Structure and Seasonality of Interannual and Interdecadal Variability of the Geopotential Height and Temperature Fields in the Northern Hemisphere Troposphere

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ABSTRACT
Spatial patterns and seasonality of interannual and interdecadal variability in the 500-hPa geopotential height, sea level pressure, and 1000–500-hPa thickness field are examined based on NMC analyses over the Northern Hemisphere extratropics from 1946 onward. The leading empirical orthogonal function (EOF) of wintertime seasonal mean 500-hPa height is closely related to the Pacific/North American (PNA) teleconnection pattern. The time series of its expansion exhibits a trend from predominantly negative values (below-normal heights over western Canada) in the early part of the record to predominantly positive values during the 1980s. The leading EOF of sea level pressure, which is similar in summer and winter, contains elements of the North Atlantic Oscillation (NAO) and a zonally symmetric “seesaw” between polar and temperature latitudes. Its expansion coefficient exhibits relatively little memory from season to season or from year to year.

The leading EOFs of summertime and annual-mean 500-hPa height and thickness are of the same polarity throughout almost the entire hemisphere. The time series of their expansion coefficients are strongly correlated with the time series of hemispheric-mean thickness. We refer to such modes as manifestations of a “background field” whose linear dependence on hemispheric-mean temperature is more important than the details of its spatial structure. Such a background field is evidently present year-round, but it shows up most clearly during summer when the PNA pattern and other regional teleconnection patterns are weakest. The fact that it is more pronounced in the thickness field than in the geopotential height field suggests that it is primarily associated with thermal, rather than dynamical, variability. The time series of its expansion coefficient is dominated by variations on the interdecadal time scale: it accounts for half the hemispherically integrated variance of the thickness field associated with perturbations with periods longer than five years. The large and possibly spurious drop in hemispherically averaged thickness and 500-hPa height in the NMC analyses between 1955 and 1963 contributes substantially to the variance associated with the background field, but the leading modes of the summertime and annual-mean thickness fields remain strongly correlated with one another and with hemispheric-mean thickness even when the years prior to 1963 are excluded from the record. Surface air temperature data exhibit qualitatively similar behavior, as does the extratropical Northern Hemisphere 830–515-hPa thickness field derived from a 100-year GCM simulation in which sea surface temperature is prescribed in accordance with the climatological mean annual cycle.

The long-term trend in the wintertime PNA-like pattern, with rising heights and temperatures over western Canada, has contributed substantially to the rather large rise in hemispheric-mean wintertime surface air temperature since the late 1970s but it has had little if any effect on the hemispheric mean temperature aloft, or on summertime surface air temperatures, which did not rise enough to completely offset the declines in the 1950s and early 1960s.

1. Introduction
The interannual variability of the wintertime geopotential height field is dominated by regional teleconnection patterns. Most prominent are the Pacific/North American (PNA) pattern and the North Atlantic Oscillation (NAO) (Dickson and Namias 1976; van Loon and Rogers 1978; Wallace and Gutzler 1981; Barnston and Livezey 1987), whose upper-level structures resemble the fastest growing modes associated with barotropic instability of the time-mean flow at the jet stream level (Simmons et al. 1983). In contrast to the teleconnection patterns aloft, the patterns in sea level pressure exhibit a stronger zonally symmetric component, in which fluctuations over the polar cap region are out of phase with those over middle latitudes (Lorenz 1951; Kutzbach 1970; Wallace and Gutzler 1981). Bjerknes (1964) presented observational evidence to the effect that such a “north–south seesaw” in sea level pressure over the Atlantic sector, the surface

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manifestation of the NAO, plays an important role in interdecadal climate variability.

Summertime variability in the geopotential height field is weaker and does not exhibit as clearly defined teleconnection patterns. The interannual variability of wintertime-mean 500-hPa height is almost twice as strong as that of summertime 500-hPa height in terms of temporal standard deviation at most grid points (Fig. 1). The leading summertime teleconnection patterns identified by Horel (1981) and Barnston and Livezey (1987) on the basis of rotated principal component analysis explain smaller fractions of the hemispherically integrated variance than their wintertime counterparts.

Since 1000–500-hPa thickness tends to be strongly correlated with 500-hPa height, one might expect the patterns in the two fields to be similar and, in fact, they are. Yet there are some important differences. The variability in thickness tends to be smaller than that in 500-hPa height, particularly for the wintertime fields (Fig. 1), and the spatial patterns tend to be more complex and more directly influenced by the underlying land–sea distribution and terrain.

**Fig. 1.** Temporal standard deviation of seasonally averaged (a) wintertime 500-hPa height, (b) summertime 500-hPa height, (c) wintertime 1000–500-hPa thickness, (d) summertime 1000–500-hPa thickness. Contour interval 10 m for 500-hPa height and 0.25 K for mean virtual temperature of the 1000–500-hPa layer.
Most of what is known concerning the horizontal structure of interannual and interdecadal variability in the temperature field is based upon the analysis of surface air temperature records for land stations. Barnett (1978) showed that empirical orthogonal function (EOF) 1 of wintertime-mean surface air temperature exhibits large-scale organization reminiscent of the PNA pattern, and Gutzler et al. (1988) obtained similar results for surface air temperature and 850-hPa temperature. Summertime temperature fields were not explicitly considered in either of these studies, but Barnett (1978) showed that EOF 1 of annual-mean surface air temperature tends to be of the same sign over virtually the entire Northern Hemisphere, and the time series of its expansion coefficient resembles the time series of hemispherically averaged surface air temperature. It is reasonable to expect that the summertime-mean field should exhibit a similar structure. The notion of a fundamental distinction between the horizontal structure of wintertime and summertime variability is supported by results of Bradley et al. (1987), who showed that time series of seasonal-mean surface air temperature averaged over China are highly correlated with hemispheric-mean temperature for the same season, with the notable exception of the winter season. Similar distinctions between winter and summer are evident in the spatial patterns associated with interdecadal trends in surface air temperature (Jones and Briffa 1992) and 1000–500-hPa thickness (Shabbar et al. 1990) over the Northern Hemisphere.

Analysis of surface air temperature records dating back 100 years or more indicate that the interdecadal variability exhibits much less horizontal structure than the interannual variability. For example, in time series that have been low-pass filtered to eliminate variability with periods shorter than ten years, the record of spatially averaged surface air temperature for China is virtually indistinguishable from that for the Northern Hemisphere as a whole (Bradley et al. 1987). On the basis of this analysis, Bradley (1992) has argued that the data derived from a very limited station network appears to be adequate for documenting long-term trends. On the other hand, Folland et al. (1990), Trenberth (1990), and Jones and Briffa (1992) have shown that much of the rise in Northern Hemisphere mean surface air temperature during the past decade is associated with wintertime warming over the high-latitude continents. Gutzler et al. (1988) and Trenberth (1990) have linked wintertime temperature anomalies in those regions to circulation anomalies associated with the PNA pattern, a relationship that might have been anticipated on the basis of the van Loon and Williams (1976) analysis of opposing interdecadal trends in wintertime surface air temperature over western Canada and the southeastern United States.

As a contribution toward resolving such ambiguities as the one described in the previous paragraph and laying the groundwork for classifying climate variability on the basis of seasonality and structure, we present in this paper an analysis of interannual and interdecadal variability in a 43-year record of monthly mean 500-hPa height and sea level pressure (SLP) data, based on operational analyses from the National Meteorological Center (NMC). The analysis includes an explicit comparison of the degree and types of spatial organization inherent in the geopotential height and the lower-tropospheric thickness fields.

On the basis of the analysis in section 3, we will isolate a mode of variability that exhibits a less clearly defined horizontal structure and seasonality than the "teleconnection patterns" emphasized in previous studies. Its time series is strongly correlated with hemispheric-mean thickness. The variability associated with this "background field" is most clearly evident during summer, when the teleconnection patterns are weakest. It shows up more prominently in the 1000–500-hPa thickness field than in the geopotential height field itself, and the frequency spectrum of its time series appears to be redder than that of indices of El Niño–Southern Oscillation (ENSO) or the PNA pattern. We will argue that this mode of variability is real, despite some legitimate concerns regarding the quality of the NMC analyses during the early part of the record. As part of the supporting evidence we will show, in section 4, selected results from a 100-year run of a general circulation model (GCM).

In section 5 we will consider the relationship between hemispherically averaged surface air temperature and the dominant modes of variability documented in section 3. We will show that the variability associated with the background field and wintertime variability associated with the PNA pattern have both contributed to the interdecadal variability in the record. These contributions are separable because of the pronounced seasonality of the PNA pattern.

In the final section we will review our major conclusions and reflect upon the similarities between the results of our analysis of the 1000–500-hPa thickness field and results based on analyses of longer and presumably more reliable records of surface air temperature. We will also show that time series of snow cover over North America and Eurasia exhibit an analogous type of seasonality. On the basis of this evidence, we will argue that atmospheric dynamics plays an important role in the variability associated with teleconnection patterns that dominate the wintertime temperature variability, but not necessarily in the summertime background field which contributes strongly to the interdecadal variability of hemispheric-mean temperature.

2. Data and analysis techniques

The primary dataset used in this study consists of the NMC operational analyses of daily 500-hPa height and sea level pressure on the 1977-point octagonal grid, superimposed on a polar stereographic projection of the Northern Hemisphere, extending to 20°N. The data
sampling rate is once daily from January 1946 to March 1955, and twice daily from April 1955 onward. The record was produced by splicing together several different datasets that were originally prepared on different grids with different analysis routines and interpolating them onto a common grid. Lambert (1990) has pointed out a number of suspicious apparent discontinuities in the record, which occurred around the times in which different datasets were spliced together. The record is also marked by numerous changes in rawinsonde and satellite instrumentation and data assimilation procedures at NMC. The implications of these potential sources of spurious variability in the record for the interpretation of our results will be discussed in section 3f.

The record contains some minor gaps, most shorter than three days, that were filled in by linear interpolation. Daily data were time averaged to produce monthly means for the period January 1946 through May 1989. The monthly means were condensed from the full NMC grid to a 445-point half-resolution grid, using a Gaussian interpolation scheme to avoid aliasing. The climatological mean for each calendar month was computed and removed from the corresponding monthly means to generate an anomaly time series that was used as a basis for subsequent calculations.

The seasonal means referred to in the paper are for the 43 winters (December through February, hereafter referred to as DJF) starting with 1946/47 and ending with 1988/89; and the 43 summers (June through August, hereafter referred to as JJA) starting with 1946 and ending with 1988. Unless otherwise noted, the annual means are for calendar years 1946–88.

Description of the 100-year GCM experiment is deferred to section 4, where the simulated height and thickness record will be examined to complement our observational results.

The surface air temperature records examined in section 5 are monthly mean land station data interpolated onto a 5° latitude by 10° longitude grid (Jones et al. 1985), updated through 1990. This archive is maintained and distributed to the research community by the U.S. Department of Energy. It should be noted that the grid covers land areas only.

The analysis tools used in this study are conventional empirical orthogonal function (EOF) analysis and singular value decomposition (SVD), both of which are based on temporal covariance matrices. For a tutorial on SVD, the reader is referred to Bretherton et al. (1992). The squared covariance fraction (SCF) discussed extensively in Bretherton et al. is useful for comparing the relative importance of modes in a given expansion, but it is of limited value in comparing the strength of the relationship between the left and right fields in modes obtained from different SVD expansions, in which the squared covariance between the left and right fields may be much different. SCF also suffers from the problem of becoming indeterminate as the squared covariance between two fields approaches zero. Hence, a high value of the SCF does not guarantee that a mode is statistically or physically significant, as illustrated in the Monte Carlo simulations of Bretherton et al. The normalized squared covariance

\[ C_k = \left( \frac{\pi_k}{\sum_i \sum_j \sigma_i \sigma_j} \right)^{1/2} \]

where \( k \) refers to the mode number, \( \pi_k \) is the singular value for the \( k \)th mode, \( \pi_k^2 \) is the squared covariance explained by that mode (i.e., the square of its singular value), and \( \sigma_i^2 \) and \( \sigma_j^2 \) are the variances at the \( i \)th grid point in the left field and the \( j \)th grid point in the right field, respectively, is not subject to these problems. It ranges from zero if the two fields are unrelated to a limiting value of 1.0 if the variations at each grid point in the left field are perfectly correlated with the variations at all grid points in the right field. In this paper we will present results both for SCF and for \( C_k \).

3. Seasonality of the horizontal structure of climate anomalies

In this section, the seasonality of the horizontal structure of interannual and interdecadal climate variability is investigated by applying EOF analysis to annual, seasonal, and time-filtered monthly mean anomaly fields, and SVD analysis to anomaly fields, for successive seasons and years. The dominant patterns observed during the winter and summer seasons are compared, their contributions to the anomalies in the annual-mean fields are estimated, and the season-to-season and year-to-year persistence of the various patterns is documented. The analysis is applied to the 500-hPa height and SLP fields, as well as the 1000–500-hPa thickness field.

a. EOF analysis of seasonal and annual-mean 500-hPa height, thickness, and SLP

Figures 2a,c show the structure of EOF 1 of wintertime 500-hPa height over the Northern Hemisphere, scaled to unit spatial variance. This mode explains 22.7% of the variance over the domain (versus 15.6% for EOF 2). This EOF resembles the PNA pattern: the time series of its expansion coefficient is correlated with the PNA index defined by Wallace and Gutzler (1981) at a level of 0.86 (0.94 if the time series at the “centers of action” are not normalized in computing the index). In this paper, this EOF will be referred to as the “PNA-like mode.”

The eigenvalue associated with the leading mode of summertime-mean 500-hPa height over the same domain is only ~1/4 as large as that of its wintertime counterpart, but it accounts for 17.5% of the variance over the domain of the analysis. Figures 2b,d show the spatial pattern associated with this mode. The contours are scaled as in Figs. 2a,c, and in this case the negative values are shaded to emphasize the smallness of the
area that they occupy. In contrast to the wavelike PNA-like mode, EOF 1 of the summertime-mean 500-hPa height is of the same polarity over almost the entire hemisphere. Its expansion coefficient is correlated with hemispheric-mean 500-hPa height at a level of 0.96. The spatial gradients in the loading vector (Fig. 2b) are less than half as strong as those associated with the PNA-like pattern (Fig. 2a), and if the loading vectors in the two figures are weighted by the square root of the corresponding eigenvalues (i.e., the temporal standard deviation of the time series of the corresponding expansion coefficient), the summertime height gradients are only ~1/5 as strong as the wintertime ones. Hence, the geostrophic wind anomalies associated with the PNA-like mode are larger by a factor of 5 than those associated with the leading summertime pattern.

Summertime EOF1 (Figs. 2b,d) contains elements in common with the leading summertime teleconnec-
tion patterns identified by Horel (1981) and Barnston and Livezey (1987) on the basis of rotated principal component (REOF) analysis and Rogers (1981) on the basis of conventional EOF analysis. A definitive comparison of the patterns is precluded by the differences in methodology and in the period of record used in the various studies, and by uncertainties associated with the possibility of spurious trends or discontinuities in the early part of the dataset, as discussed by Barnston and Livezey (1987). The question of whether the regional features associated with this mode are statistically or dynamically significant is beyond the scope of the present study. Of primary concern is the close relationship between its expansion coefficient and the time series of hemispheric-mean 500-hPa height. In order to distinguish such modes from more regionally concentrated modes with stronger spatial gradients, we will refer to them as manifestations of a “background field.”

The second summertime EOF (not shown), which accounts for 10.2% of the variance, is much more regionally concentrated. Its spatial pattern resembles the North Atlantic Oscillation, which is also Barnston and Livezey’s (1987) most prominent summertime mode. EOF 1 of wintertime 1000–500-hPa thickness (not shown), which explains 18% of the variance (versus 14% for EOF 2), resembles the PNA-like mode in wintertime 500-hPa height. EOF 1 of summertime thickness (not shown) is best described as a manifestation of the background field. Its expansion coefficient exhibits a correlation coefficient of 0.97 with hemispheric-mean thickness. It accounts for 24% of the hemispherically integrated variance, substantially more than its counterpart for 500-hPa height.

The leading modes for the wintertime and summertime SLP field, whose correlation patterns are shown in Fig. 3, both exhibit teleconnection patterns somewhat larger in horizontal scale than the PNA-like pattern, with a prominent zonally symmetric component. They are quite similar except that the summertime pattern is more concentrated in the Atlantic sector. A similar pattern is evident year round in Barnston and Livezey’s (1987) REOF analysis of the 700-hPa height field.

Time series of the expansion coefficients of the wintertime PNA-like mode and the summertime background field for 500-hPa height are shown in Fig. 4. They are scaled in a similar manner so that the amplitudes can be compared. The temporal standard deviation of the expansion coefficient of the PNA-like mode is larger by a factor of 2 than that of the background field. Both time series exhibit substantial interdecadal variability, but the time series of the background field is redder: its one-year lag correlation is 0.68, versus 0.23 for the PNA-like mode. Much of the interdecadal variability in the background field is associated with a pronounced cooling in the mid-1950s and a weaker temperature drop around 1963. Knox et al. (1988) and Shabbar et al. (1990) have interpreted the latter feature as a discontinuity in the climate record: a break between two distinct “subclimates,” while Lambert (1990) attributes both features to discrete changes in analysis procedures involved in the production of the NMC dataset. The time series of the wintertime PNA-like mode is strongly correlated with the “North Pacific SLP index” (sea level pressure averaged over the region extending from 27.5°–72.5°N, 147.5°E to 122.5°W), which has been used by Tren-
berth (1990) as a means of characterizing large-scale circulation changes over the North Pacific that have occurred in association with the recent warming trend over the Northern Hemisphere.

The time series of the expansion coefficients of EOF 1 of winter and summer thickness (not shown) are very similar to their counterparts for 500-hPa height in Fig. 4. However, the corresponding time series for SLP (Fig. 5) are dominated by higher frequencies. The correlation coefficient between the principal components of winter and summer SLP (0.48, Table 1) is surprisingly low, in view of the strong similarity of the spatial patterns. Hence, it appears that much of the variability associated with this mode has a characteristic time scale shorter than a year.

Figure 6 shows correlation patterns for the leading EOFs of the annual-mean 500-hPa height field. The first EOF accounts for 20.1% of the variance. Like the leading summertime EOF, it is a relatively featureless background field. EOF 2, which accounts for 15.0% of the variance, resembles the PNA-like mode that dominates the wintertime variability. Figure 4c shows the time series of the expansion coefficient of EOF 1 of the annual-mean field, scaled to be consistent with the seasonal time series. Much the same interdecadal signal is evident in this time series as in the summertime mode shown in Fig. 4b: the correlation coefficient between them is 0.86 (Table 1).

It might be argued that the demotion of the PNA-like mode to the second EOF in the annual-mean statistics is due to the fact that the three winter months are divided between two consecutive calendar years. In order to determine whether this is the case, EOF analysis was also performed on the annual-mean 500-hPa height field based on averages for July through the following June. The results (not shown) proved to be very similar to those based on the traditional calendar year.

EOF analysis of annual-mean thickness yields similar results, except that the background field accounts for more than twice as much of the variance as the PNA-like mode (28% versus 14%) and the time series of the expansion coefficient of EOF 1 of annual-mean thickness is even more strongly correlated with that of summertime-mean thickness (Table 1).

As expected, EOF 1 of annual-mean SLP (not shown), which explains 23% of the total variance, looks

| Table 1. Correlation coefficient between seasonal- and annual-mean time series: W/A indicates winter with annual mean, S/A summer with annual mean, and W/S winter with the following summer. |
|---------------------------------|------|------|------|
|                               | W/A | S/A | W/S |
| EOF 1 500-hPa height           | -.40 | .86  | -.22 |
| EOF 1 thickness               | -.34 | .93  | -.26 |
| EOF 1 SLP                     | .64  | .44  | .48  |
| Hemispheric-mean thickness    | .87  | .95  | .82  |
very similar to EOF 1 of wintertime SLP. The time series of the expansion coefficients for this mode is shown in Fig. 5c.

b. EOF analysis of monthly mean 500-hPa height and thickness

In this subsection, a somewhat different analysis approach is used to document how the background field becomes increasingly prominent as more and more of the high-frequency fluctuations in the record are filtered out. A continuous monthly mean time series, comprising data for all seasons, is examined.

EOF analysis was performed on unfiltered, one-year low-pass-, two-year low-pass-, and five-year low-pass-filtered monthly mean 500-hPa height and thickness anomaly fields. Figure 7 shows the frequency response of the three filters, which have their half-power points at 1.0, 0.5, and 0.2 cycles per year, respectively. It is worth noting that the one-year low-pass filter does not smooth as strongly as a 12-month running mean filter: it removes virtually all of the intraseasonal variability but it has very little effect on the interannual variability.

Table 2 shows the percentage of the variance explained by the PNA-like mode and the background field for the unfiltered and filtered monthly mean 500-hPa height and thickness fields. In interpreting the results, it should be borne in mind that the hemispherically integrated variance drops off as progressively stronger low-pass filters are applied to the data. The rate of decrease is more rapid for 500-hPa height than for thickness. For example, the hemispherically inte-

| Table 2. Percentage of the hemispherically integrated variance explained by the PNA-like mode and the “background field” in EOF analysis based on different low-pass-filtered 500-hPa height and 1000-500-hPa thickness fields. |
|-------------------------------------------------|-------------------------------------------------|
| PNA-like mode (500-hPa height/thickness) | Background field (500-hPa height/thickness) |
| Unfiltered | 13.4/10.0 | **/8.3 |
| 1-year low pass | 15.8/11.6 | 15.1/22.2 |
| 2-year low pass | 15.2/12.6 | 22.1/30.5 |
| 5-year low pass | 14.0/** | 41.0/49.2 |

** The mode is not well defined.
The leading EOF of the unfiltered, monthly mean fields, which accounts for 13.4% of the variance (Fig. 8), resembles the PNA-like mode. As progressively stronger low-pass filters are applied to the dataset, the variance associated with this mode declines at about the same rate as the hemispherically integrated variance, so that the percentage of explained variance listed in Table 2 remains nearly constant. In contrast to the PNA-like mode, the variance associated with the background field declines much more slowly than the hemispherically integrated variance, so the explained variance increases as progressively stronger smoothing is applied to the time series. In the one-year low-pass filtered data, from which the intraseasonal variability has been removed (Fig. 9), the PNA-like mode and background field account for nearly equal fractions of the variance. In the two-year low-pass filtered data the background field explains more variance than the PNA-like mode and in the five-year low-pass filtered data it accounts for nearly half of the hemispherically integrated variance.

In the unfiltered data and in each of the filtered datasets, the background field is more prominent in the thickness field than in the 500-hPa height field. For example, in the case of the one-year low-pass filtered data, in which the background field and the PNA-like pattern explain comparable amounts of variance of the 500-hPa height field, the background field explains almost twice as much variance of the thickness field as the PNA-like pattern.

In order to determine how the variance explained by a particular EOF mode is distributed among different calendar months, the following calculation was performed.

Fig. 9. As in Fig. 8 but for the two leading principal components of the one-year low-pass filtered 500-hPa height anomalies. In (b), areas of negative correlation are shaded.
1) Time series of gridpoint values of 500-hPa height and expansion coefficients of selected EOF modes were separated into 12 subseries, one for each calendar month.

2) Maps of temporal variances \( \sigma_{im}^2 \) and the correlation coefficients \( r_{im} \) between the \( i \)th gridpoint subseries and the subseries of the expansion coefficients of specified EOFs were computed for each calendar month (\( m \)). Then \( \sigma_{im}^2 r_{im}^2 \) is the variance explained by a particular EOF mode at the \( i \)th grid point, as computed from the subseries for the \( m \)th calendar month, and

\[
R_m = \frac{\sum_i \sigma_{im}^2 r_{im}^2}{\sum_i \sigma_{im}^2}
\]

is the fraction of the total variance of the 500-hPa height field explained by that EOF mode, as computed from the subseries for the \( m \)th calendar month.

Figure 10 shows \( R_m \) as a function of calendar month for the two leading EOFs of one-year low-pass filtered 500-hPa height. Consistent with results in the previous subsection, the variance of the PNA-like mode comes mainly from the winter months, December through March, while the variance of the background field comes mainly from the summer months. The fact that the seasonal modulation of the background field is not as pronounced as that of the PNA-like mode suggests that it might be present year-round, which would help to explain why it emerges as the dominant mode in the EOF analysis of annual-mean 500-hPa height. Further evidence that the background field is, indeed, present year round will be presented in the next subsection.

\textit{c. SVD analysis of height and thickness in successive seasons}

In order to document the persistence of the various patterns from winter to summer, from one winter to the next, and so forth, SVD analysis was performed on different combinations of winter and summer 500-hPa height, thickness, and SLP fields. Properties of the leading modes derived from these expansions are summarized in Table 3. The percentage of the squared covariance, summed over all pairs of grid points in the two fields is listed first, followed by the correlation coefficient between the expansion coefficients of the two fields. The third entry in the table is the normalized root-mean-squared covariance \( C_{ki} \), as defined in section 2. The first part of the discussion is focused on the analysis of the 500-hPa height field, but these results will subsequently be compared with corresponding statistics for thickness and SLP. The spatial patterns derived from the analyses will not be shown since they are similar to ones that have already been discussed.

In the SVD analysis of the wintertime 500-hPa height field with the 500-hPa height field for the following summer, the summertime pattern for the first SVD pair, which explains 40% of the squared covariance, is the background field. The correlation coefficient between the time series of the expansion coefficient of its summertime field and hemispheric-mean summertime 500-hPa height is 0.97. The corresponding winter pattern contains elements of both the PNA-like mode and the background field. The same analysis based on the thickness yields more definitive results. In the first SVD pair, which explains 58% of the squared covariance, both summer and winter patterns can be identified with the background field: they are correlated with hemispheric-mean thickness for their respective seasons at levels of 0.88 and 0.97, respectively, and they are much more strongly correlated with one another than the corresponding time series derived from SVD analysis of 500-hPa height. Corresponding results for SVD analysis between the summertime fields and the fields for the following winter are qualitatively similar. They

<table>
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<tr>
<th>SLP</th>
<th>500-hPa Z</th>
<th>Thickness</th>
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<tr>
<td>W/S</td>
<td>46/66/12</td>
<td>? 40/68/10</td>
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<tr>
<td>S/W</td>
<td>31/74/09</td>
<td>? 33/70/10</td>
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<td>W/W</td>
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<td>W/A*</td>
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provide further evidence that the background field is present year round, and that it is more prominent in thickness than in 500-hPa height.

The first SVD pair between the 500-hPa height fields in successive summers explains 51% of the squared covariance. The expansion coefficients for the earlier and later fields are correlated with hemispheric-mean summertime 500-hPa height at levels of 0.93 and 0.95, respectively, and they are correlated with one another at a level of 0.85. Corresponding results based on thickness are similar in this case, except that the first SVD pair explains more of the squared covariance (70%) and exhibits a larger normalized root-mean-squared covariance (0.20 versus 0.14).

In the analysis of the 500-hPa height fields for successive winters, both earlier and later fields resemble the PNA-like pattern: the correlation coefficients between their expansion coefficients and the expansion coefficient of EOF 1 of wintertime 500-hPa height are 0.90 and 0.82. However, they are also correlated with hemispheric-mean 500-hPa height at levels of 0.54 and 0.46, respectively. This “contamination” by the background field probably explains why the winter-to-winter persistence reported in the table (0.66) is so much higher than that of the expansion coefficient of EOF 1 of wintertime 500-hPa height (0.23). Results of the corresponding analysis based on the thickness field are qualitatively similar. Hence, despite the contamination of the winter-to-winter SVD analysis by the background field, these results confirm that the wintertime teleconnection patterns are not as persistent from year to year as the summertime background field.

As expected, the results based on SLP are much different from those based on 500-hPa height and thickness. When the wintertime SLP field is paired with the SLP field for the following summer, the spatial patterns in the leading mode resemble their counterparts based on EOF analysis, but the temporal correlation coefficient between their expansion coefficients (0.66) is much weaker than in corresponding results based on thickness. SVD analysis for the other three combinations of seasons (summer with the following winter, winter with the following winter, and summer with the following summer) did not yield any recognizable spatial patterns in the leading mode.

In all cases, the thickness field exhibits stronger season-to-season and year-to-year persistence than either the 500-hPa height or sea level pressure fields.

The bottom two rows in Table 3 contrast the strength of the relationships between the annual-mean thickness field and the thickness field in the winter and summer seasons. In the calculations for the winter season, the annual means are defined as extending from July of the preceding year through June of the following year so that winter occurs near the middle of the year over which the annual average is taken. In both cases, the relationships are quite strong: the wintertime-mean and annual-mean fields are linked through the PNA-like pattern, and the summertime-mean and annual-mean fields are linked through the background field (not shown). Despite the larger variances associated with the winter season, the linkage between the summertime-mean and annual-mean fields is substantially stronger.

d. Relation of the leading modes to hemispherically averaged thickness

In the EOF and SVD analyses in the three previous subsections, the background field consistently shows up more prominently in the thickness field than in the geopotential height field. The time series of its expansion coefficient is virtually indistinguishable from the time series of hemispheric-mean (poleward of 20°N) thickness shown in Fig. 11. (The correlation coefficient is 0.97 for both summer and annual-mean time series.)

The PNA-like pattern that dominates the wintertime 500-hPa height and thickness field does not project strongly onto the hemispheric mean. Therefore, it is not surprising that the winter time series in Fig. 11 bears little relation to time series of the PNA-like pattern in Fig. 4 (the correlation between them is only ~0.1). Wintertime hemispheric-mean thickness is much more strongly correlated with its summertime counterpart in Fig. 11 (r = 0.82), as might have been anticipated on the basis of results presented in the previous subsection.

e. Local signatures of the background field

The interdecadal signal in lower-tropospheric thickness is evident, not only in the hemispheric average,
Fig. 12. Normalized three-year running means of annual-mean 1000-500-hPa thickness for the polar cap region and the latitude belts, as indicated, together with hemispheric mean (poleward of 20°N) annual-mean thickness. The temporal standard deviations of these time series are listed in Table 4.

but also in time series for individual latitude belts. Figure 12 shows normalized time series for the polar cap region and zonal averages for selected latitude belts, which exhibit a common pattern of interdecadal variability. In this and subsequent figures in the subsection, the time series have been lightly smoothed with a three-year running mean filter to show the interdecadal variability more clearly. Table 4 lists the correlation coefficients between three-year running means of hemispherically averaged thickness and a more complete selection of zonally averaged time series. The correlations range from ~0.95 throughout much of the temperate latitudes to ~0.86 along the outer edge of the grid and in the polar cap region. The corresponding standard deviations shown also in Table 4 indicate that the amplitude of the interdecadal variability increases with latitude. The corresponding regression coefficient (i.e., the correlation coefficient in the first column times the standard deviation in the second column), which is a measure of the amplitude of the fluctuations associated specifically with variations in hemispheric-mean thickness, also increases with latitude. A similar temporal signature in lower-tropospheric temperature over the Arctic has been reported by Flohn (1986), based on summertime data. [His time series is reproduced as Fig. 7 of Shabbar et al. (1990).]

Table 4. Correlation coefficient between 3-year running means of hemispherically averaged annual-mean 1000-500-hPa thickness and corresponding averages over latitude belts, together with the temporal standard deviation in K.

<table>
<thead>
<tr>
<th>Latitude Belt</th>
<th>Correl.</th>
<th>St. dev. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°–25°N</td>
<td>0.86</td>
<td>0.25</td>
</tr>
<tr>
<td>25°–30°N</td>
<td>0.96</td>
<td>0.28</td>
</tr>
<tr>
<td>30°–35°N</td>
<td>0.96</td>
<td>0.30</td>
</tr>
<tr>
<td>35°–40°N</td>
<td>0.95</td>
<td>0.32</td>
</tr>
<tr>
<td>40°–45°N</td>
<td>0.94</td>
<td>0.33</td>
</tr>
<tr>
<td>45°–50°N</td>
<td>0.93</td>
<td>0.39</td>
</tr>
<tr>
<td>50°–55°N</td>
<td>0.91</td>
<td>0.37</td>
</tr>
<tr>
<td>55°–60°N</td>
<td>0.89</td>
<td>0.38</td>
</tr>
<tr>
<td>60°–65°N</td>
<td>0.90</td>
<td>0.42</td>
</tr>
<tr>
<td>65°–70°N</td>
<td>0.89</td>
<td>0.49</td>
</tr>
<tr>
<td>70°–90°N</td>
<td>0.85</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Fig. 12 shows three-year running mean annual-mean thickness averaged over regions corresponding roughly to the United States (28°–48°N, 80°–120°W), China (20°–50°N, 75°–130°E), and western Europe (40°–60°N, 0°–80°E), together with their correlation coefficients with three-year running mean hemispherically averaged thickness. The hemispheric signal is evident, even in averages over these limited regions. Figure 14 shows analogous results for five representative grid points along 45°N. Even most of these time series show the gross features of the hemispheric-mean time series. The two series for grid points in the Pacific sector are somewhat different from the others, with less evidence of warming in the first few years of the record and in the years since the late 1970s.

Fig. 13. Normalized three-year running means of 1000–500-hPa thickness for regions corresponding roughly to the United States (28°–48°N, 120°W), China (20°–50°N, 75°–130°E), western Europe (40°–60°N, 0°–80°E), and the entire hemisphere poleward of 20°N. The numbers at right indicate the correlation coefficient (expressed in hundredths) between the regional and hemispheric-mean time series.
4. Evidence of a “background field” in simulated climate variability

As further evidence in support of the concept of a background field whose temporal variations are strongly correlated with hemispheric-mean thickness, we present in this section selected results from a 100-year GCM simulation performed at GFDL using a spectral model with rhomboidal truncation at wavenumber 15. Sea surface temperature is prescribed as the seasonally varying, climatological mean. Other boundary conditions, such as sea ice, continental snow cover, land surface temperature, and hydrology, as well as clouds are predicted by the model. A more detailed description of the model and this particular experiment can be found in Gordon and Stern (1982) and Ting and Lau (1993). The root-mean-squared interdecadal variability in hemispheric-mean thickness simulated in this GCM run, which lacks interannual variability in sea surface temperature and trends in the concentrations of aerosols and greenhouse gases, is about 1/3 as strong as that in the 43-year record of NMC analyses.

For purposes of the present study, time series of the monthly, seasonal, and annual-mean height anomalies at the 515- and 830-hPa levels were derived from the model history tapes using procedures similar to those described in section 2. For consistency with section 3,

\[
\begin{align*}
| \text{Table 5. Selected statistics relating to the background field, based on three different periods of record. The notation } r(x, y) \text{ denotes the temporal correlation coefficient between } x \text{ and } y. \text{ Wherever EOFs are mentioned, the correlations are based on their expansion coefficients. } Z_{500} \text{ refers to 500-hPa height and } T \text{ to 1000–500-hPa thickness. Overbars denote hemispheric means, summer refers to summertime (JJA) means, and annual to annual means.} |

\begin{tabular}{|c|c|c|c|}
\hline
 & 1946–89 & 1958–89 & 1963–89 \\
\hline
$r(EOF \text{ 1 of } Z_{500}, Z_{500})$, summer & 96 & 97 & 96 \\
$r(EOF \text{ 1 of } T, \bar{T})$, summer & 47 & 89 & 93 \\
$r(EOF \text{ 1 of } T, \bar{T})$, annual & 42 & 87 & 91 \\
$r(EOF \text{ 1 of } T \text{ summer, EOF } 1 \text{ of } T \text{ annual})$ & 92 & 94 & 83 \\
$r(\bar{T} \text{ summer, } \bar{T} \text{ annual})$ & 86 & 92 & 92 \\
\hline
\end{tabular}
\end{align*}
\]

4. Evidence of a “background field” in simulated climate variability

As further evidence in support of the concept of a background field whose temporal variations are strongly correlated with hemispheric-mean thickness, we present in this section selected results from a 100-year GCM simulation performed at GFDL using a spectral model with rhomboidal truncation at wavenumber 15. Sea surface temperature is prescribed as the seasonally varying, climatological mean. Other boundary conditions, such as sea ice, continental snow cover, land surface temperature, and hydrology, as well as clouds are predicted by the model. A more detailed description of the model and this particular experiment can be found in Gordon and Stern (1982) and Ting and Lau (1993). The root-mean-squared interdecadal variability in hemispheric-mean thickness simulated in this GCM run, which lacks interannual variability in sea surface temperature and trends in the concentrations of aerosols and greenhouse gases, is about 1/3 as strong as that in the 43-year record of NMC analyses.

For purposes of the present study, time series of the monthly, seasonal, and annual-mean height anomalies at the 515- and 830-hPa levels were derived from the model history tapes using procedures similar to those described in section 2. For consistency with section 3,
the term "hemispheric mean" will be used in this section to represent the average over the region poleward of 20°N.

Time series of the 100-year hemispherically averaged summer-, annual-, and winter-mean 830–515-hPa thickness are shown in the three panels of Fig. 15. It is evident that the annual-mean time series are much more strongly correlated with the summertime means (0.71) than with the wintertime means (0.17); and there is also almost no correlation between the hemispheric means for winter and summer (0.11).

The structure of the dominant fluctuations in the seasonal- and annual-mean 830–515-hPa thickness time series was identified on the basis of EOF techniques. Consistent with the observational results, EOF 1 of summertime thickness in the model is characterized by anomalies of the same polarity over most of the hemisphere, while EOF 1 of wintertime-mean thickness is associated with more regional, wavelike features (not shown). The structure of annual-mean EOF 1 resembles that of the summertime EOF 1, and the expansion coefficient of annual-mean EOF 1 is more strongly correlated with its summertime counterpart (0.51) than with its wintertime counterpart (0.03). In a similar manner, annual-mean hemispherically averaged thickness is more strongly correlated with its summertime counterpart (0.66) than with its wintertime counterpart (0.30).

For both summer- and annual-mean thickness, the expansion coefficients of EOF 1 are highly correlated with the corresponding hemispheric-mean thickness time series (0.91 and 0.76). These results show that the concept of a background field whose temporal variation is strongly correlated with the hemispheric mean is also useful for characterizing the thickness variations in the GCM simulation.

Consistent with the observational results, the fraction of the hemispherically integrated (local) variance that can be explained on the basis of fluctuations in the hemispheric-mean field increases as the emphasis shifts toward lower frequencies. However, the increase, from 11% in the 1-year low-pass-filtered data to 18% in the 10-year low-pass filtered data, is not as dramatic as in the observations, perhaps because the root-mean-squared interdecadal variability of hemispheric-mean temperature in the model is only about one-third as strong as that in the real atmosphere. As in the observations, the prominence of the PNA-like mode does not increase as stronger low-pass filters are applied to the data.

The background field shows up most clearly in calculations involving the 830–515-hPa thickness field, but the 515-hPa height field (not shown) displays similar characteristics.

5. Role of the PNA pattern in interdecadal variability of surface air temperature

In this section we will consider the relationship between the two modes of variability emphasized in this study (i.e., the background field, as represented by the time series of hemispheric-mean thickness, and the PNA-like pattern) and surface air temperature averaged over the Northern Hemisphere poleward of 20°N.

Time series of hemispherically averaged, annual-mean thickness and surface air temperature based on land stations are compared in Fig. 16. The correlation coefficient between them is 0.43. Correlation coefficients as high as 0.60 can be obtained by restricting the data to the summer months only. In comparison to the thickness time series, the land surface temperatures exhibited less pronounced cooling from 1955 to 1963, and less warming since the late 1970s. If these differences are real, they are indicative of a long-term decrease in lower-tropospheric static stability. However, as noted by Lambert (1990), they may be a reflection
of changes in analysis procedures in the production of the NMC dataset.

Now let us consider how fluctuations associated with the wintertime PNA-like pattern impact the hemispherically averaged surface air temperature. Gutzler et al. (1988) have shown that the PNA index defined in Wallace and Gutzler (1981) is positively correlated with surface air temperatures over western Canada and much of Siberia. Because of their large temporal variability, these regions are influential in determining hemispheric-mean temperature anomalies at these levels and because of its large variability, the winter season exerts a strong influence upon the annual mean. Gutzler et al. noted that the PNA index is positively correlated with hemispheric-mean surface air temperature. For the period of record 1946–89 the correlation coefficient between the time series in Figs. 4a and 16 is 0.37, not as impressive as that reported by Gutzler et al. based on a much shorter period of record, but still strong enough to be of relevance to the interpretation of the surface air temperature record.

In contrast to the situation at the earth’s surface, the PNA index is not well correlated with hemispheric-mean 1000–500-hPa thickness (e.g., the correlation coefficient between the time series in Figs. 4a and 11a is only 0.09). The differing correlations at the two levels reflect the differing vertical profiles of the temperature and geopotential height anomalies associated with the PNA pattern at its centers of action over the North Pacific and western Canada.

To document these differences, wintertime-mean values of selected variables were linearly regressed on the PNA index as defined in Wallace and Gutzler (1981). The record for Edmonton from the World Monthly Surface Station Climatology was used to represent surface air temperature at the center of action over western Canada and COADS (Comprehensive Ocean–Atmosphere Data Set) data were used to represent sea surface temperature and surface air temperature at the center of action over the North Pacific. All sea level pressure and upper-air data are based on the NMC analyses. The slopes of the regression lines serve as estimates of the amplitudes of the anomalies that occur in association with a value of +1 standard deviation of the wintertime-mean PNA index. The results are presented in Table 6a. As might have been expected on the basis of the variance map in Fig. 1a, the 500-hPa height anomalies are almost 50% larger at the center of action over the North Pacific than over Edmonton. However, the thickness perturbations are ~50% larger at Edmonton than over the North Pacific, reflecting the stronger baroclinicity of the perturbations over western Canada. The distinction between the 500-hPa height and thickness patterns is further illustrated by Fig. 17, which shows regression maps, constructed in the same manner as the statistics in Table 6a.

At the earth’s surface, the wintertime temperature perturbations observed at Edmonton in association with the PNA pattern are about five times as large as the largest perturbations observed over the North Pacific, which confirms that positive values of the PNA index should be conducive to warmer hemispheric-mean temperatures. The regression coefficient between the wintertime-mean PNA index and hemispherically averaged surface air temperature (which is based on land stations only) is +0.18 K per unit standard deviation of the PNA index. If SST data were included in computing the hemispheric mean, the coefficient would be somewhat smaller, but it would almost certainly still be positive. In contrast, in the thickness field,

<table>
<thead>
<tr>
<th>Variable</th>
<th>Edmonton (E)</th>
<th>North Pacific (NP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500-hPa height</td>
<td>+44.3</td>
<td>-64.6</td>
</tr>
<tr>
<td>1000-hPa height</td>
<td>-1.4</td>
<td>-35.9</td>
</tr>
<tr>
<td>1000–500-hPa height</td>
<td>+45.7</td>
<td>-28.7</td>
</tr>
<tr>
<td>1000–500-hPa virtual temp</td>
<td>+2.2</td>
<td>-1.4</td>
</tr>
<tr>
<td>Surface air temp</td>
<td>+2.7</td>
<td>-0.51</td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>-0.43</td>
<td></td>
</tr>
</tbody>
</table>

(b) Changes in wintertime heights and temperature from the reference period (1951–80) to the decade of the 1980s.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Edmonton (E)</th>
<th>North Pacific (NP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500-hPa height</td>
<td>+40.5</td>
<td>-67.0</td>
</tr>
<tr>
<td>1000-hPa height</td>
<td>+2.7</td>
<td>-28.6</td>
</tr>
<tr>
<td>1000–500-hPa height</td>
<td>+37.8</td>
<td>-38.4</td>
</tr>
<tr>
<td>1000–500-hPa virtual temp</td>
<td>+1.9</td>
<td>-1.9</td>
</tr>
<tr>
<td>Surface air temp</td>
<td>+2.3</td>
<td></td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>-0.4</td>
<td></td>
</tr>
</tbody>
</table>
a considerable degree of compensation is observed between the temperature perturbations in the vicinity of the opposing centers of action over western Canada and the North Pacific, so that the net contribution of fluctuations in the PNA index to changes in hemispheric-mean temperature anomalies is smaller and opposite in sign (the corresponding regression coefficient is $-0.08$).

A clear signature of the PNA pattern is evident in the field of 1000–500-hPa thickness change from 1951–80 to 1981–89, shown in Fig. 18a (see also Fig. 5 of Shabbar et al. 1990). Because of the strong cancellation between the warming over western Canada and the cooling over the North Pacific, the change in hemispherically averaged thickness is rather small (0.08 K). However, down at the earth’s surface the warming over western Canada is much stronger than the cooling over the North Pacific (Table 6b) so that the anomalies associated with the PNA pattern contribute substantially to the higher mean temperature of the Northern
Hemisphere during the 1980s. Vestiges of the same spatial signature are evident in the pattern of annual-mean thickness change shown in Fig. 18b.

The pattern of wintertime thickness change from the warm decade 1946–55 to the cooler 20-year period beginning in 1964, shown in Fig. 19a, also exhibits the signature of the PNA pattern with the same polarity: that is, warming over western Canada and cooling over the North Pacific and the southeastern United States (see also Fig. 5 of van Loon and Williams 1976). This pattern is consistent with the pronounced increase in the expansion coefficient of EOF 1 of wintertime 500-hPa height from the earlier to the later period (Fig. 4a). Again, vestiges of the PNA pattern are evident in the pattern of changes in annual-mean temperature (Fig. 19b), reflecting the strong influence of the winter season on annual-mean temperature. However, it is notable that during this period the hemispheric-mean surface air temperature was dropping, despite the substantial increases in wintertime surface air temperatures over western Canada. Hence, although the circulation changes that occur in association with the PNA pattern exert a detectable influence on long-term hemispheric temperature trends, it is clear that they do not control them.

It is possible to make a somewhat more quantitative assessment of the contribution of wintertime circulation changes to the observed interdecadal changes in hemispherically averaged surface air temperature simply by stratifying the temperature data by warm and cold season as shown in Table 7 and invoking the argument that dynamically induced temperature changes associated with the PNA pattern should be largely restricted to the cold season, while changes associated with the background field should be felt during both seasons. The fact that the warming from the 1951–80 reference period to the 1980s was nearly three times as large during the cold season as during the warm season (Table 7, top row) suggests that wintertime circulation anomalies that favor above-normal temperatures over the high-latitude continents should have accounted for \( \sim \frac{2}{3} \) of the temperature rise during the cold season. The trend in the index of the PNA pattern could have accounted for the warming over western Canada in Fig. 18a: presumably other circulation features were instrumental in producing the equally strong warming over Siberia. Hence, we estimate that the trend in the PNA pattern might have been responsible for roughly half the dynamically induced temperature rise and \( \sim \frac{1}{3} \) (\( \sim 0.15 \) K) of the observed warming over the Northern Hemisphere during the cold season. We obtain a slightly smaller value if we regress wintertime (DJF) hemispheric-mean surface air temperature upon the normalized PNA index as in Table 6a and multiply the resulting regression coefficient (+0.18 K per standard deviation of the PNA index) by the change in the wintertime-mean PNA index from 1951–80 to 1981–89 (+0.54). In agreement with the

<table>
<thead>
<tr>
<th>Surface air temperature</th>
<th>1000–500-hPa thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-A</td>
<td>M-O</td>
</tr>
<tr>
<td>1981/89–1951/80</td>
<td>+0.44</td>
</tr>
<tr>
<td>1963/78–1946/55</td>
<td>−0.14</td>
</tr>
<tr>
<td>1981/89–1946/55</td>
<td>+0.36</td>
</tr>
</tbody>
</table>

FIG. 19. As in Fig. 18, but for 1964–83 minus 1946–55.
above discussion, the corresponding increases in hemispheric-mean thickness, which should be largely independent of the trend in the PNA index, do not exhibit a strong seasonal dependence.

If the above reasoning is correct, we should expect the drop in surface air temperature that took place between 1946–55 and 1964–78 (Fig. 19) to be more pronounced during the warm season than during the cold season when it presumably should have been partially cancelled by warming over western Canada associated with the upward jump in the index of the PNA-like pattern (Fig. 4a). It is evident from the second row of Table 7 that the drop in surface air temperature during the warm season was, in fact, about twice as large as that observed during the cold season. The temperature changes aloft were quite comparable (and suspiciously large) during the two seasons.

The net change in hemispheric-mean surface air temperature from the first decade of our 43-year record to the last decade (Table 7, third row) exhibits a strong seasonality. Averaged over the warm season, which is relatively free from the influence of the PNA pattern, the 1980s were actually slightly cooler than the period 1946–55. The large rise (+0.36 K) during the cold season presumably includes a substantial contribution from the trend in the PNA pattern. In contrast to the strong seasonality at the surface, the temperature changes aloft in the NMC analyses were quite comparable during the two seasons. Some of the decrease in hemispheric-mean thickness and the corresponding drop in mean 500-hPa height during the early part of the record may be spurious, but just how much is difficult to say.

Figure 20 shows time series of monthly mean anomalies in 1000–500-hPa thickness, expressed as layer-mean virtual temperature and surface air temperature based on gridded data from land stations, both averaged over the area poleward of 20°N. In order to reduce the influence of the PNA pattern and other teleconnection patterns that might impact surface air temperature more than thickness, only data points for the months of the warm season (May through October) are shown. A visual comparison of the two curves supports the notion of a positive bias in thickness in the first ten years of the record. However, on close inspection it is evident that the pronounced drops in thickness around 1956 and 1963 are reflected in the time series of surface air temperature, as are a number of subsequent features in the record. Hence, despite the possibility of biases, it appears that the early part of the thickness record contains useful information.

6. Discussion and concluding remarks

In section 3 it was shown that the low-frequency variability in the geopotential field with a time scale of months or longer exhibits a substantially higher degree of spatial organization, in terms of regional teleconnection patterns, than the corresponding variability in the thickness field. A larger fraction of the temporal variability of the thickness field is associated with fluctuations in the hemispheric-mean value; for example, in Table 5 it is shown that the leading principal components of the summertime- and annual-mean thickness fields are correlated with the corresponding time series of hemispheric-mean thickness at levels ~0.9. As a label for the loading vectors or EOFs whose expansion coefficients are linearly dependent on the time series of the hemispheric mean, we have coined the term background field, which serves to distinguish them from the plethora of teleconnection patterns in which regional centers of action are emphasized. The modes that we have identified with the background field are not totally devoid of spatial structure, but the associated horizontal gradients and geostrophic winds are substantially weaker than their counterparts in the dominant teleconnection patterns. Although the observational evidence is far from definitive at this point, we are inclined to interpret the dominant teleconnection patterns as signatures of dynamical processes such as instability of the climatological mean flow, and the background field as a more passive thermodynamic response to perturbations in the radiation and/or surface energy balance.

The evidence presented in section 3b indicates that the background field becomes increasingly prominent as the emphasis shifts toward longer time scales. For fluctuations in thickness with periods longer than five years it accounts for on the order of half the hemispherically integrated variance. This result must be considered tentative at this point because of the pos-
sibility of spurious discontinuities or trends in the earlier part of the NMC dataset. However it is notable that Bradley et al. (1987) and Bradley (1992) have reached essentially the same conclusion based on the analysis of a much longer and presumably more reliable record of surface air temperature.

Teleconnection patterns are most prominent during winter, while the background field is most prominent during summer. This result is consistent with the findings of Barnett (1978) and Bradley et al. (1987) based on surface air temperature, as summarized in the Introduction. It is also consistent with the finding that the signature of interdecadal variability in hemispheric-mean surface air temperature is more clearly evident in scatterplots of monthly means for the warm season than for the cold season (Wallace 1993), and with the fact that EOF analysis of annual-mean 500-hPa height and thickness fields yields results remarkably similar to those based on the summertime-mean fields, despite the fact that the local variability is much larger during wintertime. Some key pieces of observational evidence in support of the reality of the background field are replicated in the GCM results presented in section 4.

Although the record length is still too short to support definitive conclusions, an analogous seasonality appears to be evident in time series of seasonally-mean snow cover averaged over the Eurasian and North American continents, as displayed in Robinson (1993a,b,c). For the Northern Hemisphere as a whole, annual-mean snow cover is more strongly correlated with summertime-mean snow cover than with wintertime-mean snow cover, even when the year is redefined as the 11 months centered on the season in question (0.89 for JJA with February through December versus 0.62 for DJF with August through June). This result is particularly remarkable in view of the fact that the mean snow cover during summer is less than 1/5 as extensive as that during winter. The Eurasian and North American snow cover time series are also more strongly correlated with one another during summer than during winter (0.83 versus 0.63), consistent with the notion of a “background field,” highly correlated with the hemispheric mean and most prominent during the summer season.

Whether the regional features associated with the background field are statistically and physically significant remains an open question. The observed tendency for amplitude to increase with latitude (e.g., see Table 4) is consistent with analyses based on surface air temperature (e.g., see the discussion in Bradley 1992).

The leading wintertime PNA-like mode in the 500-hPa height field exhibits a surprising amount of interdecadal variability despite its modest (0.23) one-year lag correlation. Evidently the temporal behavior of the mode is not well simulated by a first-order Markov process. The contrast between the first and last decades of the record (1946–55 versus the 1980s) is particularly striking: wintertime-mean 500-hPa heights at selected grid points over the North Pacific were as much as 120 m lower, on average, during the later period, while heights over parts of western Canada were as much as 60 m higher and surface air temperature at Edmonton averaged 4 K warmer. The signature of this pattern is clearly evident in difference maps for decadal-mean wintertime surface air temperature and thickness and vestiges of it are apparent even in the corresponding charts for annual-mean temperature (Figs. 18b, 19b). Trenberth (1990) and Trenberth and Hurrell (1993) have argued that the interdecadal variability of this mode is linked to the El Niño–Southern Oscillation phenomenon.

In agreement with previous studies, the leading EOFs of the wintertime and summertime sea level pressure field were found to be dominated by a meridionally oriented dipole structure with largest amplitude over the Atlantic sector. The interdecadal variability associated with this mode does not appear to be as pronounced as that associated with the background field or the PNA-like mode. It is not clear how to reconcile this result with the large interdecadal variability in the Atlantic sector documented by Bjerknes (1964) on the basis of data from the earlier part of this century.

The analysis presented in this paper would have been more straightforward and the conclusions more convincing if it were possible to take for granted the reliability of the analyses of geopotential height and thickness. This problem will hopefully be at least partially resolved by global reanalysis projects that NMC and other operational numerical weather prediction groups are planning to undertake over the course of the next few years (Bengtsson and Shukla 1988; Kalnay and Jenne 1991), together with further analysis of interdecadal trends in radiosonde data analogous to those of Angell (1988) and Oort and Liu (1993), but based on longer periods of record. Tropospheric (layer-averaged 1000–300 hPa) temperature time series derived from the microwave sounding unit carried aboard the TIROS satellites (Spencer and Christy 1990, 1992) will soon be long enough to serve as an additional basis for studies of interannual variability.

Acknowledgments. The authors are grateful to the two anonymous reviewers and to Robert Livezey, Richard Seager, and Nathan Mantua for their critical comments and suggestions, and to James Renwick, who performed the analysis of the surface air temperature data. This work was supported by the National Science Foundation through the Climate Dynamics Program under Grants ATM 8822872 and 9215512 and by the NOAA Office of Global Programs.

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