Progress in Physical Geography
34(1) 101–109

DOI: 10.1177/0309133309357012
ppg.sagepub.com
SAGE

Synoptic climatology and the general circulation model

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Abstract
One of the main research directions of synoptic climatology in recent years has been its application to the output of general circulation models. These applications have spanned the wide array of synoptic techniques, from traditional ones such as correlation-based maps to more recently developed ones such as self-organizing maps and fuzzy clusters. Here, we review the main themes of recent articles, including assessments of the ability of GCMs to replicate historical circulation pattern frequency, as well as the incorporation of synoptic methods to assess GCM capability in producing estimates of precipitation and the likelihood of extreme events. Results from these articles are quite heterogeneous, suggesting that the selection of the GCM, the variables that are used to drive the categorization, and the specific methodology chosen are all important in determining the efficacy of the research and application.

Keywords
climate change, downscaling, GCM, reanalysis, synoptic climatology

I Introduction

The field of synoptic climatology has advanced significantly over recent decades. Two of the primary drivers of its evolution have been the exponential growth in computer technology and the rapid improvement in climate data availability, in particular the NCEP/NCAR (Kalnay *et al*., 1996) and ECMWF (Uppala *et al*., 2005) reanalysis data sets. These developments have served to help the field develop from the earliest manual map classifications (eg, Lamb, 1972) to a wide array of computer-assisted classifications, from more traditional correlation-based classifications (eg, Kirchhofer, 1974) and principal component analysis methods (eg, Kalkstein and Corrigan, 1986; Huth, 2000) to newer techniques such as self-organizing maps (SOM; Kohonen, 2001) and fuzzy clusters (eg, Bárdossy *et al*., 2002). Applications of these synoptic techniques have similarly expanded to address many environmental issues (eg, Huth *et al*., 2008).

Further encouraging innovation in synoptic climatology has been the issue of climate change, with the proliferation of general circulation model (GCM) output along with a concomitant increase in impact studies. Synoptic climatology is naturally suited to support the advance of climate change projections from mean temperature and precipitation values to more nuanced

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assessments of circulation variability and probabilistic forecasting.

In this review paper, we discuss recent advances in synoptic climatology with regards to GCM output, focusing particularly on papers over the past five years. We assemble these advances into general categories based on research goals, from assessing whether GCM output can reliably replicate circulation patterns of the climate system to evaluating their utility in downscaling precipitation and predicting likelihoods of extreme weather events. Due to the number of methodologies addressed in this paper, detailed methodological descriptions are beyond its scope. For a more detailed discussion of synoptic methods, please see Yarnal (1993) or Huth *et al*. (2008).

II The ability of GCMs to replicate synoptic circulation patterns

Crane and Barry (1988) were the first to assess the ability of a GCM to replicate synoptic patterns more than 20 years ago, as they compared actual and modeled Kirchhofer (1974) based sea-level pressure clusters over the Arctic and North America. As GCM performance has improved, a number of recent papers have focused upon projecting future circulation-type frequencies based on GCM projections of IPCC scenarios (Nakićenović *et al*., 2000). Only some of these papers, however, have spent significant effort comparing the ability of GCMs to replicate historical circulation patterns. Demuzere *et al*. (2009) evaluate the ability of three scenarios of the ECHAM5 model to reproduce Lamb (1972) circulation weather types for Belgium, similar to Mediterranean work done with HadAM3P by Anagnostopoulou *et al*. (2008; 2009). Schoof and Pryor (2006) utilize the Kirchhofer correlation-based map method to test the efficacy of two GCMs (CGCM2 and HadCM3) in reproducing NNR 500 hPa map pattern frequencies over the Midwestern USA for the period 1990–2001. In an ambitious pair of articles, the ability of an ensemble of 10 GCMs to reproduce the Arctic (Cassano *et al*., 2006) and Antarctic (Lynch *et al*., 2006) SLP circulation patterns in both the ERA-40 and NNR reanalysis data sets is assessed via SOMs. Finnis *et al*. (2009) carry their work further, with a focus on just the Mackenzie River basin in Canada.

Results from these papers generally suggest that GCMs can reproduce synoptic circulation patterns, with a number of caveats. The Lamb types produced by Demuzere *et al*. (2009) are better in the cold season than the warm season, when westerly types are overproduced; Anagnostopoulou *et al*. (2009) uncover a slightly better match in winter than in summer with Lamb types in the Mediterranean, although their results only present a cyclonic/anticyclonic subdivision. In an earlier work only for Greece, Anagnostopoulou *et al*. (2008) discover a systematic overrepresentation of several anticyclonic types at the expense of cyclonic types, though which patterns were misrepresented varies by season. In most cases, interannual frequency variability is underestimated by the GCM. Schoof and Pryor (2006) also report a general agreement between circulation pattern frequencies and the North Atlantic Oscillation (NAO) and Pacific North American (PNA) patterns, but find significant model differences between the CGCM2 and the HadCM3, the latter of which overrepresents meridional flow. Cassano *et al*. (2006), Lynch *et al*. (2006), and Finnis *et al*. (2009) find a wide range of model abilities with their work. In the Arctic, the 10-model ensemble, as well as three individual models, adequately reproduces map frequencies in the winter; in the summer, the ensemble does not, while five individual models do. Their Antarctic work shows that ensemble model performance is reasonable in both summer and winter, although a small number of outlier models are also observed. Finnis *et al*. (2009)'s study in the Mackenzie River basin suggests better model replication of circulation patterns in summer and winter than in transitional seasons, although performance varies significantly across models and diverges in some cases from the Arctic-wide results of Cassano *et al*. (2006), particularly with regard to the CCSM3, which performs well in the Arctic basin as a whole, but poorly in the Mackenzie River basin.

Future extrapolations also show varied results. Demuzere *et al*. (2009) see marked increases of the westerly circulation types at the expense of the easterly circulation types, although the authors note that these types were the ones the model reproduced least successfully in the historical run. Schoof and Pryor (2006) do not observe circulation pattern frequency changes in either model that exceed the historical level of uncertainty, thus suggesting the two models do not clearly forecast significant circulation changes in the Midwestern USA. Cassano *et al*. (2006) and Lynch *et al*. (2006) show in their ensemble prognoses that in the Arctic an increased north Atlantic storm track is predicted in winter, with lower pressure near Greenland in the summer; in the Antarctic increased cyclonicity is observed.

III Synoptic methods and GCM generation of precipitation

With the combined importance of precipitation as a variable and the difficulty that GCMs have in adequately simulating precipitation on local scales, it is unsurprising that one key focus of the incorporation of synoptic methods into GCM output is the role of synoptic circulation in GCM precipitation estimates. In Finnis *et al*.'s (2009) development of SOMs for the Mackenzie River basin, GCM-modeled precipitation is assessed relative to the circulation patterns. The large positive bias in precipitation in all models in all seasons except summer actually occurs with a negative frequency bias in the wettest patterns. In analyzing specific patterns, GCMs systematically carry too much precipitation across the Western Cordilleras into the study region, thereby suggesting that precipitation errors are primarily precipitation-process related and not upper-level circulation related.

Also using SOM-derived circulation patterns (from Hope *et al*., 2006), Hope (2006) compares GCM-derived precipitation values for Western Australia and GCM-derived SOMs for eight models. In all cases, GCM historical precipitation is less than observed data, in some cases by a factor of four. Synoptic type frequency is less divergent. All models predict a further decrease in precipitation, although the concomitant circulation pattern change is not the same. In most models, a decrease in trough frequency is observed as primary circulation shifts poleward, although in at least one model circulation pattern frequencies significantly diverge from other models, with a greater frequency of zonal patterns.

Three papers have also employed Lamb circulation types to assess precipitation in the Mediterranean basin. Anagnostopoulou *et al*. (2009) apply Lamb weather types separately at three points in the Mediterranean Basin. In many cases, the GCM (HadAM3P) simulated precipitation within each Lamb type is lower than that observed, with decreased variability within type as well. However, a general agreement between the NNR (with observed precipitation) and the HadAM3P (with simulated precipitation) is noted in correlation coefficients relating Lamb type frequencies and total precipitation (Anagnostopoulou *et al*., 2008). Tolika *et al*. (2006) discover similar results, although they compare precipitation generated in the NNR to observations as well. While the NNR better represents the spatial pattern of winter precipitation overall, when stratified by circulation types, the GCM actually performs better than the NNR does, although both still underestimate precipitation.

With a somewhat different goal, MacKellar *et al*. (2009) utilize a synoptic methodology to assess the effects of land cover on precipitation, as well as surface temperature and radiative fluxes. They utilize MM5 regional climate model (RCM) output of 850 hPa and 500 hPa geopotential heights, and precipitable water, to create SOMs for southern Africa. Separate runs are performed with current land use and natural land use; their results suggest that precipitation decreases due to land surface change come about because of circulation changes more than localized feedbacks.

IV The assessment and use of synoptic climatological methods as a statistical downscaling tool

While RCMs are becoming more frequently used to downscale GCM precipitation, there is still significant research that is exploring statistical downscaling of GCM output. Synoptic climatology has played a significant role in statistical downscaling, especially for precipitation, as the larger-scale circulation patterns that are correlated well with precipitation processes are better resolved in GCMs than the precipitation generated within the GCM itself (eg, Saunders and Byrne, 1996; Randall *et al*., 2007; Wetterhall *et al*., 2009). Saunders and Byrne (1996; 1999) were among the first to utilize synoptic categorization in precipitation downscaling, using a straightforward Kirchhofer map classification to predict rainfall over the Canadian plains. Their work showed promise, although precipitation variability during convective periods of the year was underestimated.

Two recent papers have examined fuzzy-rule classifications as a tool for downscaling precipitation. Wetterhall *et al*. (2009) aim to capture future extreme precipitation occurrence in Sweden by using a classification of 850 hPa geopotential height patterns. Their results show that the use of statistical downscaling with incorporation of synoptic patterns produces far more realistic precipitation totals and occurrence of wet or dry periods than the GCM data. Precipitation increases projected for the twenty-first century by the GCM are due to increases in moisture flux across Sweden and not due to circulation pattern frequency changes. Using a monthly timescale, Ghosh and Mujumdar (2006) utilize fuzzy clusters on principal components of monthly mean 500 hPa heights and SLP values over Orissa, India; multiple regression models then predict monthly precipitation. Using the CGCM2, their model projects circulation changes which increase summer rainfall and winter drought across the state.

Enke *et al*. (2005b) devise a hybrid method of determining weather classes, by first creating composite maps of 10 surface temperature and precipitation classes over Germany, and then utilizing discriminant function analysis with upper-level weather variables as predictors to explore categorical relationships. In Enke *et al*. (2005a), they utilize this methodology within a stochastic weather generator to downscale precipitation and temperature values from a GCM data set, but historical comparisons of GCM with observed temperature and precipitation values are not provided.

V The assessment and use of synoptic climatological methods as a statistical downscaling tool for extreme events

Synoptic classifications have also been used to infer likelihood of extreme events from GCM output. As upper-level circulation patterns can be connected to a diversity of surface weather responses, in contrast to previous articles where the synoptic patterns were derived from GCM output and then related to surface conditions, three recent articles use statistically downscaled surface data from GCM output to drive the categorization of synoptic weather types. Cheng *et al*. (2007a) utilize a large suite of variables to derive 18–24 weather types at each of several stations across southeastern Canada, and correlate these clusters with the likelihood of freezing rain events. Validation and future projection show good correlation between mean frequency of freezing rain events between the four GCM models and observed historical events, and prognoses suggest increased winter freezing rain episodes and spatially varying changes in late autumn and early spring events. Cheng *et al.* (2007b; 2007c) use a similar methodology to project future air pollution. Three different pollution scenarios are assessed; results from this study suggest high-ozone days will invariably increase due to higher temperature values, while, for other pollutants, future emission levels will be the primary determinant. Hayhoe *et al.* (2010) forecast future heat wave occurrence in Chicago using the Spatial Synoptic Classification (SSC; Sheridan, 2002), which classifies a given day into one of several weather types based on surface observations. Output from three GCMs is used to downscale surface observations, from which weather types are derived. Their results show that hot weather types that have been connected to increased mortality increase from approximately 10 days per year to 30–70 by century's end, depending upon the model and scenario.

McKendry *et al.* (2006) evaluate the CGCM2's ability to replicate the NNR data set using k-means clustering of principal components. Aside from some resolution issues involving the terrain of the Canadian Pacific Coast, they discover that the GCM significantly underestimates several Arctic flow types in this region. They then correlate this research with previous work of theirs (Stahl *et al.*, 2006) regarding pine beetle mortality, which is most dependent on occurrence of one of the cold types that is significantly underrepresented in the model.

VI Synthesis

Several important themes can be taken from the body of work discussed in this article. The majority of articles do not elucidate as to why one particular GCM was chosen for their particular study. In cases where the focus of the paper is a demonstration of a new synoptic technique, this may not be critical, but for applied research where only one model is used, the robustness of the results is difficult to interpret. Previous evaluations of models may not be helpful, as Finnis *et al.* (2009) note much poorer results from the CCSM3 in precipitation modeling in the Mackenzie River basin than Cassano *et al.* (2006) produce with the same model when simulating circulation patterns in the Arctic. Different levels of atmospheric modeling may be the culprit, as Cassano *et al.* evaluate sea-level pressure, while Finnis *et al.* note potential problems with wind speeds in the middle troposphere. This dichotomy is similar (though inverse) to Saunders and Byrne (1996), who found sea-level pressure clusters poorly represented but 500 hPa clusters well represented in the CGCM. While GCM performance has significantly improved over time, there are clearly still important differences from model to model and within models, which suggests that all future studies should utilize multiple models to account for the uncertainty present in any single model simulation.

Where different IPCC scenarios are chosen, usually two are picked (usually A1B, A1FI, or A2 versus B1) to frame the range of changes that can be expected in the future. Results typically show, unsurprisingly, that greater circulation frequency changes occur with the higher-GHG scenarios than the lower ones. However, in general, changes only differ by magnitude between scenario, and not direction (eg, Hope *et al.*, 2006; Demuzere *et al.*, 2009; Hayhoe *et al.*, 2010).

Without question, the availability of the ERA-40 and NNR reanalysis data sets has greatly streamlined data acquisition for synoptic climatologists. However, as with GCM selection, there is little mention in many articles as to the reasons behind the selection of a particular data set. While the discrepancies are less significant than inter-GCM discrepancies, the data sets are not identical. We found only one study that directly compares the two using synoptic climatology (Vrac *et al*., 2007), although numerous other relevant studies have been done. For instance, Trigo (2006) shows discrepancies in mid-latitude cyclone frequencies between the two, with greater discrepancies where subsynoptic scale systems are important. Assessing the reliability of the reanalysis data set itself, Schoof and Pryor (2003) perform a two-step cluster analysis on data taken from radiosondes across the Midwestern USA and compared results with NNR reanalysis clusters in the same region. While the modes of variability were similar, differences in the classifications are significant enough to warrant caution in the casual tendency in much literature to label either reanalysis data set as 'observed'. As mentioned above, Tolika *et al*. (2006) notice significant differences between observed precipitation and NNR precipitation over Greece; Serreze *et al*. (2005) show significant differences between both reanalysis data sets and observed data. As a 'Class-C' reanalysis variable, meaning its value is entirely a product of model calculations, reanalysis precipitation data sets should not be used except in limited cases (eg, Finnis *et al*., 2009) where verification of data has shown it to be reliable, or where observations are sparse or missing.

Domain size and grid spacing varies considerably in a number of papers that have been reviewed, though in most cases, domain size is on the synoptic scale. Few studies have explicitly presented comparative results of the use of different domain sizes since Saunders and Byrne (1999) showed better results emerge in downscaling precipitation in Alberta, Canada, from a larger domain (one that includes much of the Pacific) than a smaller domain centered over the Prairie provinces; domain size was clearly more crucial than grid spacing within the domain. Demuzere *et al*. (2009), in using Lamb weather types, find that too small a resolution (2.5°) results in too many unclassified days, while 5° and 10° resolutions produce similar, better results. Overall domain size is critical in their study, as too fine a grid domain does not correctly resolve cyclonicity. However, in other cases, it is intimated that smaller domains are used to filter out irrelevant noise, such as Hope *et al*. (2006), whose Western Australia SOMs were being dominated by eastern Australia SLP variability, resulting in their exclusion of the eastern half of Australia in the final SOM domain. In a small region across Germany and the Czech Republic for which Enke *et al*. (2005a; 2005b) perform statistical downscaling, they suggest the ideal domain differs from western to eastern sites, although little information is lost in using one domain for all sites; this same conclusion is reached by Wetterhall *et al*. (2009) in using a single weather-pattern classification for Sweden versus locally derived weather types. Anagnostopoulou *et al*. (2009), on the other hand, arrive at better results when using individual Lamb weather types for sites in Italy, Greece, and Cyprus. While the ideal grid domain clearly varies according to region of the world and by application, more systematic comparisons should be published.

The most commonly examined variables in circulation pattern analysis are sea-level pressure and 500 hPa or 700 hPa geopotential heights, as these fields are among the most reliably reproduced and climatologically relevant in reanalysis and GCM data sets (eg, Vrac *et al*., 2007). While certain methods, such as the Lamb weather types, inherently standardize variables in order to determine cyclonicity, use of raw variables, not seasonally standardized, dominates in GCM-related work, since one significant issue of climate change is seasonal shifts in frequencies of events, something more difficult to assess using standardized values. In some research, subtracting mean GCM model bias (compared to a reanalysis data set) from the mean fields (eg, Hope, 2006; Demuzere *et al*., 2009) produces a vastly improved correlation with reanalysis data sets. The number of clusters retained and decisions made in the classification process may also significantly affect the interpretability of the resulting circulation patterns (eg, Vrac *et al.*, 2007), and thus we urge all authors to fully document their methods.

The outlook for employing synoptic methods with GCM output data is promising. Until GCMs can overcome some of their well-documented present-day shortcomings (eg, precipitation generation), synoptic methods can serve as a necessary metric in evaluating the adequacy of GCM output as well as connecting fields which GCMs replicate well to the parameters most important for analysis. Moreover, as the need for impact assessments on the regional and local scales continues to grow, the synoptic methodology is clearly valuable for the specialized data needs many of these studies have. However, the divergent results seen with much of the research to date suggests that the validation of GCM output must be thorough. With increased ease of data availability from multiple GCM and reanalysis data sets, more comparative studies assessing the robustness of synoptic methodologies should be undertaken.

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