Blue Waters Supercomputing Applications in Climate Modeling with the WRF Model

Morgan Smith Department of Geosciences 108 Hilbun Hall, P.O. Box 5448 Mississippi State, MS, 39762-5448 1-662-325-3915 mls561@msstate.edu Andrew Mercer Department of Geosciences 108 Hilbun Hall, P.O. Box 5448 Mississippi State, MS, 39762-5448 1-662-325-3915 a.mercer@msstate.edu

ABSTRACT

Long-term atmospheric forecasting remains a significant challenge that in the field of operational meteorology. These long-term forecasts are typically completed through the use of climatological variability patterns in the geopotential height fields, known in the field of meteorology as teleconnections. Despite heavy reliance on teleconnections for long-term forecasts, the characterization of these patterns in operational weather models remains inadequate.

The purpose of this study is to diagnose the ability of an operational forecast model to render well-known teleconnection patterns. The Weather Research and Forecasting (WRF) model, a commonly employed regional operational forecast model, was used in the simulation of the major 500 mb Northern Hemisphere midlatitude teleconnection patterns. These patterns were formulated using rotated principal component analysis on the 500 mb geopotential height fields. The resulting simulated teleconnection patterns were directly compared to observed teleconnection fields derived from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis 500 mb geopotential height database, a commonly utilized observational dataset in climate research. Results were quite poor, as the resulting teleconnection patterns only somewhat resembled those constructed on the observed dataset, suggesting a limited capability of the WRF in resolving the underlying variability structure of the hemispheric midlatitude atmosphere. Additionally, configuring the regional model to complete this simulation was met with a series of computational challenges, some of which were not successfully overcome. These results suggest future needs for improvement of the WRF model in reconstructing teleconnection fields and for use in climate modeling.

Keywords

Teleconnections, interannual variability, climate modeling, rotated principal component analysis, Weather Research and Forecasting model

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1. INTRODUCTION

Long-term forecast ability in meteorology remains heavily linked with climate-scale interannual variability patterns within the midlatitude geopotential height fields. These interannual variability patterns, known in the field of meteorology as teleconnections, are a result of cyclical internal atmospheric dynamics (in particular synoptic-scale waves - Feldstein 2003, Woolings et al. 2008) coupled with ocean circulation patterns and sea-surface (Franzke et al. 2011). The importance of these fields in long-term forecasting is evident (Wagner 1989) in the numerous studies that have applied them for this purpose. For example, Johansson (2007) diagnosed prediction skill from two of the most commonly cited teleconnections, the North Atlantic Oscillation (NAO) and the Pacific North American Oscillation (PNA), noting that the forecast skill of the PNA exceeds the NAO and that both are improved by larger values of the PNA indices. Luo and Cha (2012) diagnosed the relationship between the NAO and the variability within the North Atlantic polar jet, which is directly linked to long-term predictability in that region. Lin et al. (2009) even noted a relationship between the NAO and a shortertemporal scale tropical teleconnection, the Madden-Julian Oscillation (MJO - Madden and Julian 1971). Additionally, smaller-scale studies such as Pablo and Soriano (2007), which defined the relationship between the phase of the NAO and winter lightning in western Europe and DiNezio et al. (2009), which looked at Florida wind patterns as they relate to the NAO, are two of countless examples of applications of teleconnection patterns used in medium and long-term predictability research. Clearly, if improvements of long-term operational forecasts are desired, it is imperative that the predictability of these teleconnection patterns be ascertained.

Teleconnections were initially proposed in the literature by Wallace and Gutzler (1981) through correlation analysis of 500 mb geopotential height fields over the Northern Hemisphere midlatitudes. The teleconnection patterns were formally identified and named by Barnston and Livezey (1987), which utilized rotated principal component analysis (RPCA) to identify the common modes of variability within 700 mb Northern Hemisphere geopotential height data. The findings of Barnston and Livezey (1987) were updated by Chen et al. (2003) and van den Dool et al. (2000), which utilized empirical orthogonal functions in lieu of RPCA. More recent work conducted by Richman and Mercer (2012) concluded that these previously derived patterns were limited owing to the orthogonality constraint in their methods, as well as a limited sample size and an insufficient number of retained RPCs. Their work relaxed the

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orthogonality constraint (via Promax rotation). and updated the previous results using the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis Project dataset (hereafter referred to as the NNRP - Kalnay et al. 1996), which provide gridded geopotential height observations on a denser grid than previous studies. Richman and Mercer (2012) also identified new teleconnection patterns and updated the spatial configurations of already established teleconnections. Outside of the most commonly cited of these patterns (e.g. the NAO, the PNA), these new observed modes have had limited consideration in climate simulations, which is noted by Richman and Mercer (2012) in their study limitations.

Some efforts have been undertaken at assessing predictability of these patterns within climate models. Papadimas (2012) used a statistical climate prediction model for monthly Northern Hemisphere geopotential heights using the general concept of teleconnections (without testing for the modes from Richman and Mercer 2012) in order to find relationships between air temperature and sea-level pressure during winter. The resulting SLP oscillations were shown to correlate strongly with the air temperatures of neighboring areas with a lead time of up to two months. Phase five of the Coupled Model Intercomparison Project (CMIP5 - Sheffield 2013) used intraseasonal to multidecadal time scales to assess North American geopotential height variability in a dynamic climate simulation. Their simulations reproduced certain aspects of the geopotential height variability well, while other aspects were rendered poorly by most models. Errors were attributed to unexplained natural variability within the climate model.

While several studies (noted above, as well as many others) have quantified forecast error of teleconnections within climate models, no study has attempted to quantify such errors using an operational forecast model. However, operational models are more familiar and commonly implemented in daily and weekly weather forecasts. This lack of consideration of longer-term variability patterns in operational model verification likely contributes heavily to the poor medium to long-term forecasting ability of meteorologists. As such, the goal of this project is the formal quantification of teleconnection index forecast error from an operational weather model that can be used to educate forecasters about the limited predictability of these features at medium and long time scales.

2. DATA AND METHODS

As the primary goal of this work was quantifying an operational weather model's performance at rendering the major teleconnection modes in the 500 mb height fields, a database of observed teleconnection patterns and simulated teleconnection patterns was required. Each dataset is described in detail below.

2a. Observational Teleconnection Dataset

The derived teleconnection patterns and associated indices from Richman and Mercer (2012) were utilized as the observed verification dataset. In their study, monthly mean January 500 mb geopotential heights from the NNRP were used to derive the primary variability modes. While the Richman and Mercer (2012) study period extended from 1948-2009, issues with the weather model (as described below) limited the simulation period to 1948-1964. To maintain consistency with the simulated study period, the work of Richman and Mercer (2012) was redone for the shorter period of record, which resulted in slight deviations from what was observed in their original study (not shown).

2b. Model-derived Teleconnection Dataset

In line with the primary objectives of this research, a commonly utilized operational forecast model was required for creation of the model-derived teleconnection dataset. The Weather Research and Forecasting (WRF - Skamarock et al. 2008) model version 3.6 was used as a global climate model for this work. The WRF is a non-hydrostatic mesoscale model that can be configured for global simulations with appropriate global input data. As such, the NNRP data, a global meteorological reanalysis dataset with 2.5° latitude-longitude grid spacing and 17 vertical levels, were used as initialization data for the forecast model. The NNRP contain many important meteorological fields, including basestate fields (such as temperature, humidity, wind velocity components, geopotential heights) and derived fields (heat fluxes, radiative fluxes, precipitation, surface pressure, many others). Additionally, the NNRP have a long period of record that extends from 1 January 1948 to present with new observations provided at 6 hourly intervals. Further, the base-state fields (which are required by the WRF for the global simulation) have high reliability according to Kalnay et al. (1996), ensuring their heavy dependence on observations as opposed to simulated information, supporting using the NNRP as boundary conditions for the WRF.

The forecast model was run for the full Northern Hemisphere at 3° latitude-longitude resolution from 1948 to 2009 (the period of record of Richman and Mercer 2012). However, model instability caused the simulation to prematurely end after 1964, so the final simulation only consisted of 17 years of the full 63-year period. Attempts were made to correct this issue but were unsuccessful (as described in section 4 below). Default model physics parameterizations were selected for the forecast simulation. The global simulation, even at its coarse spatial resolution, required parallel-processed supercomputing resources owing to the duration of the simulation (17 years). This simulation was completed using Blue Waters supercomputing resources, and the project required roughly 500 node hours of simulation time.

Upon completion of the simulation, appropriate analysis was required to retain the simulated teleconnection fields. The simulated January mean 500 mb geopotential height data were used to compute teleconnection indices, maintaining consistency with Richman and Mercer (2012) which was used as the observational dataset. Note that all gridpoints south of 20°N latitude were removed prior to analysis (since geopotential heights are generally uniform in the tropical latitudes). These midlatitude monthly geopotential height fields were used to formulate teleconnection indices following the methodology of Richman and Mercer (2012), which included:

- Interpolation of the simulated geopotential height fields to a Fibonacci grid (Swinbank and Purser 2006 Fig. 1) that ensured all gridpoints were evenly spaced. Since both observation and forecast fields are provided on latitude-longitude grids, spatial correlations will artificially increase along converging longitude lines unless interpolated to an evenly spaced grid.
- Formulation of an S-mode (Richman 1986) principal component analysis through formulating the correlation matrix on the spatial dimension of the data, eigenanalysis of the correlation matrix, and computation of the RPC loadings (scaling the eigenvectors to unit length).

- Rotation of the RPC-loading vectors using Promax (nonorthogonal) rotation (Richman 1986).
- Truncation of the number of WRF-derived RPC loading dimensions to 8 to maintain consistency with the results of Richman and Mercer (2012).
- Projection of the RPC loadings onto the original data, yielding RPC scores (the teleconnection indices).

This approach yielded forecasted RPC loading patterns, which are spatial representations of the teleconnection patterns, as well as RPC scores, which represent the teleconnection index time series for each map (the phase of the teleconnection).



Fig. 1. The NNRP grid (panel a) and the Fibonacci grid from Swinbank and Purser (2006 – panel b) used in this study. Note that the Fibonacci grid retains equal grid spacing across the hemisphere, a requirement when computing spatial correlations such as those used in RPCA.

Once the simulated and observed teleconnection patterns and indices were obtained, the match between patterns was ascertained through a second spatial correlation analysis (for the RPC loading maps) and root-mean square error analysis (for the RPC score indices. The resulting verification statistics are presented below.

3. RESULTS

3.1 RPC loading map results

To ascertain pattern matching between observed and forecasted RPC loading maps, the fields were correlated against each other to identify which simulated RPC best matched the observed patterns. The correlation results (Table 1) revealed that despite retaining 8 RPCs, only four of the 8 (WRF-RPC1, WRF-RPC3, WRF-RPC4, and WRF-RPC5) had a modest correlation with the original 8 RPCs, and many of the observed RPCs correlated with the first and fifth simulated RPCs. These results are discouraging as they suggest that the forecast model is doing a poor job of distributing variance in the geopotential height fields, or that the model distribution of variance is not representative of observations. Additionally, RPC1 and RPC5 in the observed fields are the dipole height couplet over the northern Pacific (the West Pacific Oscillation, WP) and Atlantic (the North Atlantic Oscillation, NAO) Oceans, which have well-understood properties. The subtler variability characterized by the remaining 6 observed RPCs is poorly rendered by the WRF simulations, which is a discouraging result.

Table 1. List of observed (NNRP) RPCs with associated forecasted (WRF) RPC with the highest correlation (and that corresponding correlation value). Values near +/- 1 are ideal.

<u>NNRP RPC</u>	WRF RPC	Correlation
RPC1	RPC1	0.394
RPC2	RPC3	-0.405
RPC3	RPC1	-0.274
RPC4	RPC4	-0.270
RPC5	RPC1	0.421
RPC6	RPC5	-0.237
RPC7	RPC5	-0.351
RPC8	RPC5	-0.210

According to Richman and Mercer (2012), the three most commonly known (and most widely used in North American forecasting applications) patterns from the observed database were RPC1 (the WP)), RPC3 (the Pacific North American Oscillation – PNA), and RPC5 (the NAO). Interestingly, the simulated RPC1 correlated most highly with all three of these patterns. Figure 1 shows each of these observed RPCs (panels a-c) and simulated RPC1 (panel d) to provide an example of the WRF model performance.

The observed WP (Fig. 2a) showed a strong positive center located throughout the Arctic Circle and extending over the Gulf of Alaska, with the expected negative region over the northcentral Pacific, a key feature of the WP. However, the limited 17year sample size left this feature a bit farther north than is typically observed for the WP. The simulated RPC1 (Fig. 2d) showed this same maximum over the North Pole, but the associated negative region over the north-central Pacific was notably absent from the pattern. It is likely this feature was distributed to another simulated RPC or not simply not simulated, representing the variance distribution issue discussed previously.

The observed PNA (RPC3 - Fig. 2b) shows the expected tripole pattern that extends over the Gulf of Alaska, the southwestern United States, and the Northeast. However, traditional renderings of the PNA (Richman and Mercer 2012) show this pattern shifted a bit farther south than is represented by this limited sample size. The simulated RPC1 (Fig. 2d) shows two of the three poles in the PNA, the same maximum over the Gulf of Alaska and the Arctic and a local minimum over the Desert Southwest. However, as was the case with WP, the final piece of this pattern was missing from the simulation (the feature over the Northeast United States), supporting the conclusion that geopotential height variability is being improperly distributed by the WRF.

The observed rendering of the NAO (RPC5 - Fig. 2c) showed the expected maximum over Iceland (the Icelandic low) and the associated minimum over Bermuda and the central Atlantic (the Bermuda high). The smaller sample size revealed has a few other poles in addition to the two primary features which are typically not considered part of the NAO (Barnston and Livezey 1987, Richman and Mercer 2012). The simulated RPC1 (Fig. 2d) showed the maximum over the Bermuda high region and a region of the large positive area over the Gulf of Alaska that extended to cover the Icelandic low region. Many other patterns in the simulated RPC1 were not present in the observed NAO, but the important features of the NAO were sufficiently characterized, which is supportive of high correlation between the observed RPC5 and simulated RPC1 (0.421). Overall, the dipole patterns of the WP and NAO, as well as two of the three poles of the PNA, were represented as a single RPC in the WRF simulated loading field, suggesting variability is not being properly distributed among loadings when conducting global WRF simulations.

3.2 RPC score validation

In addition to a strong match between the simulated and observed RPC loading patterns, a good simulation of the teleconnections should portray the phasing of the patterns (by way of teleconnection indices) with the same success. By definition, the product of the RPC score and loading map is in units of standard anomalies, so that large errors in the RPC scores suggest phasing issues in the monthly mean fields used to derive the teleconnection indices. For example, if a root mean square error between the modeled and observed RPC score series was in excess of 1, it could suggest either a complete reversal of the pattern or an anomalously weak/strong forecast. Consider an RPC of -0.5. With an RMSE in excess of 1, this could mean that point may have a value of either 0.5 or larger (a complete phase reversal) or an RPC of -1.5, which is considerably stronger than the forecasted -0.5. Fig. 3 shows the RMSE of the RPC scores when compared to the map that contained the highest correlation (e.g. comparing the observed RPCs with their associated forecasted RPCs as per table 1). These results were quite poor, which was anticipated given the poor match between the observed and the simulated loading fields. All 8 RPCs had RMSE values in excess of 1, suggesting major phasing issues with the simulated RPC fields over time. Unfortunately, these results demonstrate several issues with using the WRF model for diagnosing teleconnections and suggest not using it for such an application.

4. DISCUSSION AND LESSONS LEARNED (EDUCATIONAL IMPACT)

The primary research objective of this study was the evaluation and validation of WRF-simulated teleconnection indices within Northern Hemisphere 500 mb geopotential height fields. A proper knowledge of these patterns is essential for medium and longterm forecasts, which are heavily based on the phases of these features. The results of the study suggest that alternatives to the WRF (such as global climate models like the NCAR Community Climate System Model – Gent et al. 2011) should be considered when forecasting teleconnection indices as climate-mode configured WRF simulations were inadequate.

This project was completed as part of the Blue Waters Undergraduate Internship Program. The primary educational component of this research came from the undergraduate student's interaction with the high-performance computing environment, including learning how to work with big-data, the limitations of traditional computing environments with big-data problems, and learning to troubleshoot parallel processed software. Two major computational issues arose when completing the research project:

- The WRF simulations were initially conducted without updating global sea surface temperature (SST) fields. However, the model parameterizations used within the WRF are not designed to update SST through the associated solar radiation model, and as such, global temperatures cooled to an infeasible value by roughly day 100 of the simulation. This required the undergraduate student to update the model with NNRP data as the simulation progressed to maintain realistic hemispheric mean temperature values. This was not ideal, since the NNRP boundary conditions could have artificially improved teleconnection depictions within the simulations (though this ended up not being the case).
- 2) Despite the claims that the WRF can be run in climate mode, the model simulations continued to fail past 1964 of the study period. This failure likely resulted from model instability with the upper-level wave patterns, which is a common problem within numerical weather prediction models with timesteps that are too large. However, lessening the timestep did not fix this issue, suggesting some larger underlying issue within the WRF itself for such an application. It is likely that the shorter sample size affected the results detrimentally, though a 17-year period is sufficient to render all phases of each of the resulting teleconnection patterns multiple times, so this impact is likely small when compared to the results of the study.

Despite these inherent issues with the implementation of the study, the undergraduate student learned many important lessons regarding climate-scale work in the field of atmospheric sciences. The student learned how to utilize RPCA on global hemispheric data and interpret the resulting variability modes, as well as common practices within operational meteorology for verifying numerical weather prediction models.

This work would have not been possible without the utilization of high-performance computing in the construction of the climate simulation. The use of the Blue Waters supercomputing center's resources helped support this climate simulation, which required a week of simulation time and tens of thousands of files. The resulting simulation produced daily Northern Hemisphere climate output for the full 17-year period, resulting in a dataset of roughly 6300 files and in excess of 70 GB, which cannot be fully analyzed utilizing traditional computing environments. Additionally, the

computing time required to complete the simulation exceeded 500 compute node hours, which was infeasible in a traditional computing setting.







Fig. 2. NNRP loading maps for RPC1 (panel a), RPC3 (panel b), and RPC5 (panel c), and their associate RPC scores. Panel d shows the WRF simulated RPC1, which is most highly correlated with all three of these patterns.



Fig. 3. RMSE for NNRP RPC scores vs. WRF RPC scores, paired based on the results in Table 1.

In addition to demonstrating the value of supercomputing, this work reveals a key issue associated with medium and long-term forecasting, that issue being the inability of a regional, operational forecast model with global capabilities to render teleconnections. Forecasts of teleconnection indices will remain based entirely on trends for the foreseeable future, and the results presented herein support the need for further development of operational teleconnection forecasts from dynamic weather models.

5. REFLECTIONS

As is the case with any student-led project, it is important to discuss the follow-up educational impact that the project has had on the student's academic success. Students who wish to conduct research or work in the operational meteorology sector require some prior research experience, and this project provided a unique opportunity to learn weather research using with state-ofthe-art technology. Operational weather offices are more frequently utilizing multi-core parallel processing computing environments to complete mesoscale weather simulations, and this experience has offered the student an edge over others competing for graduate degree positions. Additionally, this research experience has provided the student the necessary experience to be successful once beginning to work in graduate meteorology. The opportunity to complete undergraduate research is a rare one in meteorology, and the opportunity afforded by the Blue Waters Summer Internship Program will ultimately allow the student to stand out among her peers competing for jobs.

6. SUMMARY AND CONCLUSIONS

The study of teleconnections and their links to long-term weather forecasting has been an area of ongoing research over the past few decades. Research has shown that teleconnections have skill in forecasting longer-term (in excess of a week) processes (Johnson et al. 2014, Jones et al. 2011, Hamill and Kiladis 2014, many others). To this point, most operational forecasts of teleconnection indices have been limited to simple trend analysis, with no study considering the value of using an operational forecast model in recreating teleconnection indices, despite their known importance for medium and long-range forecasting. As such, the primary goal of this project was to determine any limitations associated with deriving teleconnection indices from simulations from a well-known regional forecast model run in global climate mode. This performance is a strong indicator of possible utility of such a model in medium and long-range forecasting.

Model performance was determined through a 17 year (1948-1964) simulation of Northern Hemispheric midlatitudes flow patterns computed using the WRF model. Geopotential heights at 500 mb were retained following the methodology of Richman and Mercer (2012) to formulate teleconnection maps and indices on the simulated fields. These patterns were directly compared with observation patterns derived from 500 mb NNRP, again following the methodology of Richman and Mercer (2012). The resulting RPC loadings for both the simulated and observed teleconnections were compared to ascertain WRF model performance at recreating the most commonly observed teleconnections. Additionally, RMSE computed on the RPC score time series was computed to quantify timing issues with the onset of given phases of each teleconnection pattern.

The resulting WRF simulated teleconnection maps showed generally weak correlation with NNRP (observed) RPCs, distributing variance presented in the NNRP fields among the different WRF simulations (Table 1). An example of these issues was presented associated with the simulated RPC1 (Fig. 2), which was modestly correlated with three different observed RPCs and contained some of the features of those patterns while removing others. The lack of correlation with the observed fields and the missing poles within the simulated teleconnections suggested the WRF is not retaining the proper variability structure in the 500 mb height fields.

The RPC score RMSE plot (Fig. 3) showed several concerning issues regarding the simulation of the patterns as well. All values exceeded 1, meaning that it was likely phases of the patterns were completely flipped, which suggested the WRF simulations were out of phase with the NNRP patterns. This was particularly concerning for forecast purposes, since different phasing of the teleconnection pattern lead to completely different forecast conclusions (e.g. a positive NAO suggests one forecast outcome, a negative NAO a different outcome).

Overall, these results suggested that major deficiencies remain in long-term hemispheric-scale WRF simulations, as the 500 mb geopotential height fields are a primary representation of dominant atmospheric flow patterns. It is likely that the WRF was formulating Rossby wave patterns with an improper wave phase speed when conducting longer-term simulations, and future work could help reveal this issue by using pattern recognition techniques. Additional future work involving longer simulation periods (e.g. the full period of record of the NNRP) will help reveal if the model is more stable at longer climate time-scales. Despite the limited model performance, operational forecast models such as the WRF are the best opportunity at rendering operational teleconnection forecasts that in turn will reveal patterns in medium and long-term flow variability, and further improvements to these models will likely alleviate the issues presented herein.

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