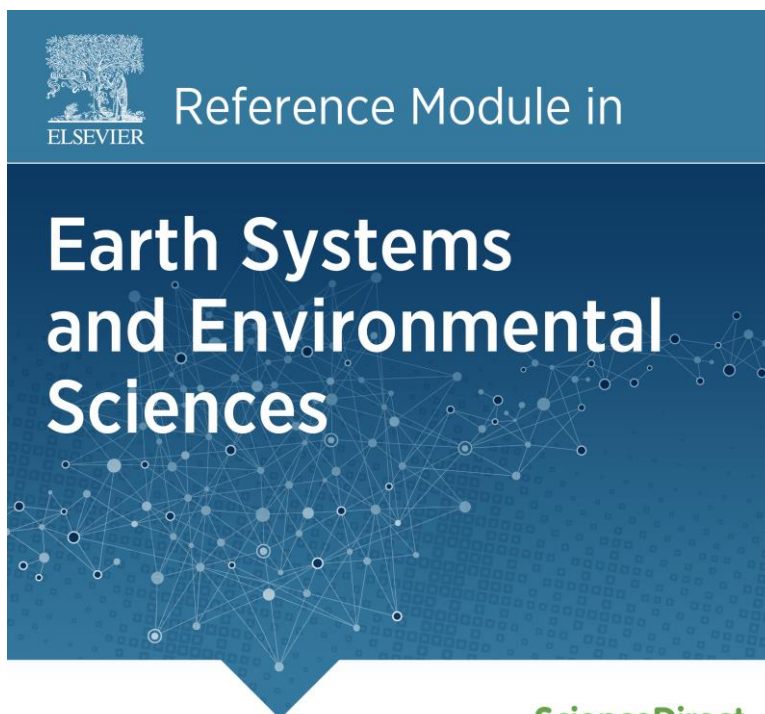


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Synoptic Climatology: An Overview

CC Lee and SC Sheridan, Kent State University, Kent, OH, USA

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|---|---|
| Introduction and Background on Synoptic Climatology | 1 |
| Key Decisions and the Human Influence in Synoptic Classifications | 2 |
| Major Themes in Contemporary Synoptic Climatological Applications | 4 |
| Future Directions and Concluding Remarks | 5 |
| References | 6 |

Introduction and Background on Synoptic Climatology

Since its first usage in 1942 (Barry and Perry, 1973; Jacobs, 1947), synoptic climatology as a discipline has been continuously evolving. Unsurprisingly, even today, the field is still somewhat abstract to those first introduced to the discipline. The term 'synoptic' is by itself somewhat unspecific; in meteorology, the term is often used in reference to the synoptic scale, an area larger than the mesoscale but smaller than the continental scale, somewhere on the order of 1000–2500 km (NOAA, 2014). Extending this meteorological definition would logically imply that 'synoptic climatology' is the averaging of the weather that happens on those scales; however, this definition is incomplete. Within the realm of climatology, the term 'synoptic' ('syn' = same + 'optic' = view) is also often meant to describe viewing the atmosphere as a holistic state, a generalized overview of the important atmospheric conditions at a certain point in time (Yarnal, 1993). Both of these perspectives on the term 'synoptic' are useful in defining the discipline of synoptic climatology however, do not fully provide an answer to what the discipline has become today.

Early in the twentieth century, the fundamental building blocks of what would eventually become the discipline of synoptic climatology were discussed by Swedish climatologist Tor Bergeron. Delivering a paper in 1929, he proposed the analysis of world climates based upon the study of larger-scale air masses, weather systems, fronts, and flow patterns (Hare, 1955) – concepts that are now synonymous with the 'Bergen School' conceptual model of midlatitude weather (Yarnal, 1993) of which Bergeron was a part. Interestingly, these concepts were initially proposed by Bergeron as forming the field of dynamic climatology (Barry and Perry, 1973) – a subfield of climatology that today is quite different. As Hare (1955) explained, the field of synoptic climatology evolved from motives stemming from weather prediction for military needs during World War II, where Bergeron's ideas of large-scale air masses and frontal passages were key indicators of smaller-scale variables such as visibility, cloud base, and wind direction, which were important for aerial warfare over a particular region. However, prior to the computing age, making climatological sense of the meteorological data available at the time was most easily accomplished via the analysis of *categories* of weather. Categorizing the weather brings structure, order, and simplicity to an unwieldy amount of climatological data, thus allowing one to both make sense of an otherwise highly complex climate system and also more easily describe the impacts of the weather using analogues (Yarnal, 1993). Classification of the climate system into discrete categories also allows the climatologist to incorporate the innate range and variability of midlatitude weather into an analysis in a manner that simple climatological averages cannot (Yarnal, 1993).

From these roots, Barry and Perry (1973) noted various authors' historical definitions of synoptic climatology throughout the 1950s and 1960s before identifying two fundamental stages of a synoptic climatological study: a categorization of the broader-scale atmospheric circulation and an analysis of the relationship between these categories and the more local weather elements. As Yarnal (1993) noted, the categorization of the atmosphere was still a key component of all synoptic climatological analyses at the time of the publication of his book in 1993; however, since 1973 (i.e., the publication of Barry and Perry's book), improved data collection and data availability in a variety of scientific disciplines had allowed for a more direct analysis of the impacts of weather on 'nonmeteorological but climatically related' surface environments. Yarnal (1993) instead offered an updated definition of synoptic climatology, as a study that involves four factors: (1) a classification of atmospheric circulation, (2) a linking of two scales of analysis (the larger-scale circulation with the smaller-scale surface environment), (3) a focus on the effect of climatic *variability* on the surface environment, and (4) that the surface environment being studied is representative of a spatial region.

In the two decades that have passed since Yarnal's seminal book, the line differentiating synoptic climatology and dynamic climatology has become more defined, as the latter ventured firmly down the path of dynamic modeling of atmospheric processes and the former has expanded its focus in many ways. As we will discuss in the sections that follow, the breadth of synoptic climatological applications has expanded immensely, with extensive use in bioclimatological studies – especially those concerning human health, pollution and pollen research, and extreme events. The issue of global climate change has spurred on synoptic climatology in recent decades as well, as *synopticians* have capitalized on the vast amount of model output data produced by the modeling community, to downscale and analyze the more local-scale potential impacts of climate change (Sheridan and Lee, 2010).

As applications of synoptic climatology have evolved since 1993, so too has the definition of what constitutes a synoptic climatological analysis, representing an evolution in the theoretical side of the discipline as well. Today, most of the four factors

that Yarnal (1993) described as mandatory for a synoptic climatological analysis are largely still true but have broadened in scope. For example, one could argue that the definition of 'circulation' itself has broadened to the point of being slightly misleading, as atmospheric classifications can take many forms in addition to traditional circulation patterns – such as defining geographic spaces or multivariate entities at a single location. Further, the term 'surface environment' might more aptly be referred to simply as a 'climate-related outcome,' as these outcomes need not be at the surface (e.g., Carleton et al., 2008), nor are they always an 'environment' in as much as they are an event or occurrence. Additionally, some synoptic studies are not concerned with the actual relationship between the atmosphere and the surface in as much as using the 'surface environment' merely for statistically validating a classification (e.g., Beck and Philipp, 2010).

While synoptic climatology is perhaps more unspecific today than ever, it holds onto one key defining characteristic: the classification (Sheridan and Lee, 2014). Contemporary synoptic climatology is a methodological perspective on climatology that creates and/or uses a classification of atmospheric variables (at nearly any spatial or temporal scale) to either simplify the climate system into a manageable set of states or gain a better understanding of how atmospheric variability impacts any climate-related outcome. Importantly, while synoptic climatology *as a discipline* involves the creation and application of classifications of the atmosphere, a synoptic climatological study need not *create* a classification, but merely *use* one.

With that historical perspective and working definition in mind, the sections that follow include a discussion of the major perspectives on synoptic classifications, key decisions in the research process, and a brief overview of popular applications in the recent literature. The aim of this manuscript is not necessarily to detail how a synoptic climatological research project can be undertaken (for that, please refer to Yarnal, 1993) or discuss specific methodologies (please see, e.g., Philipp et al., 2010), but rather to provide a brief overview of the theories and applications that have shaped contemporary synoptic climatology. Yarnal (1993) still stands as the most complete and influential literature describing modern synoptic climatology, and thus, we draw extensively upon his work and update how the discipline has evolved since.

Key Decisions and the Human Influence in Synoptic Classifications

Yarnal (1993) outlined a number of key decision points when undertaking a synoptic classification. Due to its utility in helping researchers understand the discipline, this taxonomy of classifications is still a large part of synoptic climatology today. For the sake of clarity, within this article, we will give each of these key decision points a name: *perspective*, *mode*, *approach*, and *methodology*. Further, when we discuss a synoptic climatological study, the variables used in the classification itself will simply be called *atmospheric variables* (AVs), while the variables representing the 'surface environment' to which the classification is applied will be referenced as *outcomes*.

At the very foundation of a classification is the investigator's decision to use either a circulation-to-environment (C-to-E) or an environment-to-circulation (E-to-C) perspective (Yarnal, 1993). The former is a very generalizable classification of the atmosphere that is undertaken independent of the outcome for which it is to be used. One of the key benefits of using the C-to-E perspective is that the classification could be used for predictive modeling since all observations are classified (e.g., Miller et al., 2006). Further, the C-to-E perspective allows the existing classification to be used in additional studies – such as the Lamb weather types (Lamb, 1972), Grosswetterlagen type (Hess and Brezowsky, 1952), and the spatial synoptic classification (SSC) (Sheridan, 2002) – provided that the AVs are key factors influencing the variability of the outcome within the spatial domain. For these reasons, the C-to-E perspective is much more common than its counterpart. The E-to-C perspective is more study-specific – classifying the atmosphere only when a specific outcome occurs (e.g., high ozone days, high dust days, or days when a flood occurred in Dayan et al., 2012). This perspective, therefore, is limited to use only in the study at hand, since the outcome itself is predetermining which observations of the AVs are classified. Despite its unpopularity, due to the more specific focus of the E-to-C perspective on the exact outcome, location, and place of interest, it can usually offer a greater level of detail or understanding of the various atmospheric processes that lead to an outcome than the C-to-E perspective. The E-to-C perspective can be particularly effective when the outcome is an extreme event, when the binary occurrence or nonoccurrence of that event is the criterion that must be met for an observation to be classified (e.g., Davis et al., 1997). This perspective also defines the perspective that must be used when conducting a classic compositing analysis (Seluchi and Chou, 2009; Yarnal, 1993). Thus, each perspective provides valuable insight to the researcher.

A second key decision of synoptic classification is the mode of classifying the atmosphere. Yarnal described a number of modes, including compositing (mentioned earlier), indexing (e.g., Kutiel et al., 1996), and regionalization (Brown and Kipfmüller, 2012; Comrie and Glenn, 1998); however, contemporary synoptic climatological classifications usually take one of two basic modes: a circulation pattern classification (CPC; sometimes referred to as a map-pattern classification) or a weather-type classification (WTC; often referred to as an air-mass classification). It is important to note that the specific terminology denoting these two modes is used loosely in various studies and has changed over time; for example, sometimes, a CPC is labeled as a WTC or its resultant patterns are called weather types. However, the difference between the two approaches is quite apparent (s-mode vs. p-mode of data decomposition; Yarnal, 1993) and can be discerned once reading the methodology section of any study.

The s-mode of data decomposition used for CPC is set up where each case (row in a spreadsheet) represents a different time (most commonly, a day) and each column represents a specific location (e.g., a grid point), while the spreadsheet itself represents (usually) one specific AV (e.g., 500 mb geopotential height). With this setup, each individual cell is the value of the AV at each

location at each time, and the values across a whole row quantify the circulation pattern across the spatial domain for that time. Eventually, each row is classified into one of several categories based upon the similarity of the shape of that case's pattern relative to the other cases being classified. Thus, a CPC focuses on multiple locations, typically a single (occasionally multiple, e.g., Coleman and Rogers, 2007) AV, and its spatial variability, or pattern of flow.

CPCs have a well-developed history of classification techniques. The earliest CPCs were all very labor-intensive (Yarnal, 1993), requiring individual climatologists to analyze stacks of weather maps and essentially sort them into piles representing categories of either circulation patterns over a region or locations of cyclonicity (Hess and Brezowsky, 1952; Lamb, 1972). While these manual methods were the only option prior to the digital era, they also presented serious drawbacks such as poor reproducibility (Yarnal, 1993). The very first automated methods were also CPCs. Based upon fairly simple measures of association (Kirchhofer, 1974; Lund, 1963), these correlation-based classifications helped alleviate the main drawbacks with manual CPCs (Sheridan and Lee, 2014). Since the mid-1990s, there has been a proliferation of climate data, the costs of increasing computing power have decreased markedly, and advanced statistical software has become relatively inexpensive and more accessible. More so than any other mode of synoptic classification, CPC has concurrently undergone a revolution, expanding tremendously in the variety of different classification methodologies and applications. Many of these methods involve principal components analysis (PCA) and cluster analysis, both of which can have multiple variants (Sheridan and Lee, 2014). Perhaps the newest technique to synoptic classification is that of the self-organizing map (SOM), which uses an artificial neural network for classification purposes (Hewitson and Crane, 2002; Sheridan and Lee, 2011).

Conversely to a CPC, a WTC is completed with a p-mode of data decomposition. In this mode, each case (row), again usually a day, still represents a different observation time; however, each column represents a different AV (e.g., 3 pm temperature, 3 pm dew point) and the spreadsheet typically represents one specific location. With this setup, the values across a whole row quantify a multivariate weather situation at a location on that day (somewhat akin to identifying the air mass present at a location). During the classification process, each row is classified into one of several categories based upon the similarity of that day's meteorological variables relative to those same variables on all the other days being classified. Thus, a WTC focuses most often on a single location, but multiple variables.

Often with a WTC, the classification process is repeated separately for multiple locations, thereby creating a category of surface weather conditions across an area that is representative of the synoptic-scale circulation. For example, a cold-dry anticyclonic surface weather type would likely occur on a day at a location just behind the passage of the cold front associated with northerly winds on the backside of a transient midlatitude cyclone. Much younger than CPCs, the WTC approach got its start with Kalkstein and Corrigan (1986) with the creation of the temporal synoptic index (TSI), before being modified to a spatial synoptic index (Davis and Kalkstein, 1990), an SSC (Kalkstein et al., 1996), and then finally a redeveloped SSC (Sheridan, 2002). In addition to using an entirely different mode of data decomposition than the CPC approach, WTCs are unique in that the methodology is not used nearly as often as the resultant data. That is, many of the studies using a WTC approach do not actually perform a classification, but rather use the categories developed from another study (most often, the redeveloped SSC; Sheridan, 2002) to analyze an outcome. This said, beyond the culmination of the lineage of the WTCs described earlier, alternative WTC approaches have been undertaken (e.g., Schwartz, 1991), and the original WTC methodology (the TSI; Kalkstein and Corrigan, 1986) is still used (e.g., Grass and Cane, 2008; McGregor, 1999), although not always referenced by name (e.g., McGregor and Bamzeli, 1995). Additionally, the SSC methodology has been used/modified to create that classification at new locations (e.g., Bower et al., 2007), while a gridded weather typing classification methodology has also recently been developed utilizing reanalysis data, thereby adding structure and spatial resolution to previous WTCs (Lee, 2014).

Another key decision point identified by Yarnal (1993) is the distinction between manual and automated approaches to classification, or a variation of both (termed 'hybrid'; e.g., the SSC by Sheridan, 2002; and Schwartz, 1991). Manual methods were much more common prior to the digital age (e.g., Grosswetterlagen and the Lamb weather types). However, since Yarnal's book, most new methods of classification are automated (though not all, e.g., Collins et al., 2014). As part of a larger project, Philipp et al. (2010) sorted dozens of different classification methodologies (and variants thereof) into five different categories, including four 'automated' categories: PCA-, optimization-, leader-algorithm-, and threshold-based classifications. It is important to note that the methods listed in Philipp et al. (2010) are all generally undertaken with the CPC mode; however, this is not a requirement for automated methods (e.g., the TSI; Kalkstein and Corrigan, 1986). This recent trend towards automation is perhaps best exemplified by efforts to produce an automated version of two of the most oft-used manual classifications, the Grosswetterlagen (James, 2007) and Lamb weather types (Jones et al., 1993, 2013).

Instead of the choice between manual and automated, a more recent focus in synoptic climatology has been on the evaluation of some of the human influences innate to any classification. More ubiquitous than any dilemma in the discipline is choice of the number of final categories to include in the classification. This is because the true atmosphere is dynamic in time and space (Yarnal, 1993), and therefore, essentially every day in the sample is unique. As part of a larger assessment, Beck and Philipp (2010) described the differences between a few different cluster number options. While there are some statistical measures that can help qualify a classification as satisfactory (in any regard, not just in terms of the number of categories) such as the pseudo F-statistic (and others presented in Beck and Philipp, 2010), part of the synoptic climatologist's task is to find a balance between a manageable (i.e., not unwieldy) number of meaningful patterns and a satisfactory performance of the classification in regard to the outcome being analyzed (Yarnal, 1993). The spatially cohesive plane produced by the SOM technique has proved to be particularly helpful in this regard, as SOMs allow a larger number of categories to remain 'useful' and thus SOMs have gained popularity recently (Hewitson and Crane, 2002; Sheridan and Lee, 2011).

Beyond the number of categories, there are a handful of other choices that precede any synoptic classification. Since Yarnal (1993), numerous new sources of atmospheric data have become available, such as reanalysis data and global climate model (GCM) data, each from varying modeling centers, opening up even more choices to the investigator. With the proliferation of these data sets today and the countless options for obtaining the data, one of the first decisions is which AVs to use for classification, and the source of these AVs. Ultimately, a researcher must choose AVs that they theorize will impact the variability of the outcome. Huth et al. (2008) noted that sea-level pressure (SLP) is the most popular AV used historically for CPCs, though temperature and dew point generally weigh most heavily in defining WTCs (Kalkstein and Corrigan, 1986; Lee, 2014; Sheridan, 2002). To the authors' knowledge, no systematic comparison of synoptic climatological classifications completed with different reanalysis products has been done, although Jones et al. (2013) briefly discussed differences between two products in deriving Lamb weather types and reanalysis products have been compared in other ways (e.g., Mooney et al., 2011). There are also a multitude of GCMs available today, with the common course of action involving the evaluation of GCM ability in modeling historic circulation patterns (as represented by reanalyses) and presenting a range of future projections across multiple models and emissions scenarios (cf. Sheridan and Lee, 2010). The size and resolution of the spatial domain in which the AVs are classified are also important choices. Beck et al. (2013) thoroughly examined a number of domain sizes in evaluating SLP patterns over Europe, while Demuzere et al. (2009) tested several different spatial resolutions of SLP in their study, noting that finer-scale resolution does not always equate to a better classification.

The treatment of the data prior to classification is also a critical factor in performing a synoptic climatological analysis. Wilby et al. (2004) noted that many researchers using GCM data will remove any mean bias in GCM data prior to statistical downscaling – a technique that has incorporated synoptic classifications quite regularly (Cheng et al., 2007; Schoof, 2013; Wetterhall et al., 2009). When using SLP data, often, the raw value of SLP is of less consequence than the relative value of SLP compared to the rest of the domain, or the gradient of change from high to low pressure centers. Thus, Sheridan et al. (2013) transformed SLP data into spatial anomalies prior to classification. If seasonality in synoptic type frequency is undesirable, it can also be reduced; using multiple moving-average filters, Lee et al. (2012), for example, removed the mean seasonal cycle from 500 mb geopotential height fields prior to classification. Further, while only specific to classifications involving PCA, Cuell and Bonsal (2009) detailed the influence that the number of retained principal components in a PCA can have on a synoptic classification as well.

All of these human influences are in addition to selecting a final classification methodology. While a discussion on these methodologies is beyond the scope of this overview, each classification should be evaluated for effectiveness. To this end, in the mid-2000s, the European Cooperation of Science and Technology launched Action 733 (better known as COST733 in the literature) that aimed to “achieve a general numerical method for assessing, comparing and classifying weather situations in Europe” (COST733, 2014). The resultant literature of this effort (much of which is published in a special edition of *Physics and Chemistry of the Earth* in 2010; Beck and Philipp, 2010; Philipp et al., 2010) represents the most comprehensive analysis to date of many different classification methods for CPCs. In this assessment, many of the other human influences on classification (such as the number of categories and size of domain) were also examined. One important result from the COST733 Action was the conclusion that there is no ideal classification for all purposes but that the classification needs to be tailored to the specific study at hand (Beck and Philipp, 2010; Philipp et al., 2014).

Thus, somewhat ironically, despite the ‘automated’ world of synoptic climatology today, these human influences are still numerous, meaning that all classifications are inherently subjective to some degree. It is these human influences that require the expertise of the synoptic climatologist.

Major Themes in Contemporary Synoptic Climatological Applications

The applications for which synoptic climatological output is used are as diverse as the methods. Dating back to the original midlatitude cyclone model developed by the Bergen School, synoptic climatologists realized the inherent connection between understanding broader-scale processes and understanding local or regional weather conditions. Within this context, a considerable amount of contemporary synoptic climatological research still aims to connect these broader-scale processes with surface weather conditions, typically temperature and precipitation.

Spatial patterns of surface air temperatures or temperature anomalies have long been correlated with synoptic patterns, such as composites of upper-level height anomalies (e.g., Klein and Kline, 1984) or pressure patterns (e.g., Barry et al., 1981; Chen, 2000). Historically done over data-rich areas of the globe, with the addition of quality reanalysis data sets, synoptic–temperature relationships have recently begun to move into traditionally more data-sparse places (e.g., Alaska; Cassano et al., 2011). Extreme temperature events are analyzed through synoptic typing (Ashcroft et al., 2009; Domonkos et al., 2003), often through weather typing or compositing. Smaller-scale assessments, difficult to render in model simulations, are also evaluated using synoptics, such as the urban heat island (e.g., Lee and Baik, 2010), heat events (e.g., Pezza et al., 2012), or cold-air drainage patterns (e.g., Bigg et al., 2014). Other temperature metrics, such as satellite-derived land-surface temperatures (e.g., the Middle East; Lensky and Dayan, 2014), have also been assessed.

Precipitation patterns are commonly studied with regard to their synoptic signature as well. One of the initial applications of the Muller (1977) types was to assess precipitation patterns related to circulation. This interest has continued with work attempting to disentangle the contributions to total precipitation from different synoptic types (e.g., Pook et al., 2012; Risbey et al., 2013), often with the aim of evaluating causal mechanisms or trends. As with temperature, this has evolved over time to encompass an

assessment of climate variability across more remote locations (Cohen et al., 2013) and more data sources, such as radar-estimated rainfall (Rudolph et al., 2011) and satellite-estimated rainfall (Tubi and Dayan, 2014). Research has focused on systems on various scales, from the West African monsoon (Seefeldt et al., 2012) to sea breeze-generated convection in Java (Qian et al., 2010). Given their significant impact, extreme and unusual events have been frequently assessed using the synoptic methodology, such as floods (Collins et al., 2014; Kahana et al., 2002), heavy snowfall (Esteban et al., 2005), drought (Hryciw et al., 2013), and freezing rain (Cheng et al., 2004). Addressing aspects of storminess and circulation, synoptic methods have associated circulation with tornado incidence (Lee, 2012), extreme waves (Izaguirre et al., 2012), and water clarity (Sheridan et al., 2013).

As noted in the preceding text, another common theme of recent synoptic research is its use with weather and climate model output (Sheridan and Lee, 2010). Starting with Crane and Barry (1988), many papers have subsequently validated GCM ability to represent the full range of atmospheric flow patterns (e.g., Anagnostopoulou et al., 2008; Schoof and Pryor, 2006), and multiple models have been compared in terms of their relative abilities to replicate patterns both individually and as an ensemble (Finnis et al., 2009). These methods are also used to examine very specific phenomena that are difficult to model, such as Notaro et al. (2013), which evaluates US Great Lake effect snow simulation, or Coggins et al. (2014), which evaluates reanalysis ability to simulate flows in the Ross Sea region of Antarctica. Synoptic methods can also be employed as a method of statistical downscaling with model output (Schoof, 2013), including analog methods in which historical patterns are matched with patterns in a model (Timbal et al., 2009), or through regression or neural network models on principal components (e.g., Li and Smith, 2009). Further, some studies using synoptic climatology to downscale precipitation find that using synoptic patterns can result in more realistic precipitation fields than using GCM-generated precipitation data (Wetterhall et al., 2009).

Since the 1990s, considerable research has examined variability in teleconnections and synoptic climatological patterns (Sheridan and Lee, 2012). Some works, such as Hewitson and Crane (2002), use synoptic climatology to demonstrate the ability of rendering certain phenomena within a synoptic framework (in their case, SOMs), and as noted earlier, this often is part of model validation studies as well (e.g., Demuzere et al., 2009). More commonly, the relationship between teleconnection indices and climate system response in a specific region is explored, where frequencies of different patterns are associated with teleconnection phases (e.g., Jiang et al., 2012; Johnson and Feldstein, 2010); this is then often used to assess relationships with climatic variables such as precipitation or water resources (Moron et al., 2008; Newton et al., 2014).

Given the large body of research devoted to climate change, many papers utilize synoptic methods to assess historical pattern changes as indicators of climate change (e.g., Knight et al., 2008); this has been especially true in exploring the relative contribution of differences in circulation pattern frequencies compared with 'within-pattern' warming (e.g., Cahynová and Huth, 2014; Cassano et al., 2011; Küttel et al., 2011), with most research suggesting that pattern frequency changes are not the prime driver of climate trends.

Air quality has strong connections with atmospheric conditions, as the holistic suite of atmospheric conditions – inclusive of thermal conditions, atmospheric stability, radiation, wind, and precipitation – play a role. The holistic nature of synoptic climatology allows these conditions to be evaluated in concert, and so it is especially useful for air pollution or pollen transport. Both historical and more recent studies have used the synoptic method to assess differences in pollution levels across circulation patterns (e.g., Jiang et al., 2014; McGregor and Bamzels, 1995), between rural and urban environments (e.g., Comrie, 1994), as well as to determine source regions for pollutants (e.g., Davis and Gay, 1993; Davis et al., 2010). Pollen dispersion (e.g., Bogawski et al., 2013) and phenology (Hart et al., 2007) can also be correlated well with synoptic conditions.

More broadly, it is clear that all life interacts with, and is affected by, the holistic set of weather conditions; it is hence unsurprising that synoptic climatology has been used in a variety of biometeorological assessments as well. A number of methods, most commonly WTC, stem from the aforementioned connection with air quality itself, such as Hondula et al. (2013) who used air quality–synoptic relationships and then related these to hospital admissions. Another common area is extreme temperature-related mortality, in which weather types (e.g., Sheridan et al., 2012) and circulation patterns (e.g., Vaneckova et al., 2008) measure variability by synoptic type; other studies such as Morabito et al. (2006) extend weather conditions more broadly to hospitalizations. While human health-based research using WTC methods is quite prevalent (Hondula et al., 2014), nonhuman biometeorological studies are also undertaken, including those analyzing wine (Jones and Davis, 2000) and insect transport (Frank et al., 2008).

Future Directions and Concluding Remarks

Synoptic climatology has evolved markedly since the discipline was first conceived in the 1940s. The resurgence of the applied side of the field over the last two decades is particularly encouraging. At a time when climatology has become entrenched in the international scientific, political, and public forums, synoptic climatology has helped shape our understanding of how the atmosphere interacts with the Earth system as whole. However, despite the wide-ranging *applications* discussed herein, synoptic climatology is still underutilized in many arenas (e.g., oceans, ecosystems, and agriculture) and, thus, still has potential for more widespread utility. There is also room for growth in the realm of classification *methodologies*. In particular, even the more recently developed classifications have largely underutilized the amount of climate data and computing power available today. To this end, new classification modes that identify synoptic types in greater than two dimensions (e.g., three- or four-dimensional types using latitude, longitude, time, multiple vertical levels, and/or multiple AVs) may be a natural progression.

With the flexibility of synoptic methods in linking the weather with outcomes on a variety of temporal and spatial scales, future synoptic climatological research should make a concerted effort to showcase the utility of the discipline alongside its counterparts, especially in conjunction with GCM data looking into the more specialized (i.e., small-scale and/or indirect) impacts of climate change. As these impacts continue to become more apparent with time, synoptic climatology is poised to play a key role in helping inform decision makers, as it is particularly well suited to making sense of an otherwise complex climate system.

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