) is a weather-type classification based solely on surface observations. To determine the SSC weather types for a given time and place, a hybrid system is employed using both manual and automated processes. First, "typical" meteorological conditions are chosen for each of the weather types [Dry Polar (DP), Dry Moderate (DM), Dry Tropical (DT), Moist Polar (MP), Moist Moderate (MM), Moist Tropical (MT), or Transition (TR)] at each weather station based on climatological knowledge. There is also the MT+ subset of the MT weather type, which is common in the summer across the mid-latitudes, to differentiate the days with the greatest potential for heat stress. The MT+ conditions occur when both morning and afternoon apparent temperatures are above the MT weather-type means for the location (Sheridan and Kalkstein 2004). Sliding "seed days" representing each of the weather types are created for four two-week windows during each season of the year to correspond with the hottest and coldest two weeks annually and the midway points in spring and autumn for the given location (Sheridan 2002). The sliding seed-day method permits an improved temporal continuity across various climate types and throughout the entire year, encapsulating the temporally relative nature of the SSC.

Actual conditions are then compared to the seed days, and each day is classified as the weather type it most closely resembles (lowest error score based on equal-weighted z-scoring). The groups of days identified as certain SSC types are not completely homogeneous, as the synoptic-scale circulation is a complex process not perfectly described by seven distinct groups. Meteorological variability is also identified within an SSC weather type at various scales of interest dependent on the research (e.g., division of MT and DT days into categories of higher or lower severity for heat stress (Sheridan and Kalkstein 2004), division of TR days into categories representing various frontal types (Hondula and Davis 2011)). Complete details of the classification procedure can be found in Sheridan (2002). SSC data are freely available online at http://sheridan.geog.kent.edu/ssc.html.

3. Spatial Synoptic Classification Uses

3.1. TEMPERATURE AND HUMAN HEALTH

Among the wide range of potential applications for synoptic classification schemes, the SSC has gained greatest traction in studies of the relationships between heat and human-health outcomes. SSC-based studies of heat impacts on morbidity and mortality focus largely on the DT and MT+ weather types, often referred to as the "oppressive" types (e.g., Isaksen et al. 2015; Saha et al. 2015). These oppressive days have been applied in the development of several of the initial outcomes-based heat-health watch-warning systems deployed in the USA as well as in Toronto (Canada), South Korea, Shanghai (China), and select Italian cities (Kalkstein et al. 2008, 2011; Kirchmayer et al. 2004; Sheridan and Kalkstein 2004; Tan et al. 2004). More recently, the SSC and related techniques have been applied to the study of additional health outcomes including respiratory-related hospital admissions (Hondula et al. 2013; Lee et al. 2012), influenza and pneumonia mortality (Davis et al. 2012), and cold-season cardiovascular deaths (Lee 2015).

3.2. AIR POLLUTION

The SSC has been used to help characterize the relationship between air quality and meteorology in research studies set in Canada, Korea, and the United States. To date, the main pollutants addressed have been nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and particulate matter $< 2.5\ \mu m$ ($PM_{2.5}$). Standard analyses segregate each day into a select weather type, and the individual mean air pollution levels are then calculated and statistically compared by weather type. Prior to the current SSC, Cheng et al. (1992) completed the first SSC air pollution study using the SSC1 to assess concentrations of O_3 and PM in the city of Philadelphia. Following this, Pope and Kalkstein (1996) used the SSC1 to confirm associations between respirable particles and mortality in the Utah Valley, and Smoyer et al. (2000) described relationships between weather, air pollution, and mortality in Birmingham and Philadelphia (USA), also using the SSC1. Over the last 15 years, ambient air pollution has been shown in over a dozen studies to be closely related to the SSC weather type (e.g., Davis et al. 2010; Greene et al. 1999; Hanna et al. 2011; Kim et al. 2014; Rainham et al. 2005; Vanos et al. 2013; Vanos et al. 2015,2014). The most commonly cited findings show a close association between higher concentrations of O_3 on DT days, specifically in the summer season (e.g., Davis et al. 2010; Hanna et al. 2011; Kim et al. 2014; Rainham et al. 2001, 2005; Smoyer et al. 2000; Vanos et al. 2013). Further, Vanos et al. (2014) found that when DT air is present in Canada, other pollutants, such as NO_2 and SO_2, are significantly higher than the mean for all weather types. The stagnant, dry, sunny, and hot conditions found within the DT weather type result in the greatest pollution build up for many pollutants and aid in the photochemical creation of ozone (Davis and Kalkstein 1990; Smoyer et al. 2000). Low concentrations of pollutants have been generally found in moist, cool weather types (e.g., Greene et al. 1999), as well as the TR weather type (e.g., Rainham et al. 2005; Vanos et al. 2013). TR days are indicated by shifts in synoptic conditions and are commonly associated with frontal activity (increased wind and precipitation chances), thus resulting in lower air pollution levels. Newer research also links higher aeroallergen levels to the presence of MT and DT weather types in 10 Canadian cities (Hebbern and Cakmak 2015).

3.3. CLIMATE CHANGE

The potential impacts of climate change on human health have been assessed by applying weather-type–mortality relationships derived from the present climate to SSC types projected by global climate models (GCMs). This analysis was first completed using projections of weather types into the 2020s and 2050s for 44 cities in the USA, with subsequent analysis of each city's mortality risks (Kalkstein and Greene 1997). This analysis was later updated by Greene et al. (2011) to estimate mortality during excessive heat events (EHEs) for the 2020s, 2050s, and 2090s across 40 cities in the USA. An application of the SSC by Hayhoe et al. (2010) showed that a 2003 European Heatwave-type event could occur in Chicago by 2050, with a high likelihood of 10 times the city's current annual average number of heat-related deaths occurring in only a few weeks. In a rare application of synoptic-weather typing to assess climate-change impacts outside of the US, Cheng et al. (2008) showed that heat-related mortality could more than double by the 2050s and triple by the 2080s in south-central Canada. The most recent application of the SSC in climate-change impacts assessment projected future weather types for California for the 2090s and estimated that heat-related mortality among those over 65 could increase by tenfold in major urban centers (Sheridan et al. 2012a,2012b).

3.4. OTHER SSC USES

The utility of the SSC has not been limited to topics related to human health and the associated impacts of climate change. Researchers have applied the SSC types to discriminate days that are hot vs cold, arid vs humid, or synoptically active vs inactive. Almost immediately following Sheridan's (2002) release of the updated SSC, a few researchers employed the system as an efficient proxy for air-mass types, which were not historically easy to quantify for most locations (Dixon and Mote 2003; Grundstein 2003; Kalkstein and Balling 2004; Leathers et al. 2002, 2004). While some of these projects were focused on how SSC types affect snow cover and characteristics (Grundstein 2003; Leathers et al. 2002, 2004), one paper showed that SSC types could be used to understand summer thunderstorms initiated by the urban heat island (Dixon and Mote 2003). Kalkstein and Balling (2004) then used the SSC to analyze diurnal temperature range following the attack on the World Trade Center in New York on 11 September 2001. Hence, very early in the life of the SSC, it was becoming apparent that the system would have widespread applicability in weather and climate research.

Following the initial burst of authors using SSC for applied climatology research, subsequent papers were largely related to weather and health, with further studies addressing urban effects on weather (Brazel et al. 2007; Chow and Svoma 2011; Ellis et al. 2015) and diurnal temperature ranges (Scheitlin 2013; Scheitlin and Dixon 2010). Further growth was seen as climatologists began to use SSC as a way to define "synoptically weak" or "benign" days, which is important when studying convection, lightning, and other meteorological phenomena that are driven by thermal instability rather than dynamic forcing (Ashley et al. 2012; Bentley et al. 2010, 2012; Haberlie et al. 2015; Mote et al. 2007; Owen and Dixon 2015; Shem and Shepherd 2009; Stallins et al. 2013). Similarly, some researchers have discovered the utility of the SSC to efficiently analyze weather conditions as they relate to tree growth (Huang et al. 2010; Senkbeil et al. 2007) and wildlife behavior (Esslinger et al. 2015; Palumbo et al. 2016). Our discussion of articles using the SSC is not exhaustive, but it is clear that SSC is continuing to grow in popularity among researchers studying weather–health interactions as well as several other applications, mostly within applied climatology.

4. *Limitations of SSC Methods*

The previous sections demonstrate many opportunities to apply the SSC, and it appears that such opportunities will continue to grow. Therefore, we propose a goal for the SSC of being accessible and applicable for all possible uses where it has been shown to function well. This could mean establishing an SSC for all regions of the world, but that is not currently feasible due to a lack of reliable weather data (Hondula et al. 2014). There are many locations with reliable weather data but no SSC, and there is also a question of whether all climate types are conducive to daily classification by the SSC. Likewise, not all research topics involving synoptic weather variables can benefit from the SSC or synoptic classification systems in general. Here, we address some known limitations and challenges so that researchers from various disciplines can better understand and effectively apply the SSC to benefit their research goals.

4.1. LIMITATIONS IN TEMPERATURE-HEALTH RESEARCH

With its synoptic-scale resolution, the SSC is not designed to describe human exposure to thermal stress at microscale levels. This is a limitation from the physiological perspective as behavioral factors, metabolic rate, and clothing properties are not currently considered. In this sense, it could be argued that the SSC system is not yet applicable as a heat-stress index for estimating thermal strain in individuals (NIOSH 1986; Parsons 2003). There are, however, many pre-existing heat-stress indices that have been designed for the workplace to establish safe practices and safe limits for work (Parsons 2003).

With respect to environmental epidemiology, the SSC offers a considerable shift from many of the traditional and emerging techniques applied to investigate the association between temperature and mortality, in which continuous variables (e.g., temperature, heat index, and Universal Thermal Comfort Index (UTCI)) tend to be used in statistical models (e.g., Anderson and Bell 2009; McMichael et al. 2008; Petitti et al. 2015; Urban and Kyselý 2014). The association between exposure variables and health outcomes in these models has been shown in many places to be a smooth non-linear function. Mapping discrete variables like the SSC weather types into this continuous exposure-response space would seem to be a challenge (Barnett et al. 2010; Huang et al. 2011). Operational heat-health warning systems designed around the SSC, however, include linear regression functions within the subset of days associated with each weather type that allow for continuous prediction of anomalous mortality (Sheridan and Kalkstein 2004). Whether the current algorithmic approach utilized by these warning systems most effectively accounts for within SSC-type variability is an outstanding research question that we recommend investigating in the years ahead.

Evaluation of trigger indicators for heat-health early warning systems is recommended by the World Health Organization and World Meteorological Organization and should take into account system complexity, error in weather forecast data, and acceptability among user groups (Åström et al. 2014; McGregor et al. 2010). In an evaluation of the predictive capacity of four different triggering criteria for heat warning systems (including an SSC-based approach) in four different cities worldwide, Hajat et al. (2010) found that no system was recommended to be universally preferable. Other studies from Detroit and New York City in the USA suggest that relatively simple metrics like minimum temperature and maximum heat index perform comparably to more complex models, including the SSC; therefore, the simpler triggering criteria were deemed preferable for their locations (Metzger et al. 2010; Zhang et al. 2012). Urban and Kyselý (2016) also encouraged continued comparison of the current SSC framework to other approaches for triggering operational heat warning systems, including different methods based on sequences of SSC types.

These comparative studies are of interest because they represent the incorporation of different perspectives into the design of heat-health warning systems. For example, Hajat et al. (2010) connected research groups from academic institutions and government research offices across five different countries. The SSC and its operational extension for heat-health warning systems helped to push the conversation regarding what should be included in the design of effective triggering criteria. Whether or not the SSC is ultimately used as the basis for triggering a public health alert is, for us, less interesting than the idea that its consideration, along with alternatives ranging from simple environmental variables (e.g., temperature) to complex, biophysical indices (e.g., UTCI), can expand how researchers and practitioners think about designs of heat-health warning systems.

4.2. LIMITATIONS IN AIR POLLUTION STUDIES

Air pollution and health studies conducted in the 20th century supported the development of public warning systems when potentially harmful pollution was likely due to synoptic conditions (e.g., Smoyer et al. 2000). Yet, even with technological advancements and numerous studies showing connections between SSC weather types and air pollution, few studies have attempted to produce such SSC-based forecast models. Investigations of spatiotemporal connections between air pollution and synoptic weather generally stop short of providing a physical explanation. Rather, most research yields mean levels of air pollution for each SSC weather type before proceeding with health outcomes-based approaches.

A potential reason for difficulty in using the SSC for air pollution forecasting is the complexity in determining the origin of air pollution. Weather types alone cannot be used to identify source regions of pollutants (Hondula et al. 2010), and different circulation regimes can result in the same SSC designation at a given location. Certain DM days, for example, could advect pollutants from a problematic source region or be more conducive (e.g., warmer and sunnier) to the formation of secondary pollutants than other days, but such variability would be lost by simply examining overall differences between SSC types. Indeed, using the SSC to supplement back-trajectory analysis has revealed interactive relationships that are not evident from using only the back-trajectory or synoptic analytical method (Davis et al. 2010; Hondula et al. 2010).

Changing concentrations of ground-level pollution is driven by the variables often used to characterize air masses and weather types (e.g., temperature, pressure, wind, and sunlight), which provides the physical underpinning to explain why studies examining SSC air pollution linkages often report strong associations. These results are quite intuitive, yet highly generalized as they differ by pollutant of interest, location, and time of season. Further, the SSC is of greater utility for examining air pollution variability primarily in locations that are more susceptible to high concentrations and variability of air pollution (Smoyer et al. 2000). Hence, careful consideration and analysis are still required when using SSC to assess and/or predict air pollution.

4.3. THE CHALLENGES OF SSC OUTSIDE THE MID-LATITUDES

A map of SSC locations (Figure 1) highlights the absence of SSC locations in tropical, desert, and developing locations, with a distinct lack of stations in the southern hemisphere. Access to reliable weather data is challenging in many developing countries, so there is little that can be done to remedy that in the near term. There is still a question of whether the SSC provides as much value in tropical and/or desert locations that are less likely to experience synoptic-scale frontal passages and the associated sudden air-mass changes. Such locations often experience the same synoptic weather types for months at a time. For example, Miami, Florida (USA) experiences the MT weather type on 65% of days annually and 80% of summer days (Figure 2). It is certainly feasible to break down those climates into SSC types that are relative to specific locations, but it may not be very useful if the air temperature differences between DT and MM SSC types are only a few degrees. Further, some current SSC locations along the southern tier of the USA never experience as many as three of the seven possible categories during long periods. Frequency distributions of SSC types throughout the year for select SSC locations (Figure 2) illustrate that mid-latitude locations tend to experience all SSC categories in every season while sub-tropical locations are unable to fully take advantage of the seven SSC categories. We encourage continued investigation of the relationship between SSC weather types and synoptic-scale circulation regimes in these locations to determine if there is within SSC-type heterogeneity that may be valuable to capture in new tools that aid the fields of climatology and applied climatology.

A noteworthy example of a tropical SSC location that is also in a developing country is Pune, India (the only location in India; Figure 1). Previous research has shown associations between temperature and human health in rural parts of Pune District (Ingole et al. 2012); therefore, the authors of this manuscript collaborated (along with the help of others, including Scott Sheridan) to develop the SSC for the city of Pune to work toward improved weather–health research in India and an expanded network of SSC stations. One concern among developers was a lack of the usual four seasons as Pune is dominated by the Asian monsoon, resulting in just three discernible seasons: summer, monsoon, and winter (Figure 3). Moreover, due to the altitude and overall aridity of Pune, diurnal temperature ranges can often exceed 20 °C during summer and winter. However, interseasonal differences are much less dramatic with mean monthly temperatures all within 10 °C of each other, and it is debatable whether Pune ever experiences weather types that are truly Polar (e.g., Pune has never officially recorded a temperature below freezing). There is the possibility that the SSC can ultimately prove useful in a location even if some of the categories are never experienced, but only if it helps to understand and/or predict weather-related effects on non-atmospheric variables, such as health and ecology. Researchers are currently working to test associations between SSC and health outcomes in locations like Pune.

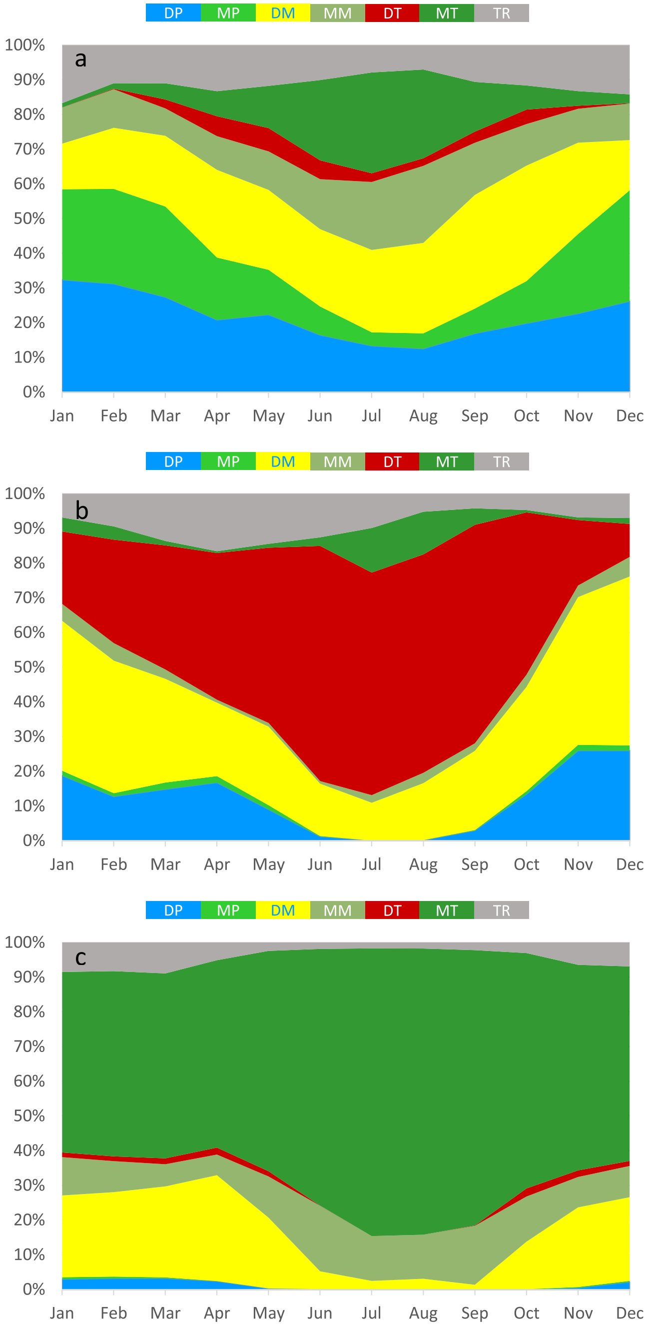

Fig. 2. Frequency distributions of each SSC category throughout the year in 10-day periods for (a) Chicago (1946–2014), (b) Las Vegas (1948–2014), and (c) Miami (1948–2014).

While confirming the lack of synoptic frontal activity across much of the land located within the tropics, Berry et al. (2011) show that some tropical regions do regularly experience fronts (Figure 4). It is probably not prudent to describe large regions of the planet as being "good" or "bad" candidates for SSC stations without a thorough review of the climatology of the

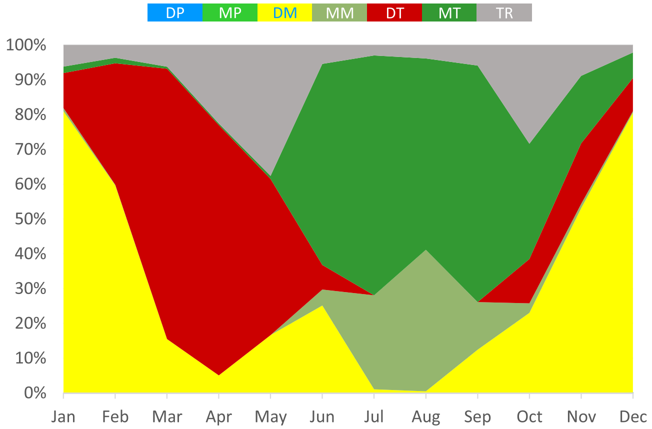

Fig. 3. Frequency distributions of each SSC category throughout the year in 10-day periods for Pune, India (1973–2014).

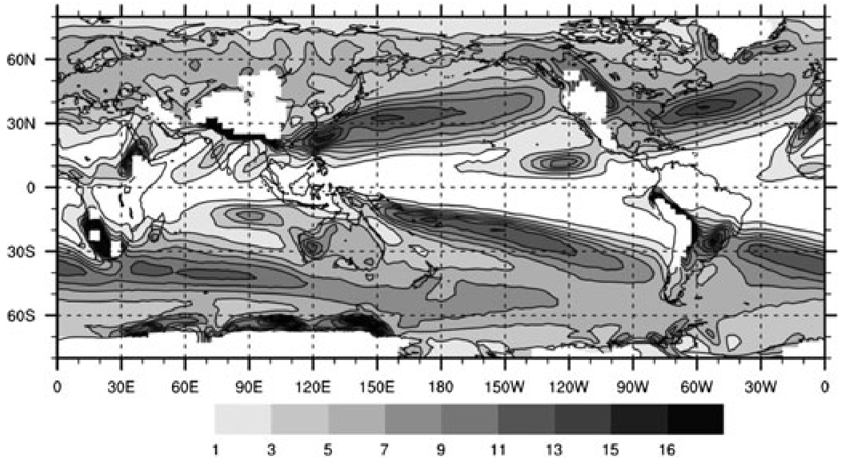

Fig. 4. Frequency (percentage of 6-hr intervals) of fronts, 1958–2001 (Berry et al. 2011).

locations in question, but it does appear that some locations would fail to make enough use of the SSC categories to justify creating them.

5. Advantages and Opportunities

The SSC has been relatively under-utilized in the assessment of climate-change impacts, both in terms of the region of application (most studies have been focused on the USA) and with respect to impacts being assessed (most focus on human health). Thus, a unique opportunity exists to explore numerous climate-change impacts around the world using the SSC. GCMs output climate variables required to develop SSCs on a grid covering the globe at resolutions as fine as 25 km (Roberts et al. 2014), so there is potential for applying the SSC to assess impacts in many regions of the globe. There is also potential to use the SSC to assess impacts such as (but not limited to): water stress, food security, energy demand, wildfires, and crop yields. These impacts typically occur across spatial domains similar to that of the SSC. These vital outcomes are similar to human health as their statuses also depend on multiple, often simultaneous, weather variables in addition to human decisions. Given the success of using SSC to study human-health outcomes, the issues listed above are likely to benefit from SSC analyses as well. In any case, comparison and evaluation between techniques should provide a framework for new applications of synoptic climatology (Huth 1996; Huth et al. 2008).

Human–weather interactions are dynamic and complex because an individual's response, both physiological and behavioral, can alter the level of exposure, which determines their well-being, health, or even survival. This interaction and any resulting physiological strain can be defined by six factors or agents (Fanger 1970):

1. ambient air temperature;
2. air motion or wind velocity
3. relative humidity;
4. mean radiant temperature;
5. metabolic heat production of the body; and
6. the clothing worn and its insulation and moisture permeability.

The first four of these agents are environmental, and they should all be considered when assessing the thermal influence of the environment on the human body (Höppe 1999), while the remaining two are behavioral. There is much debate and research surrounding which human thermal index is superior at predicting the human experience in a given environment. Difficulties arise when accounting for the complexity and interactions of all six factors. It has even been suggested that there cannot be a universal system for rating thermal stress (Belding 1970; Epstein and Moran 2006). In this sense, there may be an advantage to using a system, such as the SSC, that describes well the four climate variables and does not attempt to assume how humans may behave. Future work on the SSC system might advantageously consider behavioral factors (particularly varying levels of metabolic heat production) with respect to heat-health warning systems to determine how a weather type impacts humans performing varying levels of physical activity.

Air temperature alone is frequently used to assess the impact of the climatic environment on human health (Hondula et al. 2014; Parsons 2003) even though air temperature is seldom the lone cause of heat stress (Goldman 2001). Such a reductionist approach can limit our understanding of human–weather interactions. High humidity significantly increases heat stress by lowering the efficacy of evaporative heat loss (achieved via sweating), which is the primary human mechanism for heat loss under warm–hot conditions (Havenith 1999; Parsons 2003). Similarly, increased air velocity (wind) enhances both convective and evaporative heat loss (Havenith 1999) in most situations. The radiant temperature is directly related to the heat exchange between the environment and the human body, and can significantly contribute to heat stress, matching the heating effect of air temperature when air velocity is minimal (Höppe 1999). Thus, consideration of all four environmental factors and their interactions is essential in accurately describing the relationship between human health and the climatic environment. In this respect, the SSC and its comprehensive integration of meteorological parameters (air temperature, dew point, wind velocity, pressure, and cloud cover as a proxy for radiation) provide a meaningful and insightful description of climatic variables while combining them into one index, which is more manageable for subsequent epidemiological analyses.

A likely advantage of using the SSC for epidemiological and physiological research is its location and time specificity because weather–health interactions vary seasonally and geographically due to thermal acclimatization and adaptation strategies. For example, at the end of winter, a population may be more vulnerable to a sudden hot day. Further, populations in extreme climates are more resilient to weather variability than those in temperate regions due to adaptation strategies (behavioral responses, clothing, housing, technology, etc.). The spatial resolution of the SSC is suitable to characterize the climate sensitivity or vulnerability of different socioeconomic groups (Kalkstein and Davis 1989). Such characterization is important in understanding key modifiers that affect the interaction between human health and climate.

6. Conclusions

Ultimately, there are three closely related goals in this area of research: increase cross-discipline research, increase knowledge and awareness of SSC, and increase geographical locations with available SSC data. The success of any of these three goals seems to depend heavily on the progress of the other two, so working toward one is indirectly equivalent to working on all of them. There will be challenges in expanding the SSC network and the demand for SSC data in many parts of the world that have been underserved thus far. However, history suggests that there will be "tipping points" where it becomes quite efficient to increase the number of SSC stations in a country after the first few are established and these bursts of new data will likely be accompanied by newfound interest in those data by regional researchers. It also seems quite likely that the SSC is simply not suitable for the climates of some locations. Determining which locations fall into this category will not be easy, but this is an area of potential future research that could lead to improved synoptic classification methods and/or weather–health assessment tools.

Application of the SSC, or any synoptic weather analysis tool, in other disciplines often involves the introduction of an analytical approach (i.e., synoptic classification) that will be unfamiliar to subject experts. This situation can potentially create confusion, disagreement, and competition among researchers who ultimately have shared questions and goals. We suggest, however, that such blending of ideas can lead to a productive scientific advancement. The application of the SSC to temperature-related mortality is a fertile ground for such cross-perspective discussions that has only recently begun to appear in the scientific literature. There have been several conference sessions, workshops, and collaborative research projects available in recent years for researchers to learn more about the SSC and its potential applications. Such opportunities should be less about learning a specific tool (i.e., the SSC) and more about learning to embrace the methods, perspectives, and goals of other disciplines. The simplicity of the SSC categories makes it a great catalyst for crossing disciplinary boundaries and making meaningful progress toward solving real environmental problems, but it cannot be applied in all scenarios. It would be a great compliment to those who developed the SSC over the years if cross-discipline researchers beyond climatology find common ground in their past use of the SSC. In the past several years, the SSC has been applied to numerous research topics including human health, urban heat islands, tree growth, wildlife behavior, and climate change, and there are some obvious areas of overlap between these study topics that might lead to future collaborations. It is conceivable that the SSC could become a potential gateway to interdisciplinary efforts connecting weather, climate, human health, and ecology.

Short Biographies

Grady Dixon's research has been primarily focused on biometeorology and weather-related hazards. Most of his recent work has addressed tornado climatology, weather–suicide associations, and heat-related mortality. His research has been published in the *International Journal of Biometeorology*, *Bulletin of the American Meteorological Society*, *International Journal of Climatology*, *Journal of Applied Meteorology and Climatology*, *Monthly Weather Review, Weather and Forecasting, Natural Hazards, Geography Compass*, and others. He has been a field editor for the International Journal of Biometeorology since 2011. Dixon is currently chair and associate professor in the Department of Geosciences at Fort Hays State University in Hays, Kansas (USA). Previously, he worked for 9 years at Mississippi State University. He earned a BS in geosciences from

Mississippi State University, an MS in geography from University of Georgia, and a PhD in geography from Arizona State University.

Michael Allen is an Assistant Professor of Geography at Old Dominion University in Norfolk, Virginia (USA). His research focuses on seasonality, climate change, and the societal impacts of climate and weather particularly related to extreme temperature events. Michael's research has appeared in such journals as the *International Journal of Climatology*, *International Journal of Biometeorology*, and *Theoretical and Applied Climatology*. He earned a BS in Earth Science-Meteorology from California University of Pennsylvania and both an MA and a PhD in geography from Kent State University.

Simon Gosling's research assesses the global-scale risks of climate change to society. He uses various techniques, such as numerical modeling, meta-analysis, and literature review to understand the effects of climate change on a variety of risks, including human health, agriculture, and water resources. He has authored or co-authored over 30 research articles on climate risk in journals such as *Nature Climate Change*, *PNAS*, and *Climatic Change*. Simon is currently Director of Research and Associate Professor in Climate Risk at the School of Geography at the University of Nottingham (UK), which is ranked in the top 1% of universities internationally by the latest (2015) QS World University Rankings. Previously, Simon has held positions at King's College London, the London School of Economics and Political Science (LSE), the University of Reading, and the UK Met Office. He is a Fellow of the Royal Meteorological Society (FRMetS) and a Fellow of the Royal Geographical Society (FRGS).

David Hondula is an Assistant Professor in Climatology and Atmospheric Science in the School of Geographical Sciences and Urban Planning at Arizona State University (USA). Hondula investigates the health impacts of atmospheric hazards and strategies for reducing associated health risks with an emphasis on extreme heat. He is a lead author for the Climate and Health Profile for the State of Arizona and has authored or co-authored research articles published in journals including *Environmental Health Perspectives*, *Environmental Research*, and *International Journal of Climatology*. Hondula holds additional appointments at Arizona State University with the Center for Policy Informatics and Julie Ann Wrigley Global Institute of Sustainability and is a faculty affiliate of the Maricopa County Department of Public Health. Hondula earned his PhD at the University of Virginia (USA) and has completed fellowships at Umeå University (Sweden) and Queensland University of Technology (Australia).

Vijendra Ingole's primary research focuses on environmental epidemiology in the western rural part of India. He earned his basic degree in environmental science and GIS and remote sensing. His recent work is on weather-related mortality and impact of climate change on health in rural populations of India. He has recently published his research in the *International Journal of Environmental Research and Public Health* and the *International Journal Global Health Action*. He also worked with John Hopkins University on indoor air pollution and published his work in *American Journal of Respiratory Cell and Molecular Biology*. He is currently pursuing his PhD at Umeå University (Sweden) and Vadu Rural Health Program, KEM Hospital Research Centre, Pune, India. Previously, Vijendra worked as a teaching associate in the Department of Geography at the University of Pune (India). He is a visiting research fellow at the London School of Hygiene and Tropical Medicine (UK).

Rebekah Lucas is an integrative physiologist who is interested in how exercise and environmental medicine translate to clinical medicine and public health. Her research examines human tolerance and adaptation to physical and environmental stressors, with a particular focus on thermal vascular physiology. Her research has been published in *Experimental Physiology*, *Extreme Physiology & Medicine, and American Journal of Physics*.

Jennifer Vanos specializes in the study of human biometeorology and bioclimatology, examining the separate and combined impacts of weather and climate on human health. Specifically, she addresses the impacts of extreme heat and air pollution in urban areas on human well-being, from children to the elderly. She employs various observation and modeling techniques to understand the weather conditions now and in the future in differing geographic regions at various scales in time and space. She has authored numerous manuscripts addressing the health impacts of heat and air pollution found within journals such as *Environment International*, Applied Meteorology and Climatology, Landscape and *Urban Planning*, and Atmospheric Environment. Jennifer is a member of the American Meteorological Society's Board of Environment and Health and currently works as an Assistant Professor in Atmospheric Science at Texas Tech University in Lubbock, Texas (USA). Previously, she worked at Health Canada in the Environmental Health Research Bureau and completed her PhD and Bachelor's degrees at the University of Guelph in Ontario, Canada.

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References

Abercromby, R. (1883). On certain types of British weather. *Quarterly Journal of the Royal Meteorological Society* 9, pp. 1–25.

Anderson, B. G. and Bell, M. L. (2009). Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiology* 20, pp. 205.

Ashley, W. S., Bentley, M. L. and Stallins, J. A. (2012). Urban-induced thunderstorm modification in the Southeast United States. *Climatic Change* 113, pp. 481–498.

Åström, C., Ebi, K. L., Langner, J. and Forsberg, B. (2014). Developing a heatwave early warning system for Sweden: evaluating sensitivity of different epidemiological modelling approaches to forecast temperatures. *International Journal of Environmental Research and Public Health* 12, pp. 254–267.

Barnett, A. G., Tong, S. and Clements, A. C. A. (2010). What measure of temperature is the best predictor of mortality? *Environmental Research* 110, pp. 604–611.

Barry, R. G. (2005). Synoptic climatology. In: Oliver, J. E. (ed) *Encyclopedia of world climatology*. Dordrecht, The Netherlands: Springer.

Baur, F., Hess, P. and Nagel, H. (1944). Kalender der Großwetterlagen Europas 1881–1939. Technical Report, Forschungsinstitut für langfristige Wettervorhersage. Bad Homburg.

Belding, H. S. (1970). The search for a universal heat stress index. In: Hardy, J., Gagge, A. and Stolwijk, J. (eds) *Physiological and behavioral temperature regulation*. Springfield, Illinois: Charles C. Thomas.

Bentley, M. L., Ashley, W. S. and Stallins, J. A. (2010). Climatological radar delineation of urban convection for Atlanta, Georgia. *International Journal of Climatology* 30, pp. 1589–1594.

Bentley, M. L., Stallins, J. A. and Ashley, W. S. (2012). Synoptic environments favourable for urban convection in Atlanta, Georgia. *International Journal of Climatology* 32, pp. 1287–1294.

Berry, G., Reeder, M. J. and Jakob, C. (2011). A global climatology of atmospheric fronts. *Geophysical Research Letters* 38, L04809. DOI: 10.1029/2010GL046451

Bower, D., McGregor, G. R., Hannah, D. M. and Sheridan, S. C. (2007). Development of a spatial synoptic classification scheme for western Europe. *International Journal of Climatology* 27, pp. 2017–2040.

Brazel, A., Gober, P., Lee, S.-J., Grossman-Clarke, S., Zehnder, J., Hedquist, B. and Comparri, E. (2007). Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Climate Research* 33, pp. 171.

Carleton, A. M. (1999). Methodology in climatology. *Annals of the Association of American Geographers* 89, pp. 713–735.

Cheng, C., Campbell, M., Li, Q., Li, G., Auld, H., Day, N., Pengelly, D., Gingrich, S., Klaassen, J., MacIver, D., Comer, N., Mao, Y., Thompson, W. and Lin, H. (2008). Differential and combined impacts of extreme temperatures and air pollution on human mortality in south–central Canada. Part II: future estimates. *Air Quality, Atmosphere & Health* 1, pp. 223–235.

Cheng, S., Ye, H. and Kalkstein, L. S. (1992). An evaluation of pollution concentrations in Philadelphia using an automated synoptic approach. *Middle States Geographer* 25, pp. 45–51.

Chow, W. T. and Svoma, B. M. (2011). Analyses of nocturnal temperature cooling-rate response to historical local-scale urban land-use/land cover change. *Journal of Applied Meteorology and Climatology* 50, pp. 1872–1883.

Davis, R. E. and Kalkstein, L. S. (1990). Using a spatial synoptic climatological classification to assess changes in atmospheric pollution concentrations. *Physical Geography* 11, pp. 320–342.

Davis, R. E., Knappenberger, P. C., Michaels, P. J. and Novicoff, W. M. (2003). Changing heat-related mortality in the United States. *Environmental Health Perspectives* 111, pp. 1712–1718.

Davis, R. E., Normile, C. P., Sitka, L., Hondula, D. M., Knight, D. B., Gawtry, S. P. and Stenger, P. J. (2010). A comparison of trajectory and air mass approaches to examine ozone variability. *Atmospheric Environment* 44, pp. 64–74.

Davis, R. E., Rossier, C. E. and Enfield, K. B. (2012). The impact of weather on influenza and pneumonia mortality in New York City, 1975–2002: a retrospective study. *PLoS ONE* 7, e34091.

Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G. and Bauer, P. (2011). The ERA-interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* 137, pp. 553–597.

Dixon, P. G. and Mote, T. L. (2003). Patterns and causes of Atlanta's urban heat island–initiated precipitation. *Journal of Applied Meteorology* 42, pp. 1273–1284.

Ebita, A., Kobayashi, S., Ota, Y., Moriya, M., Kumabe, R., Onogi, K., Harada, Y., Yasui, S., Miyaoka, K. and Takahashi, K. (2011). The Japanese 55-year reanalysis "JRA-55": an interim report. *Sola* 7, pp. 149–152.

Ellis, K. N., Hathaway, J. M., Mason, L. R., Howe, D. A., Epps, T. H. and Brown, V. M. (2015). Summer temperature variability across four urban neighborhoods in Knoxville, Tennessee, USA. *Theoretical and Applied Climatology* in press.

Epstein, Y. and Moran, D. S. (2006). Thermal comfort and the heat stress indices. *Industrial Health* 44, pp. 388–398.

Esslinger, Z. A., Giersch, A., Lankutis, J. and Dixon, P. G. (2015). Observing effects of weather on white-tailed deer. 2015 Annual Meeting, Association of American Geographers, Chicago, Illinois.

Esteban, P., Jones, P. D., Martín-Vide, J. and Mases, M. (2005). Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. *International Journal of Climatology* 25, pp. 319–329.

Fanger, P. (1970). *Thermal comfort: analysis and applications in environmental engineering*. New York: McGraw Hill.

Frakes, B. and Yarnal, B. (1997). A procedure for blending manual and correlation-based synoptic classifications. *International Journal of Climatology* 17, pp. 1381–1396.

Frank, K., Geils, B., Kalkstein, L. and Thistle, H. Jr. (2008a). Synoptic climatology of the long-distance dispersal of white pine blister rust II. Combination of surface and upper-level conditions. *International Journal of Biometeorology* 52, pp. 653–666.

Frank, K., Kalkstein, L., Geils, B. and Thistle, H. Jr. (2008b). Synoptic climatology of the long-distance dispersal of white pine blister rust. I. Development of an upper level synoptic classification. *International Journal of Biometeorology* 52, pp. 641–652.

Giorgi, F. and Mearns, L. O. (1999). Introduction to special section: regional climate modeling revisited. *Journal of Geophysical Research, [Atmospheres] (1984–2012)* 104, pp. 6335–6352.

Girs, A. (1948). Some aspects concerning basic forms of atmospheric circulation. *Meteorologiya i Gidrologiya* 3, pp. 9–11.

Goldman, R. (2001). Introduction to heat-related problems in military operations. In: Pandolf, K. B., Burr, R. E., Wenger, C. B. and Pozos, R. S. (eds) *Medical aspects of harsh environments*. Washington, DC: Department of the Army, Office of the Surgeon General, and Borden Institute.

Greene, S., Kalkstein, L. S., Mills, D. M. and Samenow, J. (2011). An examination of climate change on extreme heat events and climate–mortality relationships in large U.S. Cities. *Weather, Climate, and Society* 3, pp. 281–292.

Greene, J., Kalkstein, L., Ye, H. and Smoyer, K. (1999). Relationships between synoptic climatology and atmospheric pollution at 4 US cities. *Theoretical and Applied Climatology* 62, pp. 163–174.

Grundstein, A. (2003). A synoptic-scale climate analysis of anomalous snow water equivalent over the Northern Great Plains of the USA. *International Journal of Climatology* 23, pp. 871–886.

Haberlie, A. M., Ashley, W. S. and Pingel, T. J. (2015). The effect of urbanisation on the climatology of thunderstorm initiation. *Quarterly Journal of the Royal Meteorological Society* 141, pp. 663–675.

Hajat, S., Sheridan, S. C., Allen, M. J., Pascal, M., Laaidi, K., Yagouti, A., Bickis, U., Tobias, A., Bourque, D. and Armstrong, B. G. (2010). Heat-health warning systems: a comparison of the predictive capacity of different approaches to identifying dangerously hot days. *American Journal of Public Health* 100, pp. 1137.

Hanna, A. F., Yeatts, K. B., Xiu, A., Zhu, Z., Smith, R. L., Davis, N. N., Talgo, K. D., Arora, G., Robinson, P. J. and Meng, Q. (2011). Associations between ozone and morbidity using the spatial synoptic classification system. *Environmental Health* 10, pp. 15.

Havenith, G. (1999). Heat balance when wearing protective clothing. *Annals of Occupational Hygiene* 43, pp. 289–296.

Hayhoe, K., Sheridan, S., Kalkstein, L. and Greene, S. (2010). Climate change, heat waves, and mortality projections for Chicago. *Journal of Great Lakes Research* 36, pp. 65–73.

Hebbern, C. and Cakmak, S. (2015). Synoptic weather types and aeroallergens modify the effect of air pollution on hospitalisations for asthma hospitalisations in Canadian cities. *Environmental Pollution* 204, pp. 9–16.

Hewitson, B. C. and Crane, R. G. (2002). Self-organizing maps: applications to synoptic climatology. *Climate Research* 22, pp. 13–26.

Hondula, D. M. and Davis, R. E. (2011). Climatology of winter transition days for the contiguous USA, 1951–2007. *Theoretical and Applied Climatology* 103, pp. 27–37.

Hondula, D. M., Davis, R. E., Knight, D. B., Sitka, L. J., Enfield, K., Gawtry, S. B., Stenger, P. J., Deaton, M. L., Normile, C. P. and Lee, T. R. (2013). A respiratory alert model for the Shenandoah Valley, Virginia, USA. *International Journal of Biometeorology* 57, pp. 91–105.

Hondula, D. M., Sitka, L., Davis, R. E., Knight, D. B., Gawtry, S. D., Deaton, M. L., Lee, T. R., Normile, C. P. and Stenger, P. J. (2010). A back-trajectory and air mass climatology for the Northern Shenandoah Valley, USA. *International Journal of Climatology* 30, pp. 569–581.

Hondula, D., Vanos, J. and Gosling, S. (2014). The SSC: a decade of climate–health research and future directions. *International Journal of Biometeorology* 58, pp. 109–120.

Höppe, P. (1999). The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology* 43, pp. 71–75.

Huang, C., Barnett, A. G., Wang, X., Vaneckova, P., Fitzgerald, G. and Tong, S. (2011). Projecting Future Heat-related Mortality under Climate Change Scenarios: A Systematic Review. *Environmental Health Perspectives* 119, pp. 1681–1690.

Huang, J., Tardif, J. C., Bergeron, Y., Denneler, B., Berninger, F. and Girardin, M. P. (2010). Radial growth response of four dominant boreal tree species to climate along a latitudinal gradient in the eastern Canadian boreal forest. *Global Change Biology* 16, pp. 711–731.

Huth, R. (1996). An intercomparison of computer-assisted circulation classification methods. *International Journal of Climatology* 16, pp. 893–922.

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., Kyselý, J. and Tveito, O. E. (2008). Classifications of atmospheric circulation patterns. *Annals of the New York Academy of Sciences* 1146, pp. 105–152.

Ingole, V., Juvekar, S., Muralidharan, V., Sambhudas, S. and Rocklov, J. (2012). The short-term association of temperature and rainfall with mortality in Vadu Health and Demographic Surveillance System: a population level time series analysis. *Global Health Action* 5, pp. 44–52.

Isaksen, T. B., Fenske, R. A., Hom, E. K., Ren, Y., Lyons, H. and Yost, M. G. (2015). Increased mortality associated with extreme-heat exposure in King County, Washington, 1980–2010. *International Journal of Biometeorology* 60, pp. 1–14.

Kalkstein, A. J. and Balling, R. C. Jr. (2004). Impact of unusually clear weather on United States daily temperature range following 9/11/2001. *Climate Research* 26, pp. 1–4.

Kalkstein, L. S. and Davis, R. E. (1989). Weather and human mortality: an evaluation of demographic and interregional responses in the United States. *Annals of the Association of American Geographers* 79, pp. 44–64.

Kalkstein, L. S. and Greene, J. S. (1997). An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change. *Environmental Health Perspectives* 105, pp. 84–93.

Kalkstein, L. S., Greene, J. S., Mills, D. M., Perrin, A. D., Samenow, J. P. and Cohen, J.-C. (2008). Analog European heat waves for U.S. cities to analyze impacts on heat-related mortality. *Bulletin of the American Meteorological Society* 89, pp. 75–85.

Kalkstein, L. S., Greene, J. S., Mills, D. and Samenow, J. (2011). An evaluation of the progress in reducing heat-related human mortality in major U.S. cities. *Natural Hazards* 56, pp. 113–129.

Kalkstein, L. S., Nichols, M. C., Barthel, C. D. and Greene, J. S. (1996). A new spatial synoptic classification: application to air-mass analysis. *International Journal of Climatology* 16, pp. 983–1004.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G. and Woollen, J. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77, pp. 437–471.

Kim, H. C., Choi, H., Ngan, F. and Lee, P. (2014). Surface ozone variability in synoptic pattern perspectives. In: *Air pollution modeling and its application XXIII.* Cham, Switzerland: Springer.

Kirchmayer, U., Michelozzi, P., de'Donato, F., Kalkstein, L. S. and Perucci, C. A. (2004). A national system for the prevention of health effects of heat in Italy. *Epidemiology* 15, pp. S100–S101.

Knight, D. B., Davis, R. E., Sheridan, S. C., Hondula, D. M., Sitka, L. J., Deaton, M., Lee, T. R., Gawtry, S. D., Stenger, P. J. and Mazzei, F. (2008). Increasing frequencies of warm and humid air masses over the conterminous United States from 1948 to 2005. *Geophysical Research Letters* 35, L10702. DOI: 10.1029/2008GL033697

Kohonen, T., Schroeder, M. and Huang, T. (2001). *Self-organizing maps.* Secaucus, NJ: Springer-Verlag New York, Inc.

Lamb, H. (1950). Types and spells of weather around the year in the British Isles: annual trends, seasonal structure of the year, singularities. *Quarterly Journal of the Royal Meteorological Society* 76, pp. 393–429.

Lamb, H. H. (1972). *British Isles weather types and a register of the daily sequence of circulation patterns, 1861–1971.* London: Her Majesty's Stationery Office.

Leathers, D. J., Graybeal, D., Mote, T., Grundstein, A. and Robinson, D. (2004). The role of airmass types and surface energy fluxes in snow cover ablation in the Central Appalachians. *Journal of Applied Meteorology* 43, pp. 1887–1899.

Leathers, D. J., Mote, T. L., Grundstein, A. J., Robinson, D. A., Felter, K., Conrad, K. and Sedywitz, L. (2002). Associations between continental-scale snow cover anomalies and air mass frequencies across eastern North America. *International Journal of Climatology* 22, pp. 1473–1494.

Ledrew, E. F. (1984). The role of local heat sources in synoptic activity within the Polar Basin. *Atmosphere-Ocean* 22, pp. 309–327.

Lee, C. C. (2015). A systematic evaluation of the lagged effects of spatiotemporally relative surface weather types on wintertime cardiovascular-related mortality across 19 US cities. *International Journal of Biometeorology* in press.

Lee, C., Sheridan, S. and Lin, S. (2012). Relating weather types to asthma-related hospital admissions in New York State. *EcoHealth* 9, pp. 427–439.

McGregor, G., Ebi, K., Bessemoulin, P. and Menne, B. (2010). Heat waves and health: guidance on warning system development. Report to the World Meteorological Organization and World Health Organization.

McMichael, A. J., Wilkinson, P., Kovats, R. S., Pattenden, S., Hajat, S., Armstrong, B., Vajanapoom, N., Niciu, E. M., Mahomed, H. and Kingkeow, C. (2008). International study of temperature, heat and urban mortality: the “ISOTHURM”project. *International Journal of Epidemiology* 37, pp. 1121–1131.

Metzger, K. B., Ito, K., Matte, T. D. (2010). Summer Heat and Mortality in New York City: How Hot Is Too Hot? *Environmental Health Perspectives* 118(1), pp. 80–86. Retrieved from http://www.jstor.org/stable/30249909

Mote, T. L., Lacke, M. C. and Shepherd, J. M. (2007). Radar signatures of the urban effect on precipitation distribution: a case study for Atlanta, Georgia. *Geophysical Research Letters* 34, L20710. DOI: 10.1029/2007GL031903

Muller, R. A. (1977). A synoptic climatology for environmental baseline analysis: New Orleans. *Journal of Applied Meteorology* 16, pp. 20–33.

NIOSH (1986). *Criteria for a recommended standard: occupational exposure to hot environment*. Washington, DC: National Institute for Occupational Safety and Health.

Owen, N. O. and Dixon, P. G. (2015). An investigation into the impacts of land-use/land-cover and urbanization on cloud-to-ground lightning activity. *International Journal of Biometeorology* in review .

Palumbo, M. D., Vilella, F. J., Wang, G., Strickland, B. K., Godwin, D. and Dixon, P. G. (2016). Regional differences on gobbling activity of the wild turkey in Mississippi. *Wildlife Society Bulletin* in press .

Parsons, K. C. (2003). *Human thermal environments: the effects of hot, moderate and cold temperatures on human health, comfort and performance*. London: Taylor & Francis.

Petitti, D. B., Hondula, D. M., Yang, S., Harlan, S. L. and Chowell, G. (2015). Multiple trigger points for quantifying heat-health impacts: new evidence from a hot climate. *Environmental Health Perspectives* in press .

Pope, C. A. and Kalkstein, L. S. (1996). Synoptic weather modeling and estimates of the exposure-response relationship between daily mortality and particulate air pollution. *Environmental Health Perspectives* 104, pp. 414–420.

Power, H. C., Sheridan, S. C. and Senkbeil, J. C. (2006). Synoptic climatological influences on the spatial and temporal variability of aerosols over North America. *International Journal of Climatology* 26, pp. 723–742.

Rainham, D. G. C., Smoyer, K. and Burnett, R. (2001). Spatial synoptic classification of air pollution and human mortality associations in Toronto, Canada: past relationships and policy implications. *American Journal of Epidemiology* 153, pp. 1015.

Rainham, D. G., Smoyer-Tomic, K. E., Sheridan, S. C. and Burnett, R. T. (2005). Synoptic weather patterns and modification of the association between air pollution and human mortality. *International Journal of Environmental Health Research* 15, pp. 347–360.

Roberts, M. J., Vidale, P. L., Mizielinski, M. S., Demory, M.-E., Schiemann, R., Strachan, J., Hodges, K., Bell, R. and Camp, J. (2014). Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models. *Journal of Climate* 28, pp. 574–596.

Saha, S., Brock, J. W., Vaidyanathan, A., Easterling, D. R. and Luber, G. (2015). Spatial variation in hyperthermia emergency department visits among those with employer-based insurance in the United States–a case-crossover analysis. *Environmental Health* 14, pp. 20.

Scheitlin, K. (2013). The maritime influence on diurnal temperature range in the Chesapeake Bay area. *Earth Interactions* 17, pp. 1–14.

Scheitlin, K. N. and Dixon, P. G. (2010). Variations in diurnal temperature range in the Southeast due to land-use/land-cover classifications, 1995–2004. *Journal of Applied Meteorology and Climatology* 49, pp. 879–888.

Senkbeil, J. C., Rodgers, J. C. III and Sheridan, S. C. (2007). The sensitivity of tree growth to air mass variability and the Pacific Decadal Oscillation in coastal Alabama. *International Journal of Biometeorology* 51, pp. 483–491.

Shem, W. and Shepherd, M. (2009). On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. *Atmospheric Research* 92, pp. 172–189.

Sheridan, S. C. (2002). The redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology* 22, pp. 51–68.

Sheridan, S. C., Allen, M. J., Lee, C. C. and Kalkstein, L. S. (2012a). Future heat vulnerability in California, Part II: projecting future heat-related mortality. *Climatic Change* 115, pp. 311–326.

Sheridan, S. C. and Dolney, T. J. (2003). Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, USA. *Climate Research* 24, pp. 255–265.

Sheridan, S. C. and Kalkstein, L. S. (2004). Progress in heat watch-warning system technology. *Bulletin of the American Meteorological Society* 85, pp. 1931–1941.

Sheridan, S. and Lee, C. (2014). Synoptic Climatology. *Oxford Bibliographies* in Geography. DOI: 10.1093/obo/9780199874002-0088

Sheridan, S. C., Lee, C. C., Allen, M. J. and Kalkstein, L. S. (2012b). Future heat vulnerability in California, Part I: projecting future weather types and heat events. *Climatic Change* 115, pp. 291–309.

Smoyer, K. E., Rainham, D. G. C. and Hewko, J. N. (2000). Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996. *International Journal of Biometeorology* 44, pp. 190–197.

Stallins, J. A., Carpenter, J., Bentley, M. L., Ashley, W. S. and Mulholland, J. A. (2013). Weekend–weekday aerosols and geographic variability in cloud-to-ground lightning for the urban region of Atlanta, Georgia, USA. *Regional Environmental Change* 13, pp. 137–151.

Tan, J., Kalkstein, L., Huang, J., Lin, S., Yin, H. and Shao, D. (2004). An operational heat/health warning system in Shanghai. *International Journal of Biometeorology* 48, pp. 157–162.

Urban, A. and Kyselý, J. (2014). Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *International Journal of Environmental Research and Public Health* 11, pp. 952–967.

Urban, A. and Kyselý, J. (2016). Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic. *International Journal of Biometeorology* .

Van Bebber, W. J. and Köppen, W. (1895). Die Isobarentypen des Nordatlantischen Ozeans und Westeuropas: ihre Beziehungen zur Lage und Bewegung der barometrischen Maxima und Minima. *Archiv der Deutschen Seewarte* 18, pp. 27.

Vanos, J. and Cakmak, S. (2014). Changing air mass frequencies in Canada: potential links and implications for human health. *International Journal of Biometeorology* 58, pp. 121–135.

Vanos, J. K., Cakmak, S., Bristow, C., Brion, V., Tremblay, N., Martin, S. L. and Sheridan, S. S. (2013). Synoptic weather typing applied to air pollution mortality among the elderly in 10 Canadian cities. *Environmental Research* 126, pp. 66–75.

Vanos, J., Cakmak, S., Kalkstein, L. and Yagouti, A. (2015). Association of weather and air pollution interactions on daily mortality in 12 Canadian cities. *Air Quality, Atmosphere & Health* 8, pp. 1–14.

Vanos, J. K., Cakmak, S., Kalkstein, L. S. and Yagouti, A. (2015). Association of weather and air pollution interactions on daily mortality in 12 Canadian cities. *Air Quality, Atmosphere & Health* 8, pp. 307–320.

Vanos, J. K., Hebbern, C. and Cakmak, S. (2014). Risk assessment for cardiovascular and respiratory mortality due to air pollution and synoptic meteorology in 10 Canadian cities. *Environmental Pollution* 185, pp. 322–332.

Yarnal, B. (1993). *Synoptic climatology in environmental analysis: a primer*. London: Belhaven Press.

Yarnal, B., Comrie, A. C., Frakes, B. and Brown, D. P. (2001). Developments and prospects in synoptic climatology. *International Journal of Climatology* 21, pp. 1923–1950.

Zhang, K., Rood, R. B., Michailidis, G., Oswald, E. M., Schwartz, J. D., Zanobetti, A., Ebi, K. L> and O'Neill, M. S. (2012). Comparing exposure metrics for classifying 'dangerous heat' in heat wave and health warning systems. *Environment International* 46, pp. 23–29.