Perspectives on Synoptic Climate Classification and its Role in Interdisciplinary Research

Authors: P. Grady Dixon[1], Michael Allen[2], Simon N. Gosling[3], David M. Hondula[4,5], Vijendra Ingole[6,7], Rebekah Lucas[8], Jennifer Vanos[9]

[1] Department of Geosciences, Fort Hays State University, Hays, Kansas, USA

[2] Department of Political Science and Geography, Old Dominion University, Norfolk, Virginia, USA

[3] School of Geography, University of Nottingham, Nottingham, United Kingdom

[4] Center for Policy Informatics, Arizona State University, Phoenix, Arizona, USA

[5] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, Arizona, USA

[6] Umeå Centre for Global Health Research, Umeå University, Umeå, Sweden

[7] Vadu Rural Health Program, KEM Hospital Research Centre, Pune, India

[8] School of Sport, Exercise, and Rehabilitation Sciences, University of Birmingham, Birmingham, United Kingdom

[9] Department of Geosciences, Texas Tech University, Lubbock, Texas, USA

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 researcher 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), is 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 (Greene et al., 2011, Davis et al., 2003) and various ecological systems (e.g., Frank et al., 2008a, Frank et al., 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- and time-specific (Hondula et al., 2014). Other areas of 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., 2014b), human health (Hajat et al., 2010, Vanos et al., 2014b, Vanos et al., 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 United States, 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

a. 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 ~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, 2013, 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).

b. 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

a. 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., 2011, Kalkstein et al., 2008, 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).

b. 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 µm ($PM_{2.5}$). 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 & 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., 2014a, Vanos et al., 2013, Vanos et al., 2014b). 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., 2005, Rainham et al., 2001, Smoyer et al., 2000, Vanos et al., 2013). Further, Vanos et al. (2014b) 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).

c. 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, Sheridan et al., 2012b).

d. 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., 2004, Leathers et al., 2002). While some of these projects were focused on how SSC types affect snow cover and characteristics (Grundstein, 2003, Leathers et al., 2004, Leathers et al., 2002), 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, Bentley et al., 2012, Owen and Dixon, 2015, Stallins et al., 2013, Haberlie et al., 2015, Mote et al., 2007, Shem and Shepherd, 2009). 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., 2015). 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.

a. 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, Universal Thermal Comfort Index (UTCI)) tend to be used in statistical models (e.g., McMichael et al., 2008, Anderson and Bell, 2009, Urban and Kyselý, 2014, Petitti et al., 2015). 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 (2015) 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.

b. 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); 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, 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, 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 is still required when using SSC to assess and/or predict air pollution.

c. 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.

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 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
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) provides 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.

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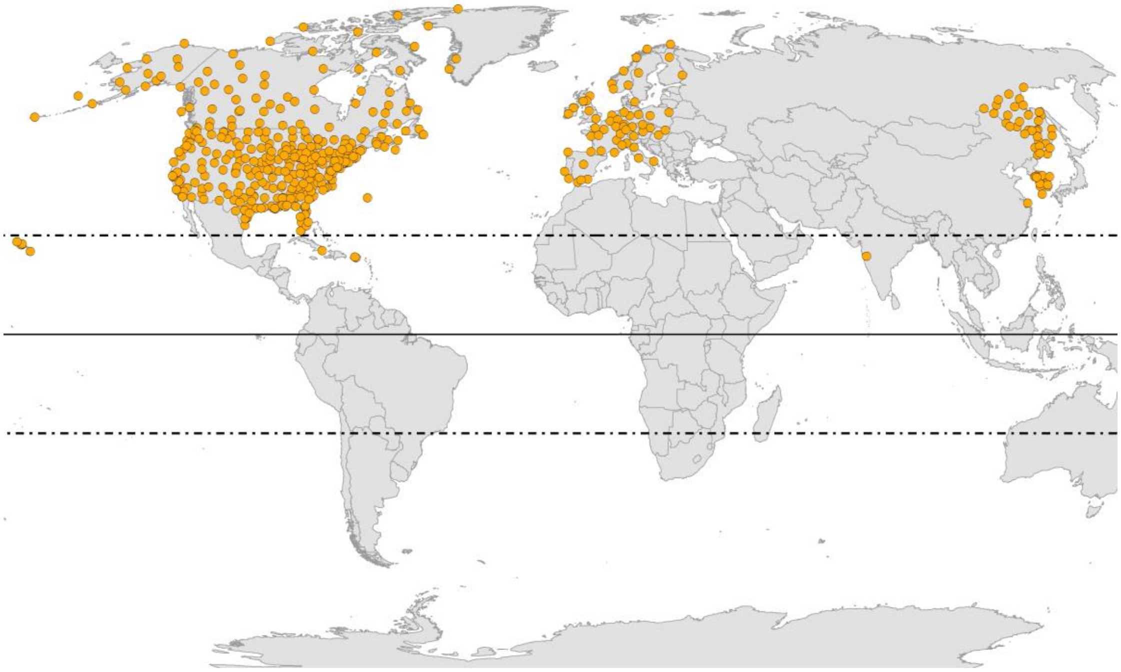
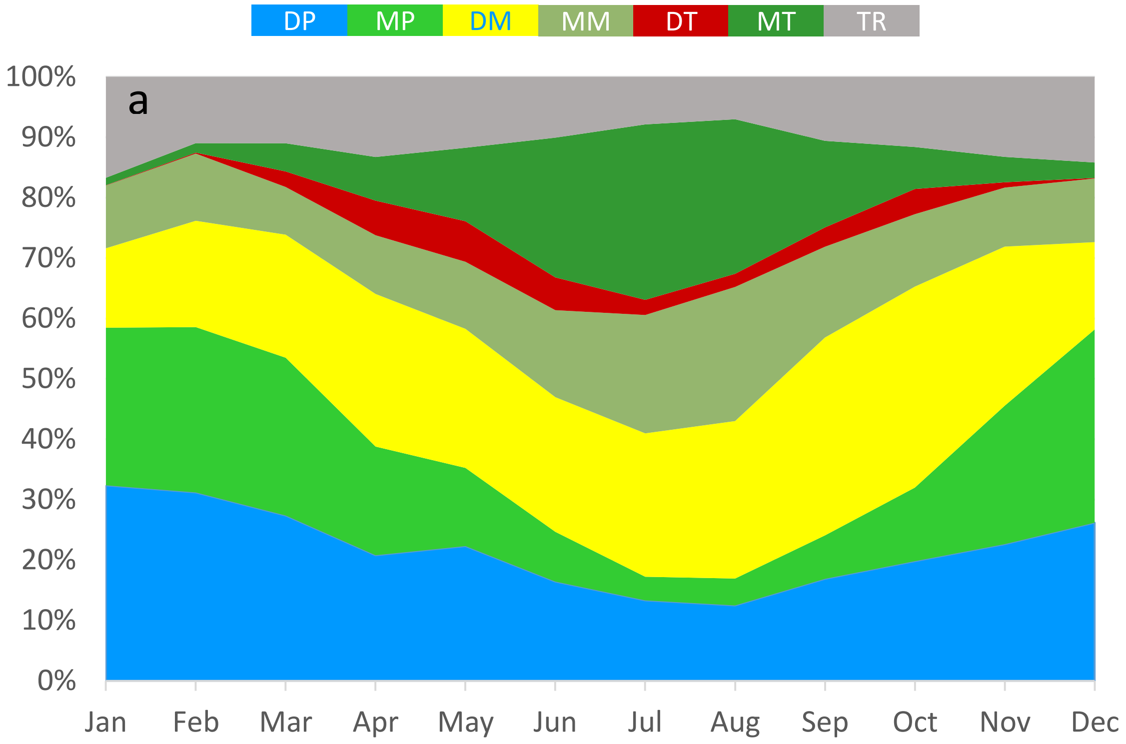


Figure 1: Map of locations with SSC data available.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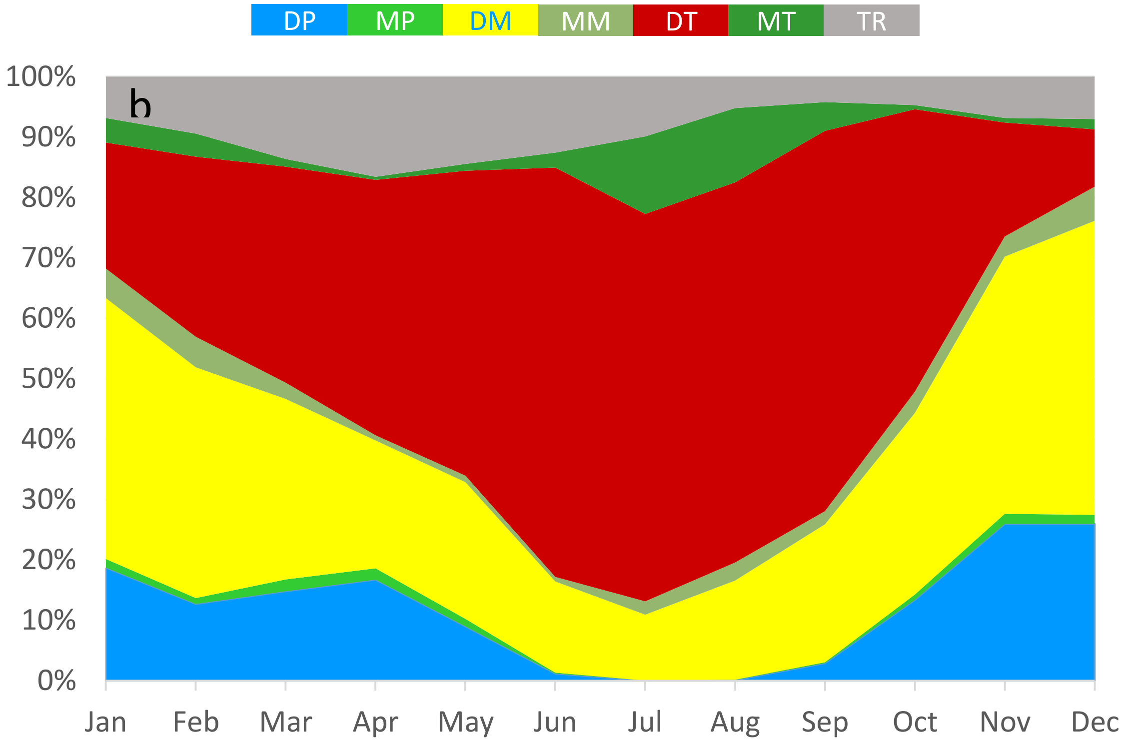
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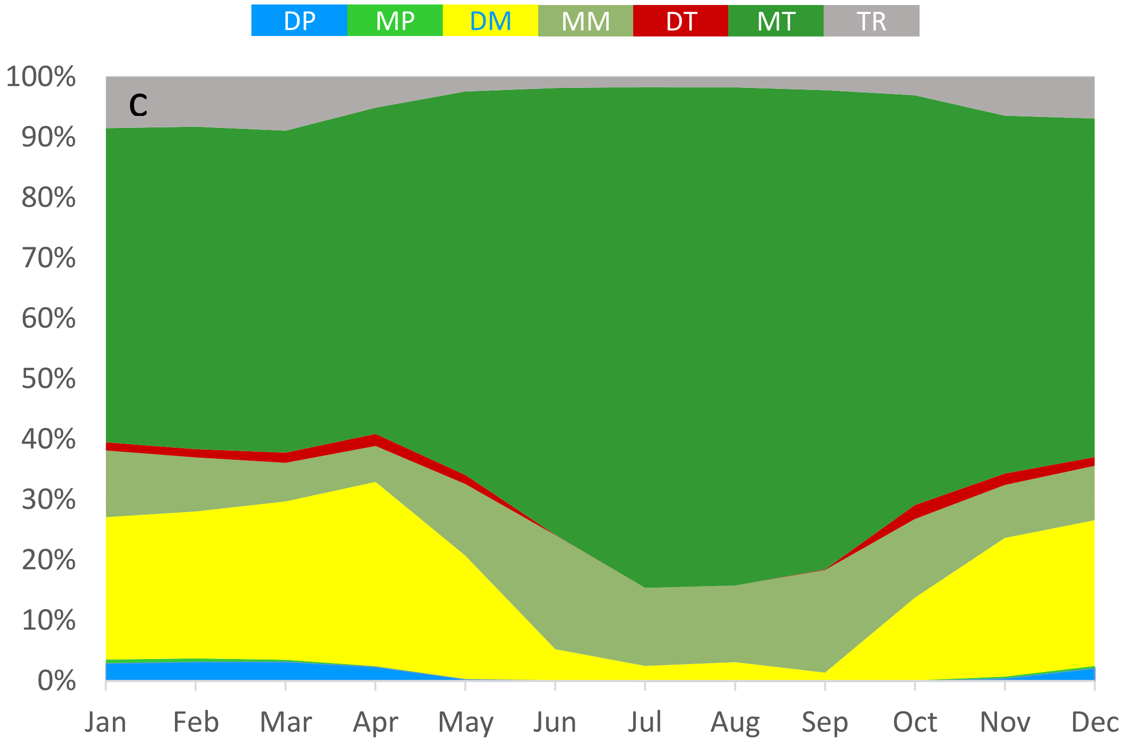

Figure 2: Frequency distributions of each SSC category throughout the year in 10-day periods for (a) Chicago (1946–2014), (b) Las Vegas (1948–2014), and (c) Miami (1948–2014).

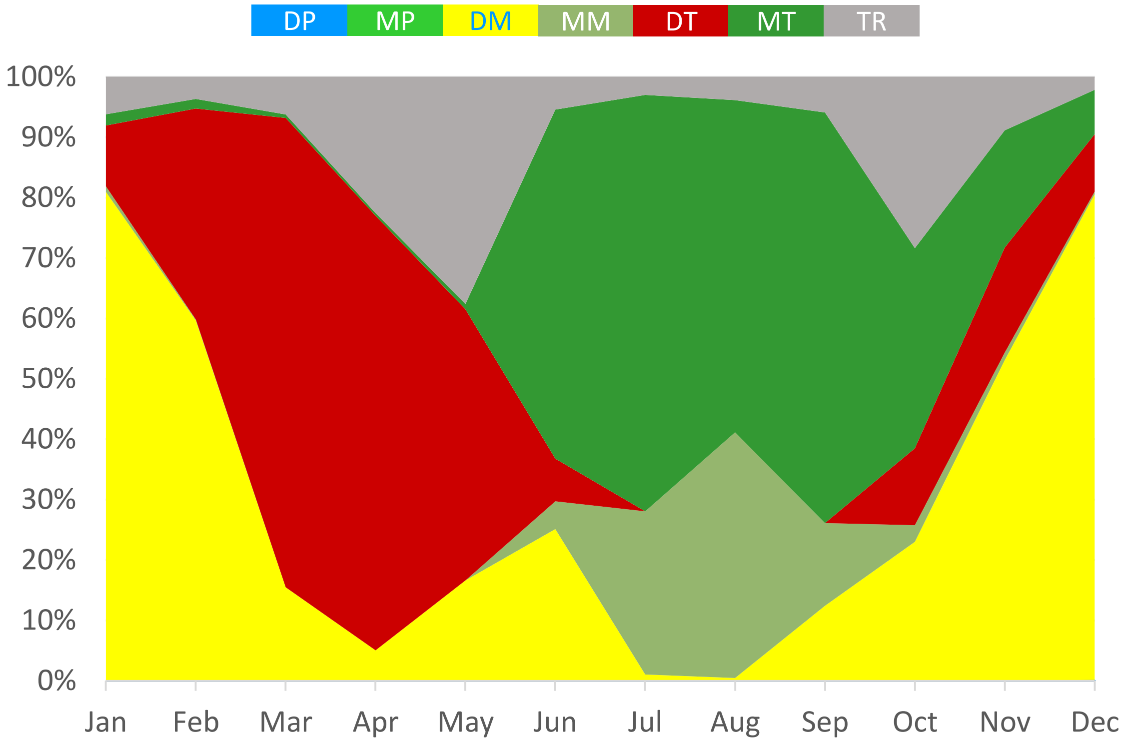

Figure 3: Frequency distributions of each SSC category throughout the year in 10-day periods for Pune, India (1973–2014).

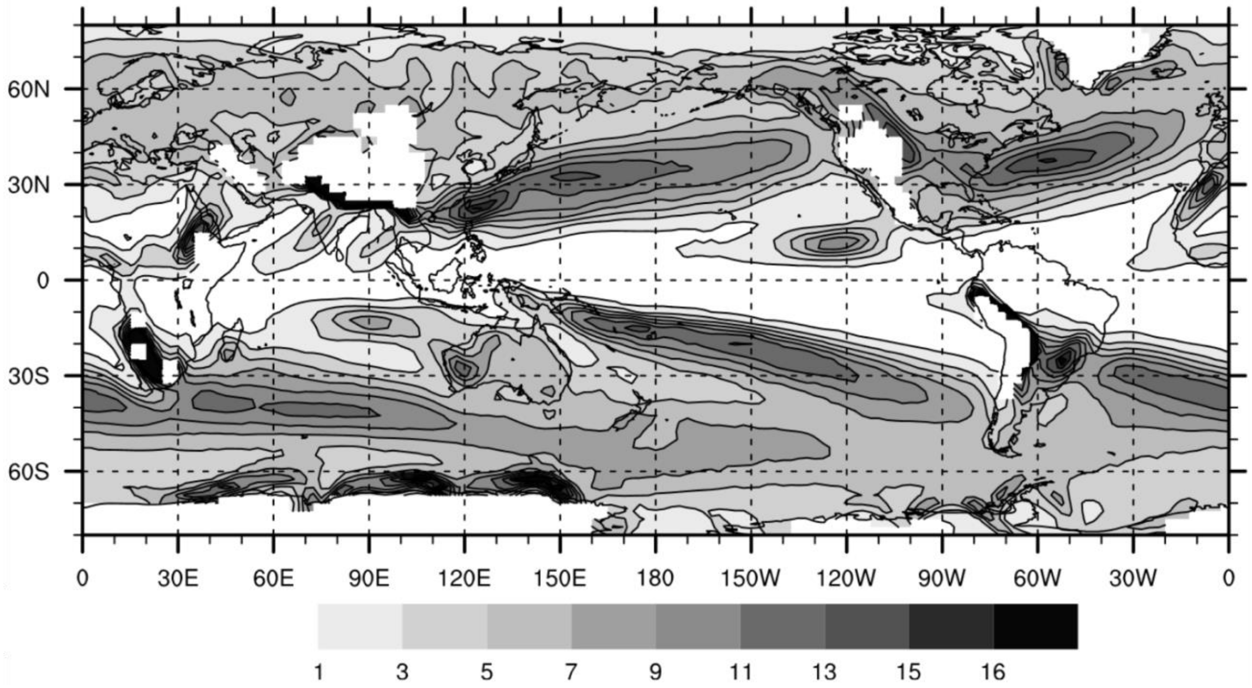

Figure 4: Frequency (percentage of 6-hr intervals) of fronts, 1958–2001 (Berry et al., 2011).