Circulation Regimes in the CFS Interactive Ensemble: Bridging Weather and Climate Predictability Promises and Challenges

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1. Introduction

The concept of circulation regimes represents one method of organizing the large and varied set of atmospheric circulation patterns that have been identified on time scales longer than a few days. We give a brief overview of the rich history of regimes from a dynamical point of view, and touch upon the statistical methodologies behind the identification of regimes in real and simulated data. The long history of El-Nino related changes to Pacific patterns / regimes will be summarized with reference to recent work on very large ensembles of atmospheric simulations.

Recent, preliminary results of regime structure in boreal winter for the Pacific – North American region from interactive-ensemble forecasts using the CFS are presented. Five forecasts have been carried out for early January atmosphere / ocean initial conditions for each of 11 calendar years. Each forecast uses the interactive ensemble, in which six atmospheres are coupled to one ocean. We also show some preliminary results for the probability distribution (pdf) of ideal model errors (i.e. ensemble spread) from the forecast.

Regime analysis was originally motivated by two different schools of thought. One was based on the recognition that extended periods of (possibly extreme) weather occur intermittently, and that such occurrences are related to the persistence of the large-scale flow. This led to the classification of regional weather patterns into a discrete number of types (the grosswetterlagen), as in Baur et al (1944), and Egger (1981) and references therein. Note that these weather patterns can be numerous. To quote Egger: “The grosswetterlagen defined by Baur …provide a valuable classification of the extended (duration longer than three days) weather types observed in Central Europe...28 large-scale weather types derived from about 70 years of observations.” Such weather regimes stimulated the second school of thought, which sought to identify non-linear interactions in the large-scale flow via highly-truncated solutions of the dynamical equations (Charney and DeVore, 1979; Charney and Straus, 1981). This approach sought to identify highly non-Gaussian (in fact multi-modal) probability distributions with weather regimes. That such multi-modal pdfs are possible in the context of atmospheric dynamics has been confirmed by recent work of Christiansen (2005), the latest of many papers over the years describing a simple index of large-scale wave activity in mid-latitudes from analyses (see Christiansen for details). This paper shows clearly that when the daily data are filtered to remove those periods of rapidly changing wave activity index, the resulting pdf is decidedly non-Gaussian and is in fact bi-modal.

Note that while the feedback of smaller, synoptic scales on the large-scale flow was neglected in the early highly truncated models, it of course is included in the observational results of Christiansen. The mutual feed-back between the qausi-stationary large scale waves and the baroclinic, synoptic disturbances was developed theoretically by Reinhold and Pierrehumbert (1982) and Vautard and Legras (1988). This feedback can be paramteterized purely dynamically (as in Reinold and Pierrehumbert), semi-empirically (as in Vautard and Legras) and completely statistically (as in Sura et al, 2005).

Attempts at diagnosing circulation regimes from reanalyses have been hampered by the short data record. Corti et al. (1999) examined Nov.-Apr. monthly means of 500 hPa height from the Northern Hemisphere (north of 20N) in EOF space. Retaining only 2 leading modes, they showed smoothed estimates of the two-dimensional pdf which indicate multiple maxima. However, Stephenson et al (2004) use statistical tests on the same monthly mean data set, and find that one cannot rigorously reject the null hypothesis of a multi-normal pdf in the two-dimensional phase space. The difficulty of rejecting a multi-normal null hypothesis was also emphasized by

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Toth (1991), who used daily full-field 700 hPa height data from the Northern Hemisphere. However, *this oft-quoted result holds only for the phase-averaged pdf*, in which only the distance to the origin is considered. When the full pdf is taken into account, Toth (1993) did find significant departures from multi-normality if quasi-stationary data were used. (Quasi-stationarity means that periods when the daily rms change in the height field is largest are not used in the analysis. This filtering thus emphasizes episodes of persistent flow.)

2. Clusters in the NCEP Reanalysis and Methods of Regime Analysis

Straus et al (2007) are able to identify regimes in the wintertime 200 hPa height fields for 54 winters from the NCEP reanalysis (1948-49 through 2002-03). Daily data are filtered to retain only variability with periods of 10-90 days (but including the seasonal mean anomaly), and quasi-stationary filtering is applied. The partitioning method described by Michelangeli et al (1995) is applied to a subspace spanned by the leading six EOFs. For a choice of 3 or 4 regimes, the null hypothesis of multi-normality can be rejected at the 90% significance level (based on tests with synthetic data generated by a suitable Markov process), the patterns are reproducible using randomly drawn half-length samples, and it was demonstrated that the clusters arise due to “clumping” in phase-space and are not an artefact of skewness in the PCs. (Choices of 2 regimes, or 5 or greater, are shown to be less reproducible.) Figure 1 shows the patterns when 4 regimes are found. The Alaskan Ridge (Figure 1a) has been shown to be related to Alaskan blocking (Renwick and Wallace, 1996), and the Pacific Trough is reminiscent of the traditional “PNA” pattern. The Arctic High has a distinct signature of an annular mode or the North Atlantic Oscillation. The relationship of these regimes to synoptic blocking (diagnosed using potential temperature on the Potential Vorticity surface corresponding to the tropopause) was studied by Stan and Straus (2007).

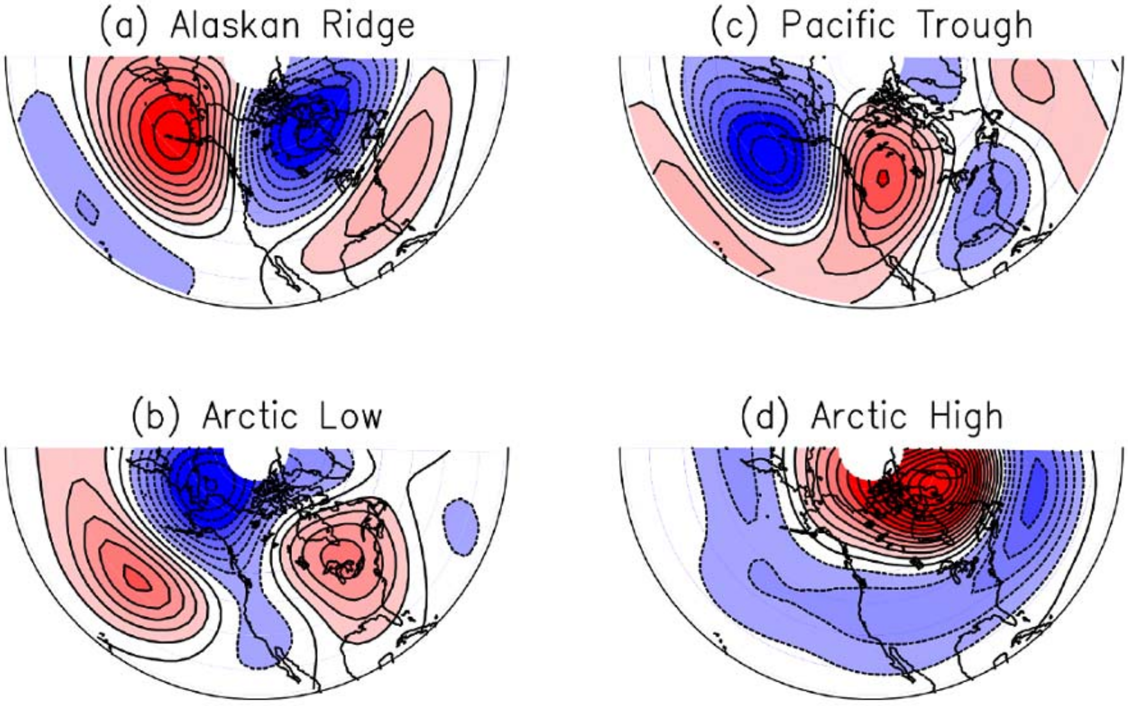
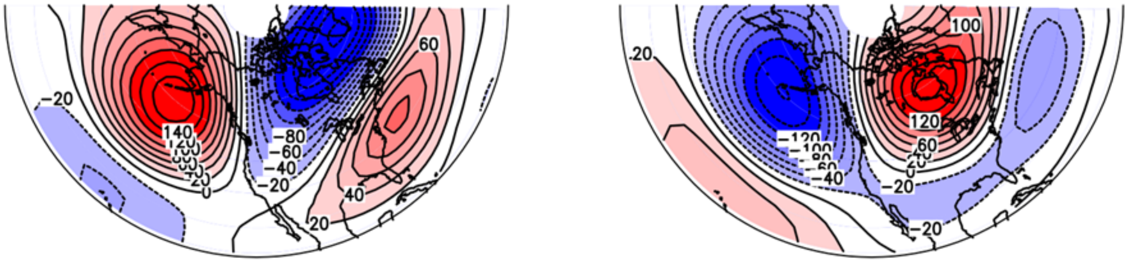


Figure 1 Four regimes identified from quasi-stationary periods during the 54 winters 1948/49 – 2002/03 from NCEP reanalysis. See text for details.

The need for long observed (reanalysis) data records in order to establish even modest statistical significance means that decadal changes in clustering properties are very hard to assess. Figure 2 shows the regimes obtained from the NCEP reanalysis for the 18 winters 1981-82 through 1997/98. From Figure 2 it is clear that the Alaskan Ridge is fairly robust with respect to period, while the Pacific Trough shows a change from a PNA-like pattern over the whole 54 years to a more ENSO-like response during the 18 years. Is this change in pattern due to the differences in SST records for the two periods (see e.g. Straus and Shukla, 2002), or is the change simply due to differing sample sizes?

(a) Alaskan Ridge

(c) Pacific Trough



(b) Arctic Low

(d) Arctic High

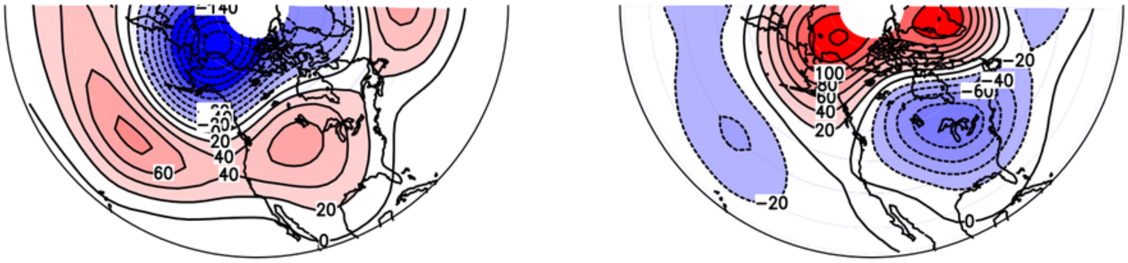


Figure 2 Four regimes identified from quasi-stationary periods during the 18 winters 1981/82 – 1998/99 from NCEP reanalysis. See text for details.

In order to assess the significance of the change in Pacific Trough, we need independent estimates of the sampling variability of the regimes. Such estimates are provided by an ensemble of wintertime atmospheric model simulations, constructed with the COLA atmospheric model forced by observed weekly SST. For each of the 18 above-mentioned winters, an ensemble of 55 simulations was run (see Straus and Molteni, 2004, for details). From this set of 55 x 18 simulations, we can construct a very large number of "samples" of simulations, each sample consisting of 18 simulations, one simulation chosen randomly per winter and so comparable to the observed record. (Call this sample Type A.) For each Type A sample, we construct an enhanced (Type B) sample of 54 winters, by augmenting the single simulation for each winter by 2 additional randomly chosen winters from the same winter. A pair of Type-A (18 members) and Type-B (18 x 3 = 54-member) samples thus represents atmospheric evolutions forced by identical SST histories, differing only in the number of simulations. For each of 100 such pairs of samples we repeat the regime analysis (as presented above), and obtain the pattern correlation between the regimes most strongly resembling the Pacific Trough. Thus a pdf of the pattern correlation between Pacific Trough regimes can be constructed. Against this pdf we evaluate the single pattern correlation between the Pacific Trough regimes shown in Figures 1 and 2 for the NCEP-54 and NCEP-18 samples, which did not see the same evolution of SST. The results (not shown) indicate that the observed pattern correlation (~0.6) lies well out into the tail of the pdf, indicating that the observed change in Pacific Trough between the NCEP-54 and NCEP-18 records is very likely to be due to the differences in SST, and not due to the differences in record length.

3. Regimes and Error Growth in the CFS Interactive Ensemble

It is widely accepted that ocean-atmosphere coupling is an important ingredient in the evolution of the climate system. Thus it is worthwhile diagnosing the regime behavior in coupled models. However, the dependence of regime properties on SST state discussed above and in Straus et al. 2007 indicates that evaluating regimes from coupled models may be difficult, since multiple atmospheric realizations with identical SST evolutions are not available. The Interactive Ensemble (hereafter IE) configuration solves this problem however. In the IE, the ocean model communicates to six realizations of the atmosphere model started from slightly different initial conditions and run in parallel. The SST of the ocean model is felt by each atmospheric realization, but it is only the ensemble means of the atmospheric fluxes of heat, momentum and fresh water that are communicated to the ocean. The atmosphere ensemble – ocean coupling occurs once per day. (See Stan and Kirtman, 2007, and Kirtman and Shukla, 2002, for more details.)

The IE configuration of the CFS model was carried out with atmospheric resolution T62 and 64 levels in the vertical (Stan and Kirtman, 2007). IE forecasts were initiated from 1 January for the 11 years: 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987, 1989, 1990, 1998. For each calendar year, 5 slightly perturbed 1 January ocean states were used to generate 5 Interactive Ensembles. For each IE, we use the first 90 days of the forecast. The regimes of 200 hPa height are computed as in described in Section 2. [In this case quasi-stationary pre-filtering was not used, so that each forecast state could be uniquely assigned a regime.] The results shown in Figure 3 are comparable to those in Figure 2. The Pacific Trough (upper right), Alaskan Ridge (lower left) and Arctic Low (lower right) are all reasonably represented. However, the fourth regime resembles a wave train, and is clearly quite distinct from the Arctic High. Interestingly, the same failure occurs for the COLA atmospheric model (not shown). Why this particular regime is so hard to simulate is not understood.

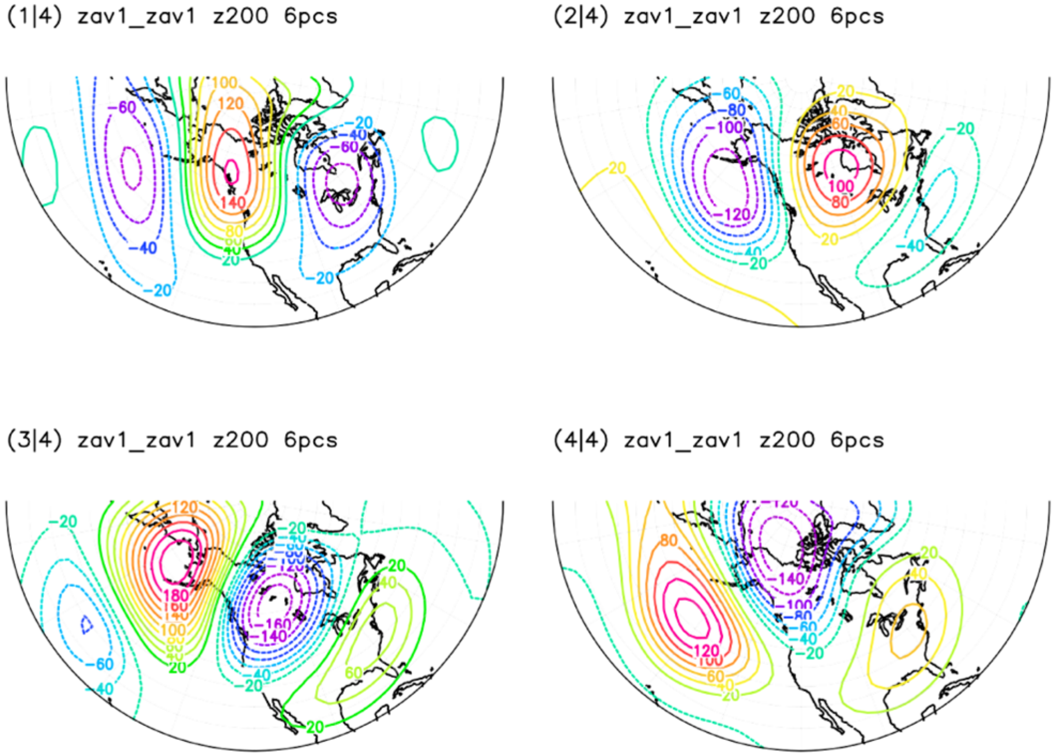


Figure 3 Four regimes identified from the CFS Interactive Ensemble forecasts. See text for details.

In order to show that these regimes correspond to preferred states in some sense, we evaluated the growth of the ensemble spread within each IE. Since Interactive Ensemble uses atmospheric initial conditions that are only slightly perturbed, we use the mean squared deviation of 200 hPa height for each atmosphere about the corresponding ensemble mean as a measure of "error." This error is then evaluated as a function of forecast day, and averaged over the 11 x 5 = 55 distinct IEs. Following Trevisan (1993), we expect that a system showing strongly preferred regimes to lead to non-Gaussian pdfs of errors.

The pdfs of IE errors is shown as a function of forecast day in Figure 4. For each panel, three separate representations of the pdf (based on different degrees of smoothing in the kernel estimator algorithm) are shown in the bright colors, while the cumulative pdf is shown in the light green. All the pdfs have been standardized to have zero mean and unit area. (This effectively normalized out the overall error growth.) The pdf at forecast day 5 looks qualitatively like that at day 1 – sharply peaked and positively skewed. However, by forecast day 10 the pdf has become much flatter (with a hint of bi-modality). Beyond forecast day 10 the pdf again relatively little change in shape. The timing of the change in error pdf, near day 10, corresponds roughly to the time when the average number of regimes represented in each ensemble starts to increase dramatically (not shown).

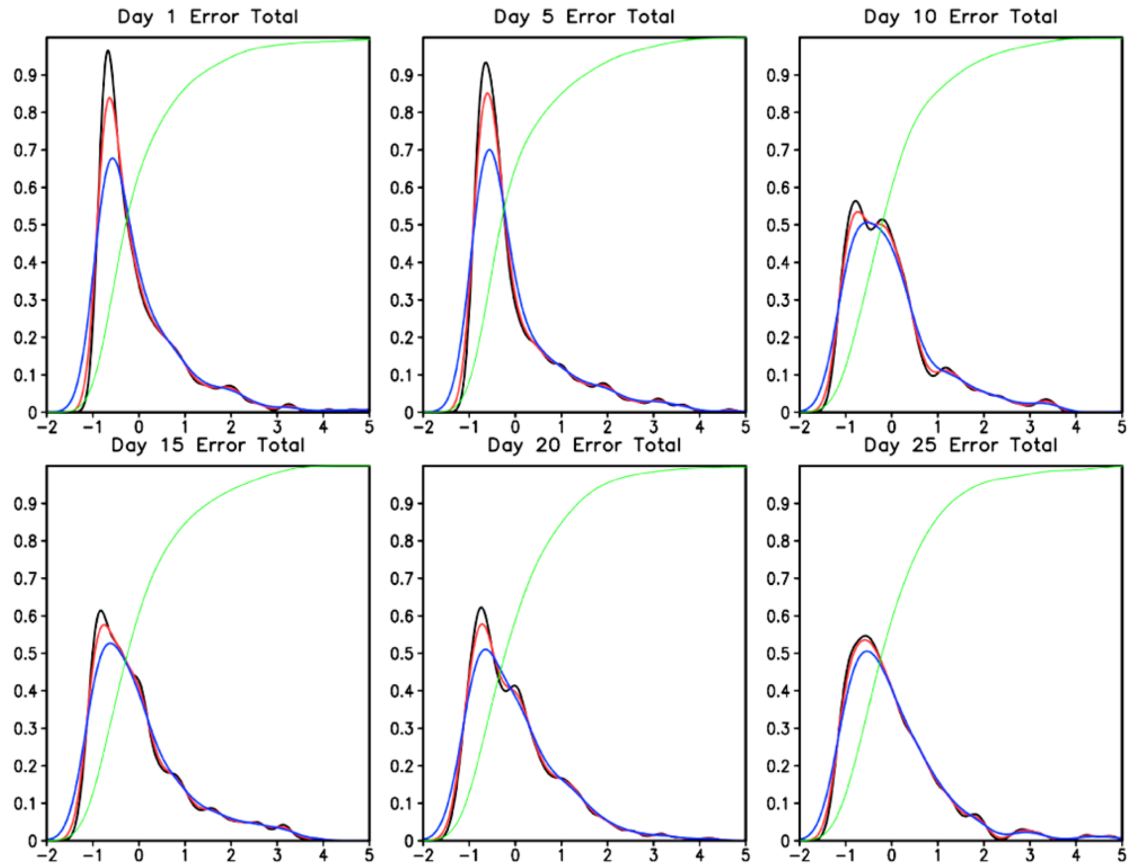


Figure 4 Standardized pdfs of error growth (ensemble spread) as a function of forecast day from the CFS Interactive Ensemble forecasts. See text for details.

4. Summary

There is enough evidence for significant circulation regimes in quasi-stationary data records of sufficient length for the concept to be taken seriously. However, statistical significance and reproducibility are still issues to be dealt with for each region, variable and period. Large ensembles of model simulations are very helpful in providing estimates of sampling statistics for regime properties. Regimes respond to changes in SST forcing both by changes in the structure of the regimes themselves, and in their population of occurrence. Preliminary results indicate that the regimes obtained from the CFS Interactive Ensemble forecasts are likely to be truly preferred states; more analysis of the CFS results is currently underway.

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References:

Baur, F., P. Hess and H Nagel, 1944; Kalendar der Grosswetterlagen Europas 1881-1969. Bad Homburg v.d.H.

Charney J. G. and J. DeVore, 1979: Multiple flow equilibria in the atmosphere and blocking. *J. Atmos. Sci.,* **36,** 1205-1216.

Charney J. G. and D. M. Straus, 1980: Form-drag instability, multiple equilibria, and propagating planetary waves in baroclinic, orographically forced, planetary wave systems. *J. Atmos. Sci.,* **37,** 1157-1176.

Christiansen, B., 2005: Bimodality of the Planetary-Scale Atmosopheric Wave Amplitude Index. *J. Atmos. Sci.*, **62**, 2528-2541.

Corti, S., T. Palmer and F. Molteni, 1999: Signature of Recent Climate Change in Frequencies of Natural Atmospheric Circulations, *Nature,* **398,** 799-802

Egger. J., 1981: Stochastically driven large-scale circulations with multiple equilibria. *J. Atmos. Sci.,* **38,** 2606-2618.

Michelangeli. P.-A., R. Vautard, and B. Legras, 1995: Weather regimes: Recurrence and quasi-stationarity. *J. Atmos. Sci.,* **52,** 1237-1256.

Reinhold, B., and R. T. Pierrehumbert, 1982: Dynamics of weather regimes: Quasi-stationary waves and blocking. *Mon. Wea. Rev.*, **121,** 2355-1272.

Renwick, J. A., and J. M. Wallace, 1996: Relationships between North Pacific wintertime blocking and, El Nino and the PNA. *Mon. Wea. Rev.*, **124,** 2071-2076

Stan, C. and B. P. Kirtman, 2008: The influence of atmospheric noise and uncertainty in ocean initial conditions on the limit of predictability in a coupled GCM. *J. Climate,* in press.

Stan, C. and D. M. Straus,, 2007: Is Blocking a circulation regime? *Mon. Wea. Rev.* **135,** 2406–2413

Stephenson, D. B., A. Hannachi, and A. O’Neill, 2004: On the existence of multiple climate regimes. *Quart. J. Ro. Meteor. Soc.*, **130,** 583-605

Straus, D. M., and J. Shukla, 2002: Does ENSO force the PNA? *J. Climate,* **15,** 2340-2358.

Straus, D. M., S. Corti and F. Molteni, 2007: Circulation Regimes: Chaotic Variability versus SST-Forced Predictability. *J. Climate*, **20**, 2251–2272

Straus.D. M., and F. Molteni, 2004: Circulation Regimes and SST Forcing: Results from Large GCM Ensembles. *J. Climate,* **17,** 1641-1656.

Straus, D. M., S. Corti and F. Molteni, 2007: Circulation Regimes: Chaotic Variability versus SST-Forced Predictability. *J. Climate*, **20**, 2251–2272.

Sura, P., M. Newman, C. Penland and P. Sardeshmukh, 2005: Multiplicative Noise and Non-Gaussianity: A Paradigm for Atmospheric Regimes? *J. Atmos. Sci.,* **62**, 1391-1409

Toth, Z., 1991: Circulation patterns in phase space: A multinormal distribution? *Mon. Wea. Rev.,* **119**, 1501-1511.

Toth, Z., 1993: Preferred and unpreferred circulation types in the Northern Hemisphere wintertime phase space. *J. Atmos. Sci.,* **50,** 2868-2888.

Trevisn, A., 1993: Impact of Transient Error Growth on Global Average Predictability Measures. *J. Atmos. Sci.* **50,** 1016–1028.

Vautard, R., and B. Legras, 1988: On the source of midlatitude low-frequency variability. Part II: nonlinear equilibration of weather regimes. *J. Atmos. Sci.*, **45,** 2845-2867.