Vertical Structure of Wintertime Teleconnection Patterns

HUANG-HSIUNG HSU AND JOHN M. WALLACE

Department of Atmospheric Sciences, University of Washington, Seattle, WA 98195

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ABSTRACT

Orthogonal rotated principal component analysis of the wintertime, Northern Hemisphere, 5-day mean sea level pressure field yielded five modes which are of some dynamical interest. One can be identified with the well-known North Atlantic Oscillation and another with the Pacific/North American pattern. Three of the other modes are highly baroclinic in the sense that their sea level pressure patterns and their associated 500 mb height patterns are different in shape and opposite in polarity over substantial areas. These more baroclinic patterns attain their largest amplitudes in the vicinity of the Himalayas and Rockies. Their spatial patterns evolve very differently in the lower and middle troposphere: the sea level pressure patterns exhibit a distinctive eastward and/or equatorward phase propagation, parallel to contours of surface elevation, along the northern and/or eastern side of the mountain ranges, while the corresponding 500 mb patterns evolve in a manner consistent with the concept of Rossby wave dispersion. It is hypothesized that the phase propagation of the sea level pressure pattern is due, in part, to the equivalent-beta effect responsible for the terrain slope.

These highly baroclinic patterns appear to be associated with the low-temporal correlations between 1000 and 500 mb height and for the deep equatorward penetration of wintertime cold air outbreaks observed along the lee slopes of the major mountain ranges.

1. Introduction

Much of the recent observational work on low-frequency variability has emphasized features with equivalent barotropic vertical structures with maximum amplitude in the middle and upper troposphere (e.g., Wallace and Gutzler, 1981; Horel, 1981; Blackmon et al., 1984a,b; Esbensen, 1984). Likewise, much of the theoretical and modeling work on this topic has emphasized processes capable of being represented in barotropic models (e.g., Hoskins and Karoly, 1981; Webster, 1981; Branstator, 1983; Simmons et al., 1983). The question of how much, if any, of the observed low-frequency variability is inherently baroclinic in nature has never really been addressed.

Van Loon and Rogers (1978) and Rogers (1981) have shown that two of the dominant patterns in the sea level pressure field [the so-called North Atlantic and North Pacific Oscillations first defined by Walker and Bliss (1932)] exhibit strong low-level horizontal temperature advection. However they did not define the vertical structure of these patterns. Wallace and Gutzler (1981) have shown that the North Atlantic Oscillation exhibits only a modest westward tilt with height and is therefore still well described in terms of the geopotential height or the circulation pattern at a single level.

There is indirect evidence which suggests that the processes included in barotropic models cannot account for the structures observed in association with low frequency variability near the major mountain ranges. Figure 1, which is motivated by the study of Blackmon et al. (1979), shows the correlation between sea level pressure and 500 mb height in 29 years of 5-day mean wintertime (2 November–31 March, inclusive) NMC data. (For further information concerning the data set used in this paper, the reader is referred to Section 2.) In agreement with the results of Blackmon et al., Fig. 1 shows marked contrasts in the vertical structure of low-frequency variability between oceanic and continental regions, with high correlations indicative of more barotropic structures over the oceans, and lower correlations indicative of more baroclinic structures over Asia and North America. Very low and even negative correlations are observed on the cold, or lee side of the major mountain ranges and strong correlation gradients are observed across the ranges.

In order to illustrate the horizontal structure of the low-frequency variability in the vicinity of a mountain range, we have displayed in Fig. 2 (left) a one-point correlation map for sea level pressure at the gridpoint (62.5°N, 130°W). This point is located near one of the centers of lowest 1000/500 mb height correlation in Fig. 1. (Sea level pressure and 1000 mb height will be used interchangeably throughout the paper. The data

1 It should be noted that throughout this paper the term "baroclinic structure" connotes a three-dimensional structure comprising a well defined pattern in the sea level pressure field which is distinctly different from the corresponding pattern in the middle and upper troposphere. It does not necessarily imply any relation to baroclinic instability.
are actually based on sea level pressure and the conversion to 1000 mb height is accomplished by using the formula $Z = 8(p - 1000)$ where $Z$ is 1000 mb height, expressed in meters, and $p$ is sea level pressure, expressed in millibars.) The pattern is somewhat larger in scale than the typical one-point correlation maps for 500 mb height displayed in Wallace and Gutzler (1981), and it exhibits strong correlation gradients across the Rockies. The corresponding 500 mb height pattern, as revealed in the correlation map between the

sea level pressure at the gridpoint (62.5°N, 130°W) and the 500 mb height field (Fig. 2, right), has a different orientation. Throughout much of central and western Canada, where the 1000/500 mb height correlations in Fig. 1 are relatively low, the sea level pressure and 500 mb height patterns in Fig. 2 are opposite in polarity.

The major purpose of this study is to investigate the possibility that highly baroclinic structures such as the one illustrated in Fig. 2 play an important role in the low-frequency variability of the geopotential height field. Such patterns have not emerged in observational studies in which the correlation patterns are defined on the basis of upper air data. However, we will show in Section 3 that a pattern very similar to the one in Fig. 2, plus two other highly baroclinic patterns appear among the leading rotated principal components of the sea level pressure field. In Section 4 we will examine the time evolution associated with each component, focusing largely on the baroclinic ones. We will demonstrate the reproducibility of these patterns in Section 5. Section 6 includes a summary of major results and a dynamical interpretation of the baroclinic patterns.

2. Analysis procedures

The data set consist of nonoverlapping, consecutive 5-day mean wintertime 500 mb heights and sea level pressures in an NMC octagonal grid, spanning from 1946 through 1977. For further details of the preprocessing procedures of the 5-day means readers are referred to Wallace and Hsu (1983). The winter season was defined as the 30 pentads (150 days) extending from 2 November through 31 March of the following calendar year. Data for the 1959/60 and 1960/61 winters were discarded because of suspicious features near
the (low latitude) periphery of the grids, leaving a total of 29 winters (870 pentads) in the data set.

In this work we have followed the analysis procedures used in Horel (1981). The data set used for orthogonally rotated principal component analysis (hereafter cited as ORPCA) was first converted, using a 16-point interpolation scheme, from the NMC octagonal grid to a 10-degree by 10-degree latitude–longitude grid (a total of \(6 \times 36\) grid points) which covers the Northern Hemisphere between 25\(^\circ\) and 75\(^\circ\)N. For details of ORPCA, readers are referred to Harman (1976) and Richman (1981). Before applying ORPCA, the 5-day mean sea level pressures at each grid point were normalized by removing the means and dividing the anomalies by the temporal standard deviation. Means and standard deviations were computed separately for each of the 30 pentads of the winter season. For better estimation of true eigenvalues, the normalized data were weighted by area factor \(\cos^2\theta\)\(^{1/2}\) where \(\theta\) is the latitude (Buell, 1978; North et al., 1982). Through the data manipulation procedures described above the effects of the seasonal cycle were removed. The method chosen for rotation is the varimax method (Harman, 1976) and the first 29 components obtained from principal component analysis that have eigenvalues greater than one were retained for orthogonal rotation, i.e. the eigenvalue–one criterion (Rummel, 1970). The input matrix for ORPCA is simply a cross product matrix of normalized sea level pressures between each pair of gridpoints. There are three products of ORPCA: rotated principal components which are time series indicating the temporal variability of the components; spatial patterns (or loading vectors) associated with the respective rotated principal components; and the amount of variance explained by each component. The rotated principal components were used as indices which served as a basis for constructing correlation coefficient maps and composites. Simultaneous and lagged (up to three pentads) correlation statistics between the leading rotated principal components and 1000 mb, 500 mb geopotential height on the NMC grid were computed and plotted to illustrate the time variation of these spatial structures.

3. Spatial patterns associated with the leading rotated principal components

The spatial patterns associated with five of the six leading rotated principal components and their corresponding 500 mb height patterns are presented in this section. The percentages of variance explained by unrotated and rotated components are shown in Fig. 3. Instead of showing direct outputs of ORPCA (i.e., loading vectors), simultaneous correlation maps between the rotated principal components and 1000 and 500 mb heights are presented. Since elements of loading vectors indicate the temporal correlation between components and 1000 mb heights at each grid point, a simultaneous correlation map for 1000 mb geopotential height bears a close resemblance to a map of the loading vector of the corresponding rotated principal component, except for the fact that it has finer spatial resolution by virtue of the higher density of the NMC grid relative to the ORPCA grid (see Appendix). Comparisons between 1000 and 500 mb correlation maps provide information concerning the vertical structure of each component.

The spatial patterns associated with Component 1 which we will refer to, for convenience, as the Atlantic (A) pattern, are presented in Fig. 4. The correlation pattern for sea level pressure consists mainly of a north–south seesaw over western Atlantic with a node around 50\(^\circ\)N and a secondary correlation center to the north of the Mediterranean Sea. A similar spatial pattern is observed at the 500 mb level. The fact that this pattern tilts only slightly westward with height suggests that the vertical structure of this mode has a strong equivalent barotropic component. The 500 mb correlation pattern is somewhat more wave-like and has a fourth center over the Caspian Sea. Comparing Fig. 4 with results of earlier studies, it is found that the spatial patterns associated with Component 1 resemble the North Atlantic Oscillation, which is characterized by a seesaw in winter temperature between Greenland and northern Europe and a seesaw in sea level pressure between Iceland and the Azores (van Loon and Rogers, 1978). The axis of the north–south seesaw associated with Component 1 is located about 40\(^\circ\) of longitude to the west of the sea level pressure teleconnection pattern associated with the North Atlantic Oscillation, but there is little doubt that the two are strongly correlated in space and time. There is also a strong association with the “Western Atlantic” teleconnection pattern described by Wallace and Gutzler (1981). Since this pattern has been well documented in the literature, we will not discuss it further here.

Figure 5 shows the spatial pattern associated with Component 2 which we will refer to as the Siberian (S) pattern. The main feature of the sea level pressure pattern is a region of positive correlations, centered slightly to the north of the climatological position of the Siberian High, which covers most of northeastern Asia. At the 500 mb level the correlation pattern comprises multiple centers suggestive of a two-dimensional Rossby wave train extending from northern China to the west coast of the United States along a “great circle route.” This 500 mb pattern resembles the Northern Asian pattern identified by Esbensen (1984, Fig. 6a), which is not among the teleconnection patterns recognized by Wallace and Gutzler. The scale of the 500 mb height correlation pattern is distinctly smaller than that of its counterpart in the sea level pressure field. Over most of China and Mongolia the pattern exhibits opposite polarity in the sea level pressure and 500 mb height fields.

In the 1000 and 500 mb height composites shown in Fig. 6, which are based on the 29 pentads with the
strongest positive values of Component 2, the Siberian High is stronger than normal and is located 10° to the north of its climatological mean position, while a cold cutoff low covers southeastern Siberia at the 500 mb level. It is evident from the backing of the geostrophic wind with height from 1000 to 500 mb that very strong low-level cold advection prevails over Manchuria and Korea. In the contrasting negative composites, shown in Fig. 7, the Siberian High is much weaker and cold advection over Manchuria and Korea is almost entirely suppressed.

The spatial patterns associated with Component 3 shown in Fig. 8 are very similar to the one-point correlation patterns in Fig. 2. We will refer to them as the

![Fig. 4. Correlation coefficient between Component 1 and (left) sea level pressure, (right) 500 mb height; contour interval 0.1. Negative contours are dashed. The percentage of variance of the sea level pressure field explained by this component is indicated. For further technical details concerning the structure of this and other figures, see the Appendix.](image-url)
Pacific (P) pattern. The SLP correlation pattern is characterized by a dipole over the Pacific sector with a node near 40°N: the northern cell centered over Alaska extends southeastward along the eastern slopes of the Rocky Mountains into the Great Plains of Canada and the northern United States. An interesting feature is the sharp correlation gradient in sea level pressure across the northern Rocky Mountains. This pattern is also evident in the teleconnectivity map in Wallace and Gutzler (1981, Fig. 8), though it was not properly interpreted in that paper and it has close resemblance to the North Pacific Oscillation which is characterized by a temperature seesaw between the western Alaska–eastern Siberia region and western Canada (Walker and Bliss, 1932; Rogers, 1981). There is a strong resemblance between our Fig. 8 (left) and the pattern in Fig. 3 of Rogers. The dipole-like pattern in sea level pressure is accompanied by a more wavelike pattern at the 500 mb level. The region of positive correlations to the east of the northern Rockies at sea level is overlain by a center of negative 500 mb height correlations centered over Alberta, indicating that this pattern exhibits a highly baroclinic vertical structure along the eastern slopes of the Rockies. Note that the
vertical structure is much more barotropic to the west of the mountains and over the Pacific. A similar pattern is observed over western North America during summertime (Chang, 1983).

Figure 9 shows 1000 and 500 mb height composites for the 29 pentads with the strongest positive values of Component 3. At sea level, the Aleutian Low is split into two weak cells, while an abnormally strong, cold anticyclone covers Alaska and western Canada. This circulation pattern corresponds to the AA mode (Aleutian Above: positive temperature anomalies at Aleutian stations and negative anomalies at Edmonton) of the North Pacific Oscillation (Rogers, 1981; Fig. 2). The corresponding 500 mb height pattern is characterized by a strong ridge over the Aleutians (a classic example of a “Pacific block”; e.g., see Fig. 3 of Elliott and Smith, 1949; Fig. 5 of Namias, 1951). Composites of the 29 pentads with the strongest negative values of Component 3, shown in Fig. 10, are characterized by a highly zonal circulation pattern over the Pacific and western North America. The 1000 mb circulation pattern corresponds to the AB mode (Aleutian Below: negative temperature anomalies at Aleutian stations and positive anomalies at Edmonton) of the North Pacific Oscillation (Rogers, 1981; Fig. 1). At the 500 mb level, a trough covers the Aleutian Islands and a strong jet stream stretches all the way across the Pacific to the west coast of North America.

Fig. 7. Composite (left) 1000 mb and (right) 500 mb height maps for the 29 pentads with Component 2 < −1.78. Contour interval 20 m for 1000 mb height and 60 m for 500 mb height.

Fig. 8. As in Fig. 4 but for Component 3.
Comparing the contrasting spatial patterns associated with the first three components, it can be seen that they seem to exhibit, in a regional way, some of the characteristics of fluctuations in the zonal index described by Rossby (1939), Rossby and Willett (1948). For example, the regional circulation patterns in the Pacific and North American sector associated with Component 3 closely resemble textbook illustrations of high and low index patterns (e.g., see Starr, 1942; Willett, 1944; Petterssen, 1956).

Another baroclinic pattern over Asia which we will refer to, for convenience, as the Chinese (C) pattern, is the one associated with Component 4 described in Fig. 11. The sea level pressure pattern consists mainly of a single cell centered over central China, poleward of the Himalayas. Comparing the surface spatial patterns associated with Components 2 and 4, it is evident that they tend to be orthogonal to one another with Component 2 explaining the low-frequency variability over northern Asia and Component 4 explaining the variability farther to the south. The 500 mb pattern is smaller in scale and more wavelike. Over much of east Asia, above-normal sea level pressure corresponds to below-normal 500 mb height and 1000/500 mb thickness. In the composite maps for positive values of Component 4, presented in Fig. 12, the Siberian High is abnormally strong and extends southeastward into southern China; note that the 240 m contour penetrates as far south as 30°N, compared to its normal position around 40°N. At the 500 mb level the climatological mean trough over east Asia is accentuated. Strong low-level cold advection covers Korea and coastal region
of China. In the negative composites shown in Fig. 13 the Siberian High is weak and the upper-level flow over this region is more zonal. Cold advection is still present over east Asia, but it is much weaker than that in the positive composite.

Components 2 and 4 are obviously related to the "cold surge" phenomenon described by Joung and Hitchman (1982), Lau and Lau (1984) and others. It is difficult to make detailed comparisons between our results and those of other investigators because the cold surges described in those papers involve higher frequency fluctuations which are not resolved by our 5-day mean data and because they evidently involve a superposition of our orthogonal components 2 and 4. Nevertheless it will be useful to keep this relation in mind in interpreting the results of the next section.

Components 5 and 6 exhibit equivalent barotropic vertical structures. Component 5 is mainly a north-south seesaw with its major center over North Africa (not shown here) and Component 6, shown in Fig. 14, resembles the Pacific/North America (PNA) pattern which has been documented by Wallace and Gutzler (1981) among others. The fact that the PNA pattern (or something closely resembling it) emerges among the leading components of an orthogonal rotated principal component analysis of the sea level pressure field is further evidence of the dynamical significance of this mode.

Fig. 11. As in Fig. 4 but for Component 4.

Fig. 12. As in Fig. 6 but for the 29 pentads with Component 4 > 1.84.
4. Evolution of baroclinic patterns

The time dependent behavior associated with each component has been examined by constructing lag-correlation maps between the various components and the sea level pressure and 500 mb height fields (see Appendix). The time dependent behavior of the equivalent barotropic patterns (e.g., Components 1, 5, 6) is characterized by either stationary features or weak dispersion of two-dimensional Rossby waves along "great circle routes" at both levels, as described by Blackmon et al. (1984a,b). Discussion in this section is focused on time evolution associated with the more baroclinic patterns (i.e., Components 2, 3, and 4, which we refer to as the S, P and C patterns, respectively).

Lag-correlation maps corresponding to Component 2 are shown in Fig. 15. In the lag-correlation map for sea level pressure throughout the hemisphere one pentad earlier (lower left), there exists a region of positive correlation centered at 70°N, 90°E and covering Siberia. A similar pattern is evident in lag-correlation maps for two or even three pentads earlier but the correlations are much weaker. In the lag-correlation map for one pentad later than Fig. 5 (two pentads later than Fig. 15, left panels), the region of positive correlation over northern Siberia has plunged southward into eastern China. At the 500 mb level (upper panels) the time sequence is more complex. The primary centers of action exhibit some eastward or southeastward movement during the sequence and there is also evidence
of Rossby-wave dispersion similar to that described in Blackmon et al. (1984a,b), with the development of downstream features over Alaska and the eastern Pacific that exhibit a barotropic vertical structure. The vertical structure of the features over Asia is highly baroclinic, particularly toward the later part of the sequence. The remainder of the sequence of lag-correlation maps (not shown) is characterized by a weakening of the pattern with time.

Lag-correlation maps for Component 3 are presented in Fig. 16. At both levels the lag-correlation statistics for one pentad earlier show a dipole with centers at 60°N, 160°W and 25°N, 165°W, with an equivalent barotropic vertical structure which is evident even one or two pentads earlier. Two pentads later (in the +1 pentad lag-correlations), the northern cell of the dipole in the sea level pressure pattern extends southeastward all the way to the east coast of the United States, although the main center remains over Alaska while the southern cell over the Pacific remains unchanged. At the 500 mb level the northern (positive) part of the dipole pattern drifts slowly northwestward during the 10-day sequence (a behavior characteristic of “blocking anticyclones” in this region) while the downstream portion of the wavetrain amplifies slightly.

The evolution of Component 4, described in Fig. 17, is qualitatively similar to that of Components 2 and 3. The center of the region of strong positive correlation in sea level pressure moves southeastward around the lee side of the Tibetan Plateau while the 500 mb height pattern evolves in a more complicated manner. It is interesting to note that the wave train in the lag-correlation map for one pentad later contains elements of the Pacific/North American pattern.

From the results presented in this section it is evident that different types of evolution prevail at different levels. In the lower troposphere, the spatial patterns associated with Components 2, 3, and 4 evolve by translating along a route (first eastward then southward) parallel to the land elevation contours along the cold
side of the mountain range, as illustrated in Fig. 18. In contrast, at the 500 mb level the time-dependent behavior is more complex and more variable from one mode to another; all three modes show evidence of downstream development characteristic of low-frequency Rossby wave dispersion.

5. Stability of the patterns

In order to examine the stability of the patterns presented in preceding sections, ORPCA was applied to the correlation matrices derived from different data sets (or variables) as follows: a) two sets of normalized sea level pressure data with the seasonal cycle removed obtained from the original data set by dividing it into odd and even years according to the year in which January falls; and b) a combined, separately normalized 500 mb height/sea level pressure data set with the seasonal cycle removed in a hemispheric domain (25° to 75°N). The time span of the combined data set is the same as described in Section 2.

a. Patterns for odd and even years

In order to demonstrate the close correspondence between the leading components derived from the data sets based on odd and even numbered years, the spatial correlations between all members of the two sets of loading vectors were computed, weighting each element by \((\cos\theta)^{1/2}\), where \(\theta\) is latitude. Results for unrotated and rotated principal components are shown in Table 1a and b, respectively.

If the unrotated principal components were perfectly reproducible, the spatial correlation matrix for their loading vectors would take the form of the identity matrix; i.e., component \(n\) for the even years would be perfectly correlated with component \(n\) for the odd years, but uncorrelated with any of the other components. It can be seen in Table 1a that three of the unrotated components (i.e., 1, 2, and 6) are reasonably reproducible in the two data sets, since there are pattern correlations in excess of 0.8 in their respective diagonal elements of the matrix. These patterns for the even and odd years exhibit even stronger (~0.9) correlations with their respective counterparts in the total data set with the even and odd years combined. Components 3, 4 and 5 are much less reproducible, as evidenced by their smaller diagonal elements and by the fact that their rows and/or columns contain off-diagonal elements as large as their corresponding diagonal elements. Component 3 for the even years seems to be
most closely associated with Component 4 for the odd years, but Component 3 for the odd years appears to be a linear combination of Components 4 and 5 for the even years. As pointed out by North et al. (1982), lack of uniqueness of the individual eigenvectors may be a reflection of the degeneracy arising from insufficient separation between the eigenvalues in Fig. 3. According to the rule of thumb proposed by North et al., only the first three eigenvalues in Fig. 3 are well separated, even if we assume that the number of degrees of freedom is equal to the total number of pentads in the data set. Thus the lack of reproducibility of eigenvectors as suggested by Table 1a is not unexpected.

The corresponding correlation matrix for the loading vectors associated with the rotated principal components is presented in Table 1b. The loading vectors have somewhat different properties than the eigenvectors from which they were derived, and therefore the interpretation of this matrix is not quite the same as the one we have just discussed. Since the rotated principal components do not derive their identity from their rank in terms of the amount of the variance of the sea level pressure field that they explain, it should be permissible to order them in the two data sets in such a way as to match like patterns (i.e., to move the largest correlations to the diagonal elements of the matrix). Hence, in Table 1b, we have identified the components, not by their rank order, but by the descriptive labels (A, S, P, C and PNA) defined in the previous section. We will use X to designate the fifth component, which we largely ignored in the discussion. In order to give an indication of the rank of the rotated principal components in the conventional ordering scheme, we have included, in the last column and row, the percentage of the variance of the hemispheric sea level pressure field explained by each component. The ability to match like spatial patterns in the ordering scheme greatly simplifies the matrix on Table 1b. However, it is readily verified that a reordering of the rows and columns in Table 1a would not significantly simplify that matrix or increase the apparent reproducibility of the eigenvectors. Since the loading vectors associated with rotated principal components are not mutually uncorrelated (Rummel, 1970), one should not neces-
necessarily expect to see zeroes in the off-diagonal elements, even if the results for even and odd years are perfectly identical.

The results shown in Table 1b indicate that the rotated principal elements are much more stable or reproducible than the eigenvectors from which they were derived. The lowest pattern correlation between matching loading vectors for the even and odd years is 0.68 for component X, which we have largely ignored. The next lowest is 0.78 for the Pacific (P) pattern. The correlation coefficient between this component and sea level pressure, as it appears in the data sets for the even and odd years, are displayed in Fig. 19. Despite the minor differences between the figures it is evident that both patterns include the essential features of the Pacific pattern displayed in Fig. 8 (left). The remaining pattern correlations between matching loading vectors A, S, C, and P are all so strong that we don’t consider it necessary to take the space to display their correlation maps. We have verified that these loading vectors all show equally strong or stronger spatial correlations with the corresponding loading vectors for the total data set.

b. Comparison with hybrid modes based on 500 mb height/sea level pressure

In test b, 500 mb heights and sea level pressures (SLP) were interpolated to the latitude–longitude grid and normalized separately in the manner described in Section 2 to form a time series of observation vectors.

| Table 1a. Spatial correlation matrix (see text) among loading vectors associated with the first six unrotated principal components derived from the sea level pressure field in odd and even years, respectively. |
|----|----|----|----|----|----|----|
| Even year component | 1   | 2   | 3   | 4   | 5   | 6   |
| Odd year component  |     |     |     |     |     |     |
| 1   | 0.84 | 0.26 | 0.02 | 0.33 | 0.22 | 0.01 |
| 2   | 0.34 | -0.84 | -0.12 | -0.26 | 0.12 | -0.13 |
| 3   | -0.24 | -0.39 | 0.33 | 0.71 | 0.14 | 0.16 |
| 4   | -0.08 | 0.13 | 0.59 | -0.34 | 0.66 | 0.05 |
| 5   | 0.15 | -0.01 | 0.63 | -0.05 | -0.58 | -0.08 |
| 6   | 0.10 | 0.02 | -0.09 | -0.24 | -0.08 | 0.85 |
Table 1b. As in Table 1a but for the rotated principal components. Note that the matrix has been rearranged in order to match like loading vectors and the rank order (e.g., 1, 2, etc.) is replaced by the descriptive labels (e.g., A, S, etc.). The percentage of the variance explained by each component is indicated in the last row and column.

<table>
<thead>
<tr>
<th>Even year component</th>
<th>Odd year component</th>
<th>% Variance</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>S</td>
</tr>
<tr>
<td>A</td>
<td>0.94</td>
<td>-0.06</td>
</tr>
<tr>
<td>S</td>
<td>-0.17</td>
<td>0.94</td>
</tr>
<tr>
<td>P</td>
<td>-0.01</td>
<td>-0.16</td>
</tr>
<tr>
<td>C</td>
<td>-0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>X</td>
<td>0.16</td>
<td>-0.14</td>
</tr>
<tr>
<td>PNA</td>
<td>-0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>% Variance</td>
<td>6.7</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Each having 216 500 mb height elements and 216 SLP elements. The observation matrix was used to generate the 432 × 432 temporal covariance matrix whose elements r ij are the correlations between SLP or 500 mb heights at the i th grid point and SLP or 500 mb height at the j th grid point. The orthogonally rotated principal components of this matrix were extracted, using the method described in Section 2, from the first 43 unrotated principal components. Application of eigenvector analysis to a hybrid observation matrix involving two or more meteorological variables is informatively discussed by Kutzbach (1967). In the output of ORPCA, the first half of each loading vector represents the corresponding spatial pattern in 500 mb height associated with its rotated principal component and the second half describes the corresponding spatial pattern in sea level pressure. For convenience, we will refer to these structures as hybrid modes, to distinguish them from the modes based on SLP alone.

In the manner described in the previous section, we computed the spatial correlation between the loading vector associated with each of the first six modes of the ORPCA expansion based on SLP alone (i.e., the modes labeled A, S, P, . . .) and the SLP part of the loading vector associated with the most closely matching hybrid mode. Results appear in the column of Table 2 labeled SLP. It can be seen that structures resembling all six SLP modes emerge among the hybrid modes. The correspondence is strongest for the Atlantic, Pacific and Chinese patterns and weakest for the PNA pattern. The ranking of the modes is different in the two data sets.

In order to obtain an indication of the similarity between the corresponding 500 mb height patterns associated with the two sets of modes we computed the spatial correlations between the patterns shown in the right-hand panel of Figs. 4, 5, 8, etc., and the 500 mb height part of the loading vector associated with the most closely matching hybrid mode, where the “closest
TABLE 2. Correspondence between spatial patterns associated with the rotated principal components derived from the sea level pressure field (designated by A, S, etc.) and those derived from the combined 500 mb height/sea level pressure field (designated by Roman numerals). Spatial correlations between corresponding sea level (500 mb) spatial patterns are shown in the second (third) column. See text for further explanation.

<table>
<thead>
<tr>
<th>SLP mode</th>
<th>SLP/500 mb height mode number</th>
<th>Spatial correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I</td>
<td>0.99 0.99</td>
</tr>
<tr>
<td>S</td>
<td>IV</td>
<td>0.81 0.77</td>
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<tr>
<td>X</td>
<td>X</td>
<td>0.86 0.82</td>
</tr>
<tr>
<td>PNA</td>
<td>VII</td>
<td>0.75 0.75</td>
</tr>
</tbody>
</table>

matching mode” is defined on the basis of the SLP patterns discussed in the previous paragraph. Results appear in the column labeled “500 mb height” in Table 2. Note that this comparison is somewhat less direct than the one involving the SLP patterns because the 500 mb height patterns derived from the rotated principal components of the SLP field are not loading vectors. Corresponding results based on temporal correlations between the rotated principal components of the SLP field and the most closely matching hybrid modes are presented in Table 3.

It is evident from Tables 2 and 3 that modes resembling the patterns emphasized in this paper (most notably, S, P and C) appear in a rotated principal component analysis of the SLP and 500 mb height fields combined. The Pacific (P) pattern is prominent among the hybrid modes, second only to the Atlantic (A) pattern, and a structure resembling the Siberian (S) pattern is also among the leading modes. The counterpart of the Chinese pattern appears lower on the list of modes. Furthermore, the loading vector of the third hybrid mode (not shown) also resembles our “Siberian Pattern”, with centers of action located farther to the west. The lag-correlation statistics for this mode (not shown) are analogous to those in Figs. 15, indicating a time-dependent behavior qualitatively similar to that of the Siberian pattern. Hence it is evident that an analysis based on the hybrid modes would have revealed virtually the same structure that we have called the Pacific Pattern (P) and it would have indicated that over the Asian sector of the hemisphere, the low-frequency variability is dominated by structures and time-dependent behaviors qualitatively similar, if not identical, to our Siberian (S) and Chinese (C) patterns.

6. Discussion and final remarks

It has been shown in preceding sections that ORPCA is capable of extracting well-defined regional circulation patterns from the sea level pressure field in a hemispheric domain. Five of the six leading components presented in Section 3 can be identified with teleconnection patterns which have been discussed in previous papers. For example, Components 1, 3, and 6 are associated with the North Atlantic and North Pacific Oscillations and the Pacific/North American pattern respectively, and Components 2, 4, and 3 appear to be related to the cold surge phenomenon in East Asia and North America, respectively.

Components 1, 5, and 6 are characterized by equivalent barotropic vertical structures while Components 2, 3, and 4 are characterized by more baroclinic vertical structures. Common properties of the baroclinic patterns can be summarized as follows:

a) The spatial scale of the features on the surface map is larger than that of the corresponding 500 mb features.

b) Positive (by our definition) polarities of the baroclinic patterns are associated with cold air masses over the continental interiors, and negative polarities are generally associated with more zonal flows. Over North America the former condition is marked by the buildup of a surface anticyclone over the Yukon or Alaska with cold advection and upslope flow to the southeast of it, while the latter condition is marked by warm, downslope, westerly flow in the lee of the Rockies. Over Asia the contrasts are more subtle: the Siberian High is always present, but it is stronger and it produces enhanced cold advection when Component 2 and/or 4 are positive.

c) These patterns are responsible for the regions of low or even negative 500/1000 mb correlation as shown in Fig. 1 and the low values of the ratio of 500 mb height standard deviation to 1000 mb height standard deviation shown in Fig. 4 of Blackmon et al. (1979).

d) Distinctly different patterns of time evolution are observed in the lower and middle troposphere: the 500 mb patterns evolve in a manner consistent with the concept of Rossby wave dispersion (e.g., see Blackmon et al., 1984a, b), while the sea level pressure patterns exhibit a distinctive eastward and/or equatorward phase propagation, parallel to contours of surface elevation along the northern and/or eastern side of the mountain ranges.

TABLE 3. Temporal correlation between the most closely matching rotated principal components derived from an expansion of sea level pressure and 500 mb height combined and those derived from sea level pressure alone.

<table>
<thead>
<tr>
<th>SLP mode</th>
<th>SLP/500 mb height mode number</th>
<th>Temporal correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I</td>
<td>0.95</td>
</tr>
<tr>
<td>S</td>
<td>IV</td>
<td>0.71</td>
</tr>
<tr>
<td>P</td>
<td>II</td>
<td>0.89</td>
</tr>
<tr>
<td>C</td>
<td>IX</td>
<td>0.89</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>0.84</td>
</tr>
<tr>
<td>PNA</td>
<td>VII</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Results of a number of modeling studies indicate that stationary waves forced by heating or orography exhibit an equivalent barotropic vertical structure away from the immediate region of the forcing (Hoskins and Karoly, 1981; Webster, 1981; Opsteegh and van den Dool, 1980). Our results indicate that more baroclinic, three-dimensional features might appear in the far-field response if mountains were incorporated into the specification of the bottom boundary condition of the models.

Wavelike features propagating along the lee slopes of mountain ranges in the same sense as those described in this paper, but with shorter time scales and smaller space scales transverse to the mountain ranges, have been reported by other investigators (e.g., Taljaard, 1972; Gill, 1977; Murakami, 1981; Murakami and Ho, 1981). These phenomena have generally been interpreted as Kelvin waves propagating along mountain barriers in a manner analogous to coastally trapped Kelvin waves in the ocean. In some of these earlier studies, the observed phase speeds were slower than the Kelvin wave mode having the same horizontal structure; e.g., Gill (1977) observed features propagating around South Africa with a phase speed of 6.5 m s\(^{-1}\), compared with a theoretical estimate of 20 m s\(^{-1}\). In our study, the discrepancy between the phase speeds inferred from Figs. 15–17 (several m s\(^{-1}\)) and that predicted by edge wave theory is even larger. Hence, it seems likely that other dynamical processes are involved. We have verified that equivalent beta-effect associated with terrain slope would produce equatorward propagation of features along the lee slopes of the mountain ranges with phase speeds comparable to those that we observed. This process is responsible for the propagation of shelf waves in the ocean (e.g., see Mysak, 1967; Rhines, 1969).

Our results indicate that the effects of the terrain slope in inducing baroclinity and phase propagation in the low-frequency fluctuations are localized in two important respects:

(i) they are observed only near and downstream from regions of sloping terrain; and

(ii) they are restricted to the lower troposphere: 700, 500, and 300 mb teleconnection patterns appear to be very similar in structure, and at these levels Rossby wave dispersion appears to be the dominant mode of evolution on time scales of a week or two.

Hence it appears that barotropic processes still play the dominant role in the dispersion of low-frequency wave energy on a planetary scale; evidently, these baroclinic effects assume first-order importance only locally.

Such an interpretation is not without historical precedent. In one of the first formulations of a two-level, dynamical weather prediction model, Reed (1958) assumed that dynamical processes at the 500 mb level could be represented by the nondivergent barotropic vorticity equation, while his prognostic equation for the 1000 mb height field allowed for the possibility of baroclinic structures in the 1000/500 mb layer which could arise as a result of a number of different processes, including the equivalent beta effect of terrain slope. His model explicitly includes a term in the effective “steering flow” for the 1000 mb potential vorticity field which has the effect of advecting features along the contours of constant surface elevation.

We conclude with a few comments on the analysis method employed in this paper. It is apparent from Figs. 4, 5, 8, 11 and 14 that time series of the rotated principal components are highly correlated with time series of sea level pressure itself in certain key geographical regions, with correlation coefficients on the order of 0.9 or even stronger. It follows that the loading vectors of these principal components must bear a close resemblance to one-point correlation patterns in those key regions. [As a specific example, note the similarity between Fig. 2 and Fig. 5 (left-hand panel).] Hence it could be argued that the analysis method used in this paper has not provided much substantive new information on spatial patterns that wouldn't have been available from an inspection of the ensemble of one-point correlation maps for each gridpoint. However, it has provided an objective basis for selecting those one-point correlation patterns that are most important in terms of the hemispheric structure of the sea level pressure field.

Horel (1981) demonstrated that there is a strong correspondence between the patterns identified by ORPCA and those identified on the basis of “teleconnection” as defined by Wallace and Gutzler, when these analysis techniques are applied to monthly mean 500 mb height data. It does not necessarily follow that the two methods would yield similar patterns when applied to sea level pressure data. The teleconnectivity approach emphasizes dipole or wavelike patterns which contain strong correlations of opposing sign, whereas ORPCA is capable of identifying prominent monopole structures which would not be evident in the teleconnectivity pattern. It is apparent, even from inspection of one-point correlation maps, that the spatial structures associated with the low-frequency variability of 500 mb height are primarily dipolar or wavelike, whereas some of those associated with sea level pressure tend to be more local or monopolar. Hence, while the Atlantic and Pacific sea level pressure patterns are evident in both kinds of analysis, one would not expect to see the Siberian or Chinese patterns emerge from an analysis based on teleconnectivity alone. It is not clear that the monopolar patterns in the sea level pressure field are of any less dynamical significance than the wavelike ones, and therefore it would appear that ORPCA is the more appropriate analysis method for identifying the dominant spatial structures in this field.

Finally, we wish to call attention to the results presented in Section 5a which indicate that, at least in this...
particular instance, the rotated principal components are much more reproducible in subsets of the data than the eigenvectors from which they were derived. Horel (1984) reached a similar conclusion based on an analysis of synthetic data. This result is not as paradoxical as it may perhaps sound. It is not at all clear that the degeneracy characteristic of eigenvectors with similar eigenvalues should apply to rotated principal components, which derive their identity and uniqueness from a different set of mathematical criteria. Furthermore, it is not obvious to us that lack of separability of the eigenvectors (which implies that any linear combination of the eigenvectors is itself an eigenvector) should compromise the reliability of the linear combinations of the eigenvectors that constitute the rotated principal components. On the other hand, we are not aware of any mathematical basis for interpreting this result or for testing the statistical significance of rotated principal components.

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APPENDIX

A Brief Mathematical Description of the Figures

We will use $r(u, v)$ to denote the temporal correlation coefficient between time series $u$ and $v$. Implicitly, $u$ and $v$ carry an index $i$ which denotes their position (i.e., their particular pentad) in the time series. In this study, fields of $r(u, v)$ are defined over the entire NMC grid to form correlation maps. We use the subscript notation $v_j$ to refer to the time series of $v$ at the $j$ grid point of the NMC grid; hence $r(u, v_j)$ denotes a field whose gridpoint values are formed by correlating the unique time series $u$ with time series of $v_j$ at each of the NMC grid points. A lag correlation map for $u$ is denoted by $r(u, v_j)_n$, where $n$ is the number of pentads by which the time series $v_j$ lags $u$; e.g., if $n = -1$, $v_j$ leads $u$ by one pentad.

For convenience, we let $x_j$ denote normalized sea level pressure (or 1000 mb height) and $y_j$ denote 500 mb height time series at grid point $j$. Hence, the field in Fig. 1 may be denoted symbolically as $r(x_j, y_j)$, and the fields in Fig. 2 correspond to $r(x_{92.5^\circ N, 130^\circ W}, x_j)$ and $r(x_{92.5^\circ N, 130^\circ W}, y_j)$, respectively. Furthermore, we let $X_k$ refer to the time series of the $k$ rotated principal component of the normalized sea level pressure (or 1000 mb height) field and $Z_k$ refer to the $k$ rotated principal component of the combined normalized sea level pressure and 500 mb height fields; the latter time series correspond to the hybrid modes described in Section 5b.

Formally, the left-hand panels in Figs. 4, 5, 8, 11 and 14 correspond to $r(X_k, x_j)$ for $k = 1, 2, 3, 4$ and 6, respectively, and the right-hand panels correspond to $r(X_k, y_j)$. Figures 15, 16, and 17 show the corresponding lag correlation maps for $n = -1$ (left-hand panels) and $n = +1$ (right-hand panels). The entries in Table 3 correspond to $r(X_k, Z_m)$.

The maps in the left-hand panels of Figs. 4, 5, 8, 11 and 14 are closely related to the loading vectors $e_{jk}$ associated with the $X_k$, where $J$ denotes the $J$ grid point of the $(10^\circ \times 10^\circ)$ ORPCA grid, as distinguished from the much finer NMC grid, which carries the $j$ subscript. If $e_{jk}$ is normalized so that the sum of the squares of its components is equal to unity, it can be easily shown (e.g., see Morrison, 1976) that

$$r(X_k, x_j) = \frac{1}{S_j \sqrt{V_k}} \sum_i X_i x_j = e_{jk},$$

where $i$ is the time index, $N$ the number of points in the time series, $S_j$ the temporal standard deviation of $x_j$, and $V_k$ the temporal variance of $X_k$ and also the eigenvalue $\lambda_k$ associated with $X_k$. If the input data had been normalized so that $S_j = 1$ for all $J$, then the spatial distributions of $r(x_k, x_j)$ and $e_{jk}$ would be identical shape and differ only by a scaling factor $V_k^{1/2}$. In this study we have set $S_j = (\cos \theta)^{1/2}$ so that $r(X_k, x_j)$ and $e_{jk}$ are similar, but not identical in shape. The fields of $r(X_k, x_j)$ and $r(X_k, y_j)$ are virtually identical at the ORPCA grid points, but the latter field has higher spatial resolution. It is these higher resolution maps, rather than the pure loading vector maps, that are displayed in Figs. 4, 5, 8, 11 and 14.

REFERENCES


