Varied Expressions of the Hemispheric Circulation Observed in Association with Contrasting Polarities of Prescribed Patterns of Variability

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ABSTRACT

The low-frequency (>5 day period) variability observed within four different subsets of the climatology (H1, L1, H2, and L2) as defined by the high and low index polarities of the two leading principal components (PCs) of the sea level pressure field is compared, with emphasis on distinctive flow configurations and teleconnection patterns. The analysis is based on wintertime 500-hPa height, sea level pressure, and 1000–500-hPa thickness fields derived from the NCEP–NCAR reanalyses for the period of record, 1958–99. “Spaghetti diagrams” display specified contours for ensembles of individual 10-day mean charts extracted from the four different subsets of the climatology. In L1, 10-day mean maps (weak zonal flow at latitudes ~55°N) exhibit larger undulations in the barotropic component of the flow than those in H1, implying larger particle displacements and deeper penetration of Arctic air masses, particularly into Europe and the eastern United States. Maps in H2 and L2, separated in accordance with the Pacific–North American (PNA)-like second mode, exhibit quite different kinds of planetary wave patterns. The L2 subset (characterized by a retracted Pacific jet) exhibits greater variability over the Gulf of Alaska and over northern Europe. Cold air outbreaks in Europe occur more frequently in L1 than H1, and over western North America, they occur more frequently in L2 than H2. The cold anomalies associated with low polarities of both PCs are observed more frequently than expected based on linear correlation; within the individual subsets of the climatology there are suggestions of multiple circulation regimes; teleconnection patterns for the subsets of the climatology are also discernibly different. These results constitute evidence of nonnormal or nonlinear behavior of 5- and 10-day mean fields and provide indications of how the intraseasonal variability depends on the mean state of the flow in which it is embedded.

1. Introduction

This paper documents the varied expressions of the hemispheric circulation observed in association with contrasting polarities of the leading principal components (PCs) of the monthly mean sea level pressure (SLP) field. Ensembles of 10-day mean 500-hPa height, sea level pressure, and 1000–500-hPa thickness fields representative of contrasting “high and low index” polarities of the PCs are compared. The ensembles are comprised of the thirty 10-day means (or decads) that exhibit the highest and lowest values of the PCs, which are defined on the basis of EOF analysis of the monthly mean sea level pressure field poleward of 20°N. The leading PC corresponds to the Northern Hemisphere annular mode (Thompson and Wallace 1998), which is very similar in structure to the North Atlantic Oscillation (Hurrell 1995). The second PC corresponds to an extended version of the Pacific–North American (PNA) pattern (Wallace and Gutzler 1981; Wallace and Thompson 2002). We document the structure of these patterns in the next section, and in the companion paper (Quadrelli and Wallace 2004), we show that they serve as a robust and convenient set of basis functions, upon which other patterns of variability may be projected.

The analysis was performed on both consecutive (nonoverlapping) 5- and 10-day mean maps, both of which explicitly resolve most of the variability in the frequency range of interest, while averaging out the high-frequency variability associated with baroclinic waves. The results for the two averaging intervals proved to be quite similar in most respects, so for the sake of brevity, only those for the latter are shown. No attempt is made to formally separate the variability into low- and intermediate-frequency ranges. Data exclusively representative of the low frequencies (i.e., monthly mean data) are used only in the definition of the principal low-frequency patterns of variability.

The emphasis in this study is not on prediction, but...
The diversity of 10-day mean flow patterns observed in association with contrasting polarities of specified patterns of variability. The 10-day mean ensembles are archetypical of the frequency distribution of hemispheric patterns whose mean is reflected in regression maps based on the leading PCs of SLP.

This paper is organized in five sections. Section 2 describes the datasets and analysis techniques used. Section 3 contrasts the variability of 10-day mean 500-hPa height, sea level pressure, and 1000–500-hPa thickness fields observed in association with the high and low index polarities of SLP EOFs 1 and 2. Section 4 shows examples of contrasting teleconnection patterns observed within the contrasting subclimatologies, defined in accordance with the polarities of the principal patterns of variability. Section 5 offers a discussion of the results.

2. Data and analysis techniques

The dataset used in this study is the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostic Center (CDC). The data are gridded on a 2.5° latitude × 2.5° longitude mesh. The fields used are SLP, 500-hPa geopotential height, and 1000 hPa for the 42-yr period of record, 1958–99. The analysis is restricted to the winter season, defined as December–January–February–March (DJFM). Principal component analysis (PCA) is performed on the temporal covariance matrix of monthly mean DJFM SLP anomalies. The anomalies...
are area weighted by the square root of the cosine of latitude, and only the region north of 20°N is included in the analysis.

The leading two PCs of monthly mean DJFM SLP anomalies poleward of 20°N explain 24% and 13% of the total variance of the field, respectively, compared to 9.5% for the third PC. Hence, PCs 1 and 2 qualify as well separated, based on the criterion of North et al. (1982). Figure 1 shows the signature of these modes in the monthly mean 500-hPa height and SLP fields.

The PCs have a monthly time resolution. In order to obtain 10-day mean indices of the patterns associated with the PCs, 10-day SLP mean maps are projected onto SLP regression maps based on the standardized monthly PCs. These time series are sorted in ascending order to identify the dectads in which the hemispheric SLP field projects most strongly (positively and negatively) onto the corresponding EOFs. These selected dectads will subsequently be referred to as high index and low index subclimatologies, respectively.

In order to ensure that the selected subclimatologies include data from many different winter seasons, an additional criterion is imposed that no more than two dectads for each winter be included in a given high or low index composite. For each of the two modes, 30 of the 504 dectads are classified as high index and 30 as low index, and the remaining 444 dectads remain unclassified.

Figure 2 shows a scatterplot of the phase space defined by the projection of the complete set of 10-day mean data onto DJFM monthly SLP PC1 and PC2. The horizontal and vertical lines delimit the high and low index subclimatologies of the data that are used in constructing many of the figures in the next two sections. Figure 3 shows how the selected dectads are distributed in time.

To contrast the atmospheric variability observed in association with high and low index subclimatologies defined on the basis of the polarities of PC1 and PC2, we present a series of 500-hPa height, SLP, and 500–1000-hPa thickness “spaghetti diagrams” in which specified contours for all 30 dectads of the respective subclimatologies are plotted together on the same chart. This method (sometimes referred to as limited contour analysis) has been used as a diagnostic tool in several previous works; for example, Kimoto and Ghil (1993) used it to investigate temporal persistence of low-frequency flow patterns.

3. Variability of 10-day means

Figure 4 shows 500-hPa mean maps for the high and low index subclimatologies of PC1, as defined in the previous section. The mean map of the high index subset
of PC1 (H1) shows a well-defined polar vortex centered over Greenland/northeastern Canada, with strong zonal flow at subpolar latitudes. The contrasting low index subclimatology (L1) is characterized by a weaker polar vortex with three fewer contours at the low end of the range. A pronounced blocking anticyclone is evident centered over the southern tip of Greenland. Consistent with the results of DeWeaver and Nigam (2000) this feature exhibits a northwest–southeast tilt, in contrast to the flat ridge over western Europe in the H1 subclimatology, which exhibits a northeast–southwest tilt.

While the distinctions between the high and low index polarities of EOF1 mainly relate to the different intensities of the polar vortex, those in EOF2, shown in Fig. 5, relate to the planetary wave configuration. In the high index subclimatology (H2), the polar vortex exhibits a secondary center over the North Pacific, the Asian jet extends nearly all the way across the Pacific, and ridges lie along the west coasts of both continents. The L2 subset is characterized by troughs over the east coasts of the continents and weak ridges over the central Pacific and Scandinavia.

a. Flow patterns associated with EOF1

Figure 6 compares a series of specified 500-hPa height contours extracted from 10-day mean maps for the H1 and L1 subclimatologies. In H1 the core of the polar vortex at the 500-hPa level is almost always centered on the Canadian side of the Arctic, whereas in L1, it is usually centered on the Siberian side. Contours higher than 510 dam rarely intrude into the core region of the vortex in H1, while heights in excess of 528 dam are frequently observed throughout the Arctic in L1. The signature of Greenland blocking is clearly evident in most of the L1 dectads, and many of these events are characterized by pronounced upstream troughs over southeastern Canada and/or downstream troughs over eastern Europe. In H1, the 528 and 540 contours assume the form of tight bundles from the Rockies eastward through Europe, whereas in L1 they exhibit much more diversity from sample to sample and some of them intrude into substantially lower latitudes. Contrasts between H1 and L1 subclimatologies are not as pronounced over the East Asian and Pacific sectors. The 540-dam contours crossing over Japan form tight bundles in both subclimatologies, but the L1 bundle is noticeably farther south. Dectads with high-amplitude ridges over Alaska are observed in both H1 and L1.

Fig. 7. As in Fig. 6, but for selected SLP contours, as indicated.

Fig. 8. As in Fig. 6, but for 500–1000-hPa selected thickness contours, as indicated.
Figure 7 shows analogous plots of the 1028- and 992-hPa SLP contours. The former surrounds strong anticyclones and the latter surrounds strong cyclones at the earth’s surface in the 10-day mean fields. The H1 subclimatology is characterized by a higher frequency of occurrence of stronger than 1028-hPa anticyclones that encompass parts of the Arctic and a relative absence of them at lower latitudes. The Siberian high is evident in both H1 and L1, but it extends farther westward toward Europe in L1. Inspection of analogous results for the 1036-hPa contour (not shown) indicates that the Siberian high also tends to be somewhat stronger during L1, in agreement with the results of Gong et al. (2001). SLP drops below 992 hPa in the vicinity of the Aleutian low and over temperate latitudes of the North Atlantic more frequently during L1 than during H1.

Figure 8 shows spaghetti diagrams for four 1000–500-hPa thickness contours. Thicknesses below 492 dam are observed most frequently over northeastern Canada and Greenland during H1 and over eastern Siberia and Mongolia in L1. The 510-hPa contour exhibits somewhat greater variability over the American and Atlantic sectors in L1 than in H1, but contrast between the overall level of variability in L1 and H1 is less dramatic than in the case of the 500-hPa height contours shown in Fig. 6. In agreement with the conjecture of Namias (1950), the area occupied by Arctic air masses, as defined by the outer edge of the envelopes of the 510- and 522-dam contours, is larger during L1 than during H1. The 540-dam contour intrudes noticeably deeper into the Middle East in H1, consistent with the lower surface air temperatures observed over this region during H1 (Thompson and Wallace 2001).

b. Flow patterns associated with EOF2

Figure 9 is the analog of Fig. 6, but for PC2. The shapes of the 500-hPa height contours for H2 show a tendency for a pronounced ridge aligned with the Rockies that separates the Arctic and Pacific lobes of the polar vortex, and a flatter ridge over the Atlantic, as best exemplified by the 522- and 540-dam contours. The trough immediately downstream of the Atlantic ridge sometimes resides over central Europe and at other times resides farther to the east over Russia. The charts for L2 exhibit a greater diversity of the 540-dam contour shapes, especially over the Pacific and western Europe where pronounced short wavelength ridges are often observed, coincident with the variance maxima in the variance maps (not shown), and sometimes accompanied by sharp downstream troughs. Hence, the weak westerly flows over these regions in the mean L2 map (Fig. 5) represent averages of flow patterns with a pronounced but varied meridional structure.

Analogs of Figs. 7 and 8 for H2 and L2 can be found in the electronic supplement (see online at http://www.atmos.washington.edu/~roberta/Pub/QuadrelliWallace_e_suppl.pdf), together with spaghetti diagrams for a more complete set of 500 hPa, SLP, and 1000–500-hPa thickness contours.
FIG. 10. The 500-hPa height anomalies regressed upon standardized time series of SLP PC1 based on the subclimatologies of the data consisting of the 30 decads with the (top) highest and (bottom) lowest values of SLP PC2. Contour interval is 15 m; negative contours are dashed. The zero contour is omitted.

FIG. 11. The 500-hPa height anomalies regressed upon standardized time series of SLP PC2 based on the subclimatologies of the data consisting of the 30 decads with the (top) highest and (bottom) lowest values of SLP PC1. Contour interval is 15 m; negative contours are dashed. The zero contour is omitted.
4. Contrasting teleconnection patterns

To further illustrate how low-frequency variations in the atmosphere’s primary patterns of variability influence the structure of the embedded variability, we constructed a series of regression maps of 500-hPa height upon PC1 and PC2, each based on subclimatologies of the data defined in accordance with the rankings of the other PC. Figure 10 shows contrasting regression maps for PC1 as obtained from high- and low-index subclimatologies of PC2, denoted by H2 and L2, respectively, and Fig. 11 shows regression maps for PC2 obtained from the H1 and L1 subclimatologies. The PCs used in this analysis are defined on the basis of the entire dataset.

The PC1 regressions based on H2 and L2 exhibit substantial differences with respect to the flow configuration over the Pacific sector: the pattern for H2 exhibits a north–south dipole reminiscent of the pattern in the Atlantic, while the pattern for L2 exhibits a pronounced wave train oriented along a “great circle route.” Both PC2 patterns are PNA-like over the Pacific sector, but they are quite different in the remainder of the hemisphere. In H1, the PNA wave train bends southward into the subtropical Atlantic and seems to rebound, forming a second wave train with strong centers of action over the North Atlantic and European Russia. In contrast, the PNA wave train in L1 is directed eastward across southern Canada toward western Europe. The tendency toward a more equatorward turning over North America in H1 is consistent with the contrasting “steering flow” configurations in Fig. 4. The difference in zonal wavelength is consistent with the Rossby dispersion relation for zonal flow with variable intensity. The patterns in Figs. 10 and 11 are reproducible in
subclimatologies based on the 60 extreme values of PC1 and PC2 (not shown).

5. Discussion

The foregoing results illustrate how partitioning the historical record on the basis of the polarity of leading patterns of hemispheric variability of the SLP field yields distinctive “subclimatologies” (H1, L1, H2, L2 . . .) whose individual maps exhibit remarkably different degrees and kinds of “case to case” variability.

The diverse flow patterns observed in each subclimatology are reminiscent of more regional “weather types” defined by Baur et al. (1944), Rex (1951), Van gengeim (1952), and Girs (1971), among others. Specific weather types such as the wave regimes over Europe illustrated in Fig. 12 tend to occur in association with high and low index subclimatologies of the PCs.

The enhanced (or reduced) variability of the flow in each of these subclimatologies is reflected in enhanced (or reduced) variability of surface weather conditions. For example, the standard deviation maps shown in Fig. 13 clearly show that lower-tropospheric temperature tends to be more variable over most continental regions in association with the low-index polarity of both patterns.

The influence of SLP PC1 and PC2 upon the probability of occurrence of extreme cold events (defined as negative 1000–500-hPa thickness anomalies in excess of two standard deviations in the 10-day mean maps) is illustrated by the composite maps shown in Fig. 14. The vectors represent the mean standardized values of PC1 and PC2 during cold dectads. This pattern exhibits a number of subtle regional features indicative of departures from the linear behavior exemplified by Fig. 19 of Quadrelli and Wallace (2004). For example, over western North America, PC1 is uncorrelated with the 850-hPa temperature, yet over parts of the region it tends to be negative during dectads with well below normal temperature.

As illustrated in Fig. 15, PC1 and PC2 have a stronger overall impact upon the frequency of occurrence of ex-
extreme cold events than would be expected on the basis of their linear correlations with the monthly mean thickness. Within the closed contours, extreme cold is more than 20 times more likely when the PC is in its negative polarity (with standardized amplitude greater than 1.5) than when it is in its positive polarity. It is evident that the area enclosed by the contours substantially exceeds that expected on the basis of the linear correlations (indicated in the figure by the shading). Hence, it seems likely that the nonlinear relationships illustrated by the spaghetti diagrams contribute to the unexpectedly strong influence of PC1 upon the occurrence of extreme cold as documented in Thompson and Wallace (2001), and presumably the same is true of PC2.

It remains to be seen whether the differences in flow variability observed for individual cases of 10-day means for contrasting polarities of the SLP PCs are representative of differences associated with lower-frequency variations in the background flow upon which the decadal-to-decadal variability is superimposed. Figures 16 and 17 compare all decads of the two winters with highest and lowest values of the seasonal mean SLP PCs for two specified contours. The high and low index ensembles do not contrast as sharply with one another as in Figs. 6 and 9, but it is notable that the distinctions between the high and low index seasonal ensembles of Figs. 16 and 17 are qualitatively similar to their higher-frequency counterparts.

On this basis it can be argued that part of the contrast between the high and low index ensembles is due to systematic differences between the basic-state flow in high and low index winters. Hence, the results shown in the paper are also broadly indicative of the varied expressions of the hemispheric flow patterns observed in association with different basic-state hemispheric flow patterns.

The leading SLP PCs are more predictable on the seasonal and longer time scales than other patterns of variability—the former by virtue of its relation to volcanic eruptions, the equatorial stratospheric quasi-biennial oscillation, variations in the strength of the wintertime stratospheric polar vortex (Thompson et al. 2002), and possibly to slow variations in sea surface temperature in the equatorial western Pacific and Indian Oceans (Hoerling et al. 2001); and the latter by virtue of its relation to decadal-scale ENSO-like variability in the Pacific (Zhang et al. 1997; Mantua et al. 1997). Hence, the results presented in this paper may have some practical implications for extended range prediction of extreme events.

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