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Synoptic climatology and the analysis of atmospheric teleconnections

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Abstract

Over recent decades, analyses of the structure and impact of atmospheric teleconnections have substantially increased our understanding of the climate system and the role of climate variability. Moving beyond simple correlations between teleconnection indices and temperature and precipitation anomalies, synoptic climatology has been able to provide insight on the spatiotemporal manifestation of teleconnection anomalies, as well as further understanding in terms of teleconnection-related anomalies in circulation pattern frequencies that can lead to extreme events over individual areas. In this progress report, we focus on a number of recent papers that, broadly defined, assess two realms of teleconnections: the North Atlantic circulation, largely focusing on the North Atlantic Oscillation; and the north and tropical Pacific circulation, as manifest in El Niño–Southern Oscillation, the Pacific North American pattern, and the Pacific Decadal Oscillation. In each of these two regions, we highlight the major goals and results of recent synoptic research.

Keywords

applied climatology, climate variability, synoptic climatology, teleconnections

I Introduction

The discovery and understanding of atmospheric teleconnections have played a substantial role in climatology over the past century. Initial syntheses of atmospheric and oceanic anomalies led to the understanding of teleconnections such as El Niño–Southern Oscillation (ENSO; Bjerknes, 1969), the North Atlantic Oscillation (NAO; van Loon and Rogers, 1978), and the Madden-Julian Oscillation (MJO; Madden and Julian, 1994), all of which depict the interconnectedness of the atmosphere across the tropics as well as the extra-tropics. Other research, such as that of Barnston and Livezey (1987), showed how statistical decomposition of atmospheric circulation could yield numerous oscillatory circulation patterns, with teleconnections often having hemispheric to global impacts on both atmospheric circulation and surface weather.

Teleconnections have been used extensively to assess climate variability, mostly at the regional scale (e.g. Coleman and Rogers, 2007; Jiang, 2011), though the spatial range

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varies from local (e.g. Knight et al., 2008; Sheridan, 2003) to global domains (e.g. Enfield and Mestas-Nunez, 1999; Kogan, 2011). In an attempt to distinguish between natural variability and anthropogenic changes (e.g. Hegerl and Zwiers, 2011), assessments of climate change attribution have incorporated teleconnections, in particular the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), though the role played by anthropogenic changes to the atmosphere in forcing teleconnections is complex (e.g. Fischer-Bruns et al., 2009; Ulbrich and Christoph, 1999). Teleconnections have been related to many societal impacts (e.g. Barry and Perry, 2001; Yarnal, 1993); indeed, the PDO was initially identified while studying cyclical patterns in salmon production (Mantua et al., 1997).

Teleconnections are generally quantified by a scalar variable whereby zero represents neutral conditions (e.g. the Southern Oscillation Index; Horel and Wallace, 1981); many studies utilize this scalar variable to assess the impacts of a teleconnection. Partially as a legacy of the 'original' teleconnection of ENSO, their impact is often assessed by binning the scalar variable into positive and negative classes (e.g. El Niño versus La Niña; NAO+ versus NAO–), often assessing these as collective categories. Much research has shown that teleconnections interact with the climate system in a non-linear fashion – that is, for example, that the impacts of El Niño are not the precise inverse of La Niña; nor are the impacts of El Niño events always consistent from event to event. This discrepancy arises due to the difficulty in quantifying the intensity of a particular teleconnection, particularly ENSO, as well as confounding factors of other teleconnection influences (e.g. Mantua and Hare, 2002).

Early research tended to focus on temperature or precipitation anomalies that could be correlated with either a teleconnection index (e.g. Leathers et al., 1991) or phase (e.g. Halpert and Ropelewski, 1992). As there is significant interest in exploring more nuanced impacts of teleconnections, such as incidence of extreme events, many new methods for assessing teleconnections have emerged. The synoptic climatological approach is one such framework. To a synoptic climatologist, the fundamental basis for linking the atmospheric circulation to any environmental response involves the classification of atmospheric conditions into one of a number of different states, such as circulation patterns, weather types, or air masses (Huth et al., 2008; Yarnal, 1993). The success of this method of course hinges upon the assumption that the atmosphere can be validly partitioned into states, that these partitions will represent some relatively homogeneous and meaningful set of cases, and that these partitions collectively represent all relevant atmospheric states.

Assuming this is the case, synoptic climatology can then be a useful tool in discerning how teleconnections affect the climate of a given region by virtue of assessing how atmospheric circulation itself varies across a given region in response to teleconnection forcing. This method can be useful for assessing not only simple climatological anomalies, but also climate variability, and the likelihood of extreme events or other surface phenomena.

In this progress report, we review the efforts of recent years at using synoptic climatological methods to assess impacts of teleconnections. While we provide an overview of the literature, we refer readers to work including Huth et al. (2008), Yarnal (1993), and Yarnal et al. (2001) for a more comprehensive discussion on synoptic methodological details and concerns. We divide our review into two broad categories, focused upon Atlantic and Pacific teleconnections, respectively. We then summarize the themes of the reviewed works and offer perspectives on future research.

II North Atlantic Oscillation and other Atlantic–European modes

Synoptic-based studies of the North Atlantic Oscillation have encompassed a range of methods and goals, many of which are fundamentally related to understanding the teleconnection itself, as well as the asymmetry of its modes. Several studies have used the NAO-synoptic type relationship to validate methodologies and models. Hewitson and Crane (2002) demonstrate that the frequency of self-organized map (SOM) nodes, derived from eastern North America sea-level pressure data, is correlated with the NAO index. Other articles, including Schoof and Pryor (2006) and Demuzere et al. (2009), examine the ability of GCMs to replicate the NAO-classification pattern relationship (and with Schoof and Pryor, the Pacific North American (PNA) pattern relationship as well), concluding that a better relationship is generally observed in the winter than in the summer.

Sheridan (2003) and Knight et al. (2008) show statistically significant shifts in the frequency of Spatial Synoptic Classification (SSC; Sheridan, 2002) polar weather types across North America, with the suggestion that decreased polar weather types across the eastern USA are associated with the increased positive NAO frequency and overall warmer temperatures. A larger number of papers have evaluated the role of NAO in climate extremes and trends across Europe and the Middle East. Beniston and Jungo (2002) use the Schüepp (1978) classification system – broadly similar to Lamb weather types (Lamb, 1972) – to assess the variability of 40 weather types in the Swiss Alps. They note a sharp shift in the 1990s to an increase in high-pressure systems and a decrease in easterly advective situations; they then relate this to an increased prevalence of the positive phase of NAO during the period, and surmise that the shift to persistent and positive NAO (through the time of their study) resulting in warmer weather types is a major cause for the warming temperature trends observed in that period. They also correlate weather types with cold extreme events and find shifts over time in terms of which circulation patterns are affiliated with the coldest outbreaks. Along the same lines, Küttel et al. (2011) cluster winter sea-level pressure anomalies over the North Atlantic and Europe from 1750 to 2000, and uncover significant correlations between NAO and cluster frequencies; however, beyond this correlation, they uncover within-cluster temperature and precipitation variability that, in their assessment, explains the majority of temperature variability over Europe, compared with changes in cluster frequency. For central Europe, Jacobeit et al. (2009) find that zonal sea-level pressure (SLP) patterns are related to high winter temperature extremes and the positive mode of NAO. Heavy winter precipitation events are associated with fewer zonal patterns and a shift in the Icelandic Low pressure center, and are only weakly correlated to NAO. Summer associations between circulation patterns and NAO are somewhat weaker.

López-Bustins et al. (2008) utilize the signs of principal component scores, while Lorenzo et al. (2008), Queralt et al. (2009), and Ramos et al. (2010) have utilized patterns similar to Lamb types to assess the impact of NAO on the Iberian Peninsula in terms of extreme events, and precipitation and snowfall anomalies. A complex relationship emerges, with Queralt et al. (2009) showing that NAO more substantially affects the frequency of extreme events in some parts of Spain, and intensity of events in others. Further, in some areas, the weather types most associated with precipitation vary between NAO phases, while in other areas this is not the case; rather, precipitation is modulated by weather-type frequency changes. López-Moreno and Vicente-Sorrano (2007) use Lamb types to examine monthly weather-type frequency with precipitation and snowpack in the Pyrenees, and discover that NAO is the most relevant teleconnection, connecting the increasing NAO values to changes in frequency of weather types, in particular the anticyclonic type, that collectively reduce snowpack. Given that NAO is most pronounced in winter, Lorenzo et al. (2008) suggest that the Eastern Atlantic (EA) pattern may be more indicative of climate variability across the region year-round.

Black (2011) utilizes the Grosswetterlagen catalog to examine precipitation variability in Israel, and finds an asymmetric relationship across NAO phases. The circulation patterns that correspond to high rainfall occur more often when NAO is in its positive phase, leading to increased precipitation, but the drier circulation patterns are not observed to increase in the negative phase, resulting in a weak correlation with precipitation variability overall. The study also assesses the East Atlantic/Western Russia pattern (EAWR), which produces converse results; that is, an association with drier types during negative phase, but no correlation during positive phase. This work is in general agreement with that of López-Moreno et al. (2011), who bin precipitation anomalies for mountainous regions around the Mediterranean basin, and find that the NAO connection deteriorates moving eastward.

Several papers have utilized synoptic typing to assess the fundamental structure of NAO and its relationship with other teleconnections. Cassou et al. (2004) utilize two different methods (Ward's and k-means) to cluster North Atlantic and European SLP data into four 'regimes' of circulation, with the aim of examining the spatial asymmetry of NAO. Of the four regimes, two resemble the phases of the NAO, while the other two include a ridge over the entire region, and a dipole between Scandinavia and Greenland. Yiou and Nogaj (2004), in clustering 500 mb geopotential heights, arrive at a similar regime partition, and from this derive which regime is most likely to trigger an extreme temperature or precipitation event over each degree of latitude and longitude over the North Atlantic and Europe. They discover that while heavy precipitation events over much of the region can be related to one of the two NAO-related regimes, most of the region's extended dry periods are related to the occurrence of the other two regimes. Casado et al. (2009) develop a clustering scheme for 500 mb height values over Europe to broadly examine pattern variability, identifying six regimes, two of which have clear connections to the opposing phases of NAO. In all of these cases, the other patterns that emerge (those that do not resemble NAO) resemble modes of the EAWR or EA patterns instead.

Reusch et al. (2007) assess the modes of variability of North Atlantic SLP through a SOM, and beyond the dipoles of the NAO, uncover a mode of variability that depends only on the strength of the Azores High. Their analysis of the period 1957–2002 shows increasing trends for both the positive NAO and a stronger Azores high during January and February. Johnson et al. (2008) utilize a SOM to examine the differences in the NAO-circulation pattern relationship over the entire Northern Hemisphere and to analyze changes in this relationship from 1978–2005. Although all of the NAO patterns existed in each time period, some of the positive NAO and eastward-displaced patterns occurred more frequently in one time period in comparison to the other. The frequency of these patterns corresponds to the eastward shift and positive NAO trend since 1978. Lee et al. (2011) utilize a SOM of 250 mb streamfunction and assess it with regard to tropical precipitation, showing that SOM pattern frequencies changed over time. Their results suggest that changes in tropical convection can be associated with changes in PNA- and NAO-like patterns, and this can modify radiative balance and dynamic warming.

III El Niño–Southern Oscillation and other Pacific teleconnections

Using synoptic climatology, the large-scale atmospheric anomalies affiliated with El Niño–Southern Oscillation events can create clear delineations of ENSO events when parameters in the equatorial Pacific are clustered; for instance, Leloup et al. (2007) show a well-defined 'El Niño (warm event) corner' and 'La Niña (cold event) corner' on their SOM produced from Pacific thermocline, sea-surface temperature (SST), and sea-level pressure data. Also using SST data, but for the Indian Ocean, Tozuka et al. (2008) create a SOM that captures the associated SST anomalies with regards to both the Indian Ocean Dipole and the basin-wide warming associated with El Niño events.

As with NAO, many papers have assessed the manifestation of Pacific teleconnections in a given region by virtue of deviations of synoptic patterns. Jiang (2011) and Jiang et al. (2011) utilize multiple classification methods to assess weather-type frequency deviations in New Zealand and southeastern Australia, respectively. Their results uncover a wide array of significant deviations, including an increased frequency of anticyclonic types during El Niño events. Jiang (2011) also uncovers increased likelihood of extreme frequency deviations associated with ENSO phases, in support of the observation of a greater relationship between ENSO phase and the frequency of temperature extremes in the region than mean temperature anomaly itself (Salinger and Lefale, 2005). Qian et al. (2010) perform a k-means cluster analysis on 850 mb winds over Java, Indonesia, and uncover a very strong correlation between weather types and ENSO phase. The weather types modulate the land-sea and mountain-valley breezes on the island, with ENSO associated with a weaker monsoon and thus stronger diurnal wind systems, resulting in increased precipitation in the mountains of Java.

Farther east, Robertson and Mechoso (2003) and Cazes-Bosio et al. (2003) cluster 700 mb height patterns across the south Pacific by season using k-means cluster analysis, uncovering episodic behavior in circulation frequency, with a consistent ENSO relationship seen only during austral spring. Bettolli et al. (2010) assess the synoptic pattern–precipitation relationship in Argentina via separate clustering schemes of 500 mb and 1000 mb geopotential heights. The most extreme ENSO events can be connected to circulation anomalies that could impact precipitation, although this is largely addressed in a qualitative way.

Research has also used synoptic methods to assess ENSO and other Pacific teleconnection influence on precipitation in western North America. Casola and Wallace (2007) use a limited-contour clustering technique that focuses just on the location of the 5400 m 500 mb height contour. Their technique identifies four patterns that well highlight the locations of ridges and troughs; in comparisons with ENSO phase, El Niño winters have a strong preference for a 'Rockies Ridge' pattern at the expense of all other patterns, whereas La Niña is associated with a greater diversity of patterns. Robertson and Ghil (1999) cluster 700 mb heights over western North America, uncovering a connection between ENSO phase and frequencies that is then connected to precipitation and temperature anomalies. Romolo et al. (2006) evaluate synoptic pattern deviations, divided up into 'wet' and 'dry' types with regard to snowpack in British Columbia, and uncover a modest relationship with ENSO phase, and a stronger correlation with PNA index. Stahl et al. (2006a, 2006b) cluster SLP patterns across the same region, and show expected deviations of synoptic types that are associated with warmer, drier winters in British Columbia during El Niño events as well as when the PDO is positive. Interestingly, both papers also explore within-type synoptic pattern variability, and show shifts in how PDO or ENSO phase modulate the SLP pattern within each type (Stahl et al., 2006b), as well as how the teleconnection phases impact the likelihood that a synoptic type will lead to cold-weather outbreaks that result in mountain pine beetle mortality events (Stahl et al., 2006a).

A number of papers have also compared the impacts of ENSO with those of other Pacific patterns, most notably the Pacific North American pattern and the Pacific Decadal Oscillation.

Both Sheridan (2003) and Knight et al. (2008) uncover better correlations between frequencies of SSC weather types and PNA than ENSO. Following a two-step cluster analysis of 500 mb heights and SLP data for the central USA into 10 clusters, Coleman and Rogers (2007) uncover a similar relationship, with PNA index significantly correlated with nearly all of the cluster frequencies; ENSO was correlated with fewer. However, the study also analyzed lagged frequency (spring frequency from winter index), and discovered that ENSO was associated with more significant correlations than PNA. PDO is also assessed in their work, though results were generally less significant. Johnson and Feldstein (2010) cluster SLP and outgoing longwave radiation values for the North Pacific, and note a significant ENSO relationship, with El Niño events associated with increased frequency of patterns with easterly displaced Aleutian low pressure anomaly, and La Niña events leading to a southerly displacement of Aleutian high pressure anomaly pattern. They also discover a significant relationship between the MJO and circulation-pattern frequency, and relate pattern occurrence with several additional teleconnection indices including PNA and Tropical–Northern Hemispheric (TNH; Mo and Livezey, 1986) patterns.

Moron et al. (2008) cluster 925, 700, and 200 mb wind fields for western Africa via k-means, producing eight clusters which were then used to assess the ENSO-precipitation relationship at 13 stations in Senegal. Some clusters are associated with the start and the end of the monsoon season; it is the frequency of these marginal types that is related to rainfall variability, while the patterns that occur mid-monsoon are not. In their research, the ENSO connection relates to some weather-type frequency changes that relate to rainfall, but not to easterly wave weather types.

North Atlantic and European SLP patterns are clustered and compared with ENSO by Fereday et al. (2008), who develop clusters separately for two-month periods of the year, and Moron and Plaut (2003), who develop one cluster set, but analyze November and December separately from January through March. Both papers' use of unconventional definitions of season depict statistically significant relationships between ENSO phase and circulation pattern frequency that shift throughout the boreal winter; Fereday et al. (2008), for instance, note that NAO positive patterns are associated with El Niño SST conditions during November and December, but La Niña SST conditions in January and February.

IV Summary

Synoptic-based research on teleconnections can broadly be categorized across several research goals. In some cases, the synoptic methodology is applied to a teleconnection as a proof of concept of a particular synoptic methodology, such as SOMs (e.g. Reusch et al., 2007; Sheridan and Lee, 2011). Several papers have utilized synoptic typing to better understand the structure of a given teleconnection (e.g. Cassou et al., 2004). Other studies have aimed at improving the understanding of teleconnection influence on a given region, either through analyzing frequency changes of circulation patterns (e.g. Jiang et al., 2011) or weather types (e.g. Knight et al., 2008), or by shifts in pressure systems (e.g. Johnson and Feldstein, 2010). Another category of papers includes those that utilize weather types or circulation patterns to assess the influence of teleconnections on surface environmental conditions, most typically precipitation (e.g. Moron et al., 2008). Fewer papers have extended their work towards exploring extreme events such as temperature extremes (e.g. Beniston and Jungo, 2002) to episodes of insect mortality (Stahl et al., 2006a). With the wide-ranging impacts of teleconnections and their documented impacts on extreme events (e.g. Grimm and Tedeschi, 2009; Walsh et al., 2000), there is substantial untapped potential in using the synoptic methodology to project teleconnection influence on these events. Several regions of the world, notably the Antarctic, have received very limited synoptic climatological study, even though there is evidence to suggest substantial synoptic forcing of extreme events related to ENSO (Bromwich et al., 2004; Spiers et al., 2010).

Some research has shown that the synoptic type–teleconnection relationship is not static, but can change with time (e.g. Johnson et al., 2008), though changes in this relationship should be explored in further depth. Historical reassessments of teleconnections could avail themselves of synoptic methods as well. While three such studies were discussed herein (Fereday et al., 2008; Jacobeit et al., 2009; Küttel et al., 2011), mostly in regard to the NAO, extending the synoptic-teleconnection relationship well into the past with the more low-frequency patterns (i.e. PNA or PDO) could prove to be a valuable avenue of research.

More critically, synoptic assessment of potential changes to teleconnections in the future is largely unexplored. Despite the large body of climate change literature, research incorporating synoptic climatological assessments of GCM projections is somewhat limited (Sheridan and Lee, 2010), with mixed results. Given the utility of synoptic decomposition of the atmosphere into states, further assessment of the teleconnection-synoptic relationship projected for the future would benefit extreme event and any climate-change impact studies.

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