Characteristic Patterns of Variability of Sea Level Pressure in the Northern Hemisphere

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ABSTRACT

Seasonal and annual mean sea level pressures for the Northern Hemisphere have been analyzed to determine the dominant modes of interannual and longer period variability using monthly sea level pressure analyses as revised by Trenberth and Paolino (1980). Empirical orthogonal function (EOF) analysis is used to reveal the modes which explain most of the variance for the period 1925–77. In winter, Kutzbach’s (1970) EOF 1 for January remains the dominant mode and a closely related pattern dominates all seasons and the annual means. Although there are differences in detail in each season, the dominant mode is basically a high-latitude zonal-index-type pattern with departures in pressure at high latitudes corresponding to anomalies of opposite sign in low latitudes. EOF 1 is linked to the North Atlantic Oscillation, but the north-south fluctuations in mass also occur in the Pacific and, to a lesser extent, elsewhere. Time series associated with this pattern have highly significant spectral peaks at the quasi-biennial and 6-year periodicities. The latter is related to the Southern Oscillation.

Time series associated with higher order EOF’s reveal significant low-frequency fluctuations. In spite of the significant non-randomness present, preliminary attempts at prediction using autoregressive techniques indicate only very limited skill to be possible.

Correlation of sea level pressures with those of Darwin are used to define Southern Oscillation patterns in the Northern Hemisphere. In all seasons and annually, a characteristic pattern is present across the United States. High pressures over the central United States are associated with low pressures in the Pacific and Atlantic, and vice versa. This pattern is often referred to as the North Pacific–North American teleconnection pattern, but it appears that its origins stem from well beyond the North Pacific and that a global perspective is needed before we can hope to fully understand interannual variability.

1. Introduction

The atmospheric circulation is characterized by various “centers of action” which are spatially interdependent. Anomalous atmospheric conditions in one area can affect another area through teleconnections. The objective of this research is to investigate interannual and long-period fluctuations in the Northern Hemispheric circulation and to document the type of patterns that are important. Some preliminary aspects of predictability of these patterns will also be considered.

One method used in this study for revealing the dominant modes of the circulation is empirical orthogonal function (EOF) analysis of the sea level pressure (SLP) fields. With this type of analysis, most of the variance of the pressure fields can usually be represented by only a few EOF patterns and their corresponding time series.

Previous studies of circulation variability using EOF’s include Kutzbach (1967, 1970), Kidson (1975a,b), Trenberth (1975), Davis (1976, 1978), Walsh (1978), Rogers (1979) and Heddinghaus and Kung (1980). Many of these are regional studies designed to study such areas as the Southern Hemisphere (Trenberth, 1975), the Northern Hemispheric polar region (Walsh, 1978) and the North Pacific Ocean region (Davis, 1976, 1978). Heddinghaus and Kung analyzed various meteorological parameters at the 700, 500 and 300 mb levels, but included the annual cycle in their data set and therefore effectively analyzed only the annual cycle. Kutzbach (1967) used EOFs to analyze monthly pressures, temperatures, and precipitation over North America. The only hemispheric EOF analyses of SLP appear to be by Kutzbach (1970), Kidson (1975a) and Rogers (1979). Kidson (1975b) also performed a global EOF analysis.

In dealing with statistics of climatic data over a specified period of time (a climatic state; N.A.S., 1975a,b), Trenberth (1975), Davis (1976, 1978), Walsh (1978), Rogers (1979) and Heddinghaus and Kung (1980). Many of these are regional studies designed to study such areas as the Southern Hemisphere (Trenberth, 1975), the Northern Hemispheric polar region (Walsh, 1978) and the North Pacific Ocean region (Davis, 1976, 1978). Heddinghaus and Kung analyzed various meteorological parameters at the 700, 500 and 300 mb levels, but included the annual cycle in their data set and therefore effectively analyzed only the annual cycle. Kutzbach (1967) used EOFs to analyze monthly pressures, temperatures, and precipitation over North America. The only hemispheric EOF analyses of SLP appear to be by Kutzbach (1970), Kidson (1975a) and Rogers (1979). Kidson (1975b) also performed a global EOF analysis.

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the problem of "climatic noise" arises. The United States Committee for the Global Atmospheric Research Program (N.A.S., 1975) defines climatic noise as statistical fluctuations in finite-time averages arising from day-to-day fluctuations in weather. These fluctuations are inherently unpredictable over time scales of climatological interest. The amplitude of this noise decreases approximately as the square root of the length of the time-averaging interval (Leith, 1973). Both Kutzbach (1970) and Kidson (1975a,b) used monthly means as the basis for their statistical analyses. Kidson's (1975a) study of the Northern Hemispheric circulation was also limited in that it used only ten years (January 1951–December 1960) of SLP data. Kutzbach (1970) analyzed the period 1899–1969 but did not include the polar regions and omitted the World War II years. These omissions result in a discontinuous data set which also contains many missing and erroneous values. Rogers (1979) analysis considered only winter.

In this research, we reconsider the modes of the Northern Hemispheric SLP fields using a thoroughly checked and continuous data base and, by using seasonal anomalies, reduce climatic noise by a factor of about \( \sqrt{3} \). The data set used is the Northern Hemispheric SLP historical map series beginning in 1899, which was also used by Kutzbach (1970). However, an extensive investigation into the quality of these analyses revealed many problems including errors, spurious trends, and discontinuities (Trenberth and Paolino, 1980). The errors have either been corrected or treated as missing, and the major discontinuities have been eliminated, as discussed by Trenberth and Paolino (1980). By using only the last 53 years (1925–77) in the primary analyses of this study, most of the problems with the data set are avoided. For this period, we also are able to include the polar regions in our analyses.

The EOF analysis is performed on each of the four seasons and on an annually averaged series. Time series of the EOFs are subjected to a spectral analysis to determine any non-randomness.

EOF patterns are not of a predetermined form but are determined from inter-relationships within the data set. However, there are some "modes" of variability within the atmosphere that seem to be established from previous studies. These are the Southern Oscillation (SO) (Walker and Bliss, 1932; Troup, 1965; Bjerknes, 1969; Kidson, 1975b; Trenberth, 1976; Wright, 1977; and others) and the Quasi-Biennial Oscillation (QBO) recently reviewed by Trenberth (1980). This study will also consider the evidence for these modes in the Northern Hemisphere SLP data set.

2. Method of analysis

An EOF analysis represents the data by several empirical functions which are determined from inter-relationships within the data set and, since they are orthogonal, efficiently represent the variance of the data fields using just a few EOF's. Each EOF is associated with a time series of coefficients which is orthogonal to the coefficient time series of all other EOF's. These series describe the evolution of the EOF's with time. The EOF's are ordered so that the first EOF explains the largest amount of the total variance of the original data; while subsequent EOF's explain the largest amount of the remaining variance. A thorough review of the formulation and properties of EOF analysis is given by Davis (1976) and a summary is provided by Trenberth (1980). In brief, the EOF's are the eigenvectors of the covariance matrix of the observations at each grid point and time. Associated with each eigenvector is an eigenvalue which corresponds to the variance accounted for by the EOF. We have used the covariance matrix since we are interested in the actual anomalies (departures from normal) that occur.

The data set to be analyzed consists of monthly Northern Hemisphere SLP grids containing 1009 data points, with a resolution of 5° latitude and 5° longitude. Performing statistical analyses on such a large amount of data would not only be beyond our resources, but is also unnecessary since the data are not independent and we are mainly interested in large-scale features of the atmospheric circulation. We therefore consider an alternative grid in which each point is representative of approximately equal area. It is then desirable to perform some averaging on the existing SLP fields in order to make each value representative of the scales we can resolve.

The data were reanalyzed onto a 13 × 13 polar stereographic grid, shown in Fig. 1, with a resolution of 1280 km at 60°N. Eight points were excluded on each corner of the grid, since they were south of 20°N, leaving 137 points. The method of interpolation to the new grid and the averaging procedure were combined in the form of a modified Cressman analysis scheme (Cressman, 1959) as outlined in the Appendix.

Owing to problems in the data set at low and high latitudes (Trenberth and Paolino, 1980), data from the first part of the century were excluded from the EOF analysis and the 53-year period December 1924–November 1977 was used. The early analyses are retained, therefore, as a possible independent data source.

The 53-year means were computed for each month at each grid point and were then subtracted out to give the anomalies. The seasonal anomalies were computed as the mean of the three monthly anomalies: winter (December, January, February); spring
(March, April, May); summer (June, July, August); and autumn (September, October, November). Annual anomaly fields are averages of the four seasonal anomalies.

3. Results

a. Mean fields

The 53-year means of the seasonal and annual fields are shown in Fig. 2. The main difference from the means of Crutcher and Meserve (1970) is the somewhat smoothed appearance which results from the relatively coarse resolution (Fig. 1). Standard deviations of the seasonal mean fields are shown in Fig. 3. It can be seen that the standard deviation in winter is much greater than any other season. The winter anomalies will therefore tend to dominate the annual mean anomalies.

b. EOF analysis

An EOF analysis was performed on the four seasonal and the annual fields. The first 10 eigenvalues, corresponding to the 10 EOF patterns which explain the largest amount of the total variance, are given in Table 1 for each season and the annual fields. These eigenvalues are expressed as a percentage of the total variance. Only a few EOF’s are needed to explain a large part of the variance for each series of fields.

The patterns for the first three EOF’s for each season are shown in Fig. 4 and the first six EOF’s for the annual series are shown in Fig. 5. Note that the sign is arbitrary. In the following discussion, we refer to the seasonal and annual eigenvectors by W, P, S, A, and Y, corresponding to winter, spring, summer, autumn and year, followed by the rank of the EOF.

Similar EOF patterns occur in all seasons. W1, P1, S1, Y1 and A2 all display essentially a high-latitude zonal pattern with a center of action centered over or near the pole and with areas of departures of opposite sign at lower latitudes. They also show centers of actions of opposite sign in the northwestern Pacific and over the northeastern Atlantic–European area, although there are differences in detail in the exact locations.

W2, P2 and Y2 are also similar in many respects and have large centers of departure over roughly the same areas. Common to all three are large departures of the same sign in the North Pacific and Northwest Canada. These patterns, and some others, such as S1, do not have compensating centers of action of opposite sign. Therefore, the fluctuations in these eigenvectors correspond to fluctuations in total mass north of 20°N. Presumably the mass compensation takes place in areas south of our analysis region.

A1, W3 and, to some extent, P3 have some similar characteristics including opposing centers of action over Siberia and the North Atlantic.

Spatial correlation coefficients among the first six EOF’s of each seasonal and annually averaged field, computed from the 137-point grid values, are given in Table 2. In this table significance levels are indicated for a two-tailed test assuming 137 independent points. Owing to the large spatial patterns, however, the points are not independent. We therefore used single-point correlations such as given by teleconnection patterns (e.g., Wallace and Gutzler, 1981) to specify spatial scales. The scale was defined by where the variance explained drops to 50% (correlation of 0.7) and we estimate that there are about 47 independent points, for which the appropriate significance level also has been indicated in Table 2. The similarities among the EOF patterns noted above are confirmed. In particular, the first yearly EOF is very similar to the first EOF in all seasons, except for autumn where it ranks second. This provides some justification for treating all seasons alike in the type of anomalies that can occur. In the following, an attempt will be made to consider interrelationships between seasons using only the annual EOF patterns to define a continuous time series.

c. Coefficient time series

The coefficient time series of the first three EOF’s for each season together with the first six EOF’s for the annual fields are shown in Fig. 6. As can be seen, most of the series are fairly stationary. Two series, however, do appear to contain dominant
low-frequency fluctuations. The time series for Y2 shows a long-term fluctuation and a check at grid points near the centers of action of Y2 revealed that the trend was part of a very low-frequency oscillation in the area over the North Pacific Ocean. Compared with the mean for 1899–1977, pressures were somewhat higher for 1899–1924 and for 1943–77, while pressures were low for 1925–42. One other time series with evidence of long term trends is S3. A check of the monthly mean time series for June, July and August at grid points near the major centers of action revealed that the trends in Fig. 6 were contributed to by all areas. These trends appear to be real. Some high frequency non-randomness also seems to be present in the time series, and this is investigated further later.

In order to consider whether it might be possible to predict the coefficients of the EOF’s in each season from those in previous seasons, the correlations among EOF coefficient time series of each season and the annual average were computed. The correlations, given in Table 3, were computed among seasons in the same year using the sequence W–P–S–A. For example, the correlation between EOF 1 of win-
ter and the following spring is $-0.06$. Only three out of 54 seasonal correlations are significant at the 95% level, which is about what would be expected by chance. Since there are no significant correlations between EOF's whose patterns are similar, there is no physical basis for believing the correlations are significant and will be present in an independent data set.

Several significant correlations do occur between the time series of individual seasons and those of the annually averaged series, also shown in Table 3. This is as expected, since the annual fields are computed from the seasonal fields and thus are not independent.

Correlation coefficients were also computed among spring, summer and autumn of one year and the winter of the following year using the sequence P-S-A-W and are shown in Table 4. There are three seasonal correlations out of 27 significant at the 95% level, somewhat more than expected by chance. One of the significant correlations is between A2 and W1, which exhibit similar departure patterns. This indicates that persistence may be a significant factor in the progression from autumn to the following winter. Persistence may arise from forcing by slowly evolving components of the climate system, such as sea surface temperatures, and thus there is a physical basis for believing that this correlation may hold up. All other cases indicate that the prediction of one season's anomalous SLP distribution from that of a previous season, using the EOF's, will show no skill. Since the EOF's in each season are different, perhaps this is not surprising. Therefore, further aspects are considered in the following sections.

**d. Continuous time series**

An inspection of the coefficient time series indicates evidence of quasi-periodicities. Some show high-frequency, perhaps quasi-biennial, fluctuations while others possess a longer period on the order of ten years or more. Since the EOF process is linear, the annual coefficient time series is simply the average of coefficients from each season generated using the annual EOF patterns. In view of the similarities of some EOF's, especially #1 (see Table 2), we have therefore used only the annual EOF patterns to generate continuous time series of 212 seasonal values which could then be investigated in more detail. The use of 212 rather than 33 values allows us to increase the Nyquist frequency from 0.5 cycle year$^{-1}$ to 2 cycles year$^{-1}$ which substantially reduces aliasing near quasi-biennial frequencies.

In order to determine if any dominant frequencies were present in the Northern Hemisphere SLP distribution, as represented by the EOF's, and to consider persistence and other lag relations, we have performed spectral analyses on the continuous time series. The power spectra were computed for these series after linear detrending and are shown for the first five annual EOF's in Fig. 7. The spectra, computed at lag 64, contain 8.8 degrees of freedom (df) and a bandwidth (bw) of 0.0208 cycles season$^{-1}$. They have been normalized by dividing by the variance so that the total area under each curve is unity and the spectra therefore show the fraction of variance at each frequency. The null hypothesis of white noise has a value of 2.

In order to interpret these spectra, we must con-
Consider the significance of our results in regard to a priori sampling theory. Madden and Julian (1971) comment on this procedure. If we have \( q \) independent spectral estimates in any frequency range, we would expect 5% of our estimates to exceed the 95% value of \( \chi^2/df \). In our case, \( q = 1/2bw = 24 \) and we expect that 1.2 of our spectral estimates should exceed the 95% significance level by chance of each EOF time series. Note, however, that the plots contain 65 points (equal to the number of lags + 1) which are not all independent.

Since we had no prior evidence to indicate any spectral peaks in our analyses, with the possible exception of the QBO, it is necessary, as Madden and Julian (1971) point out, to use a stricter significance test corresponding to a posteriori criteria. Therefore, in order to be reasonably sure that the spectral peaks also will be present in an independent data set, we follow Madden and Julian (1971) and raise the \( \chi^2/df \) significance level to the 99.9% level, in which case 0.065 points would exceed the level \( [\chi^2(0.1\%)/df] \) by chance in each spectral analysis and, even with six time series, we do not expect any points to exceed that level. We are now reasonably
confident that any estimate > 99.9% a priori significance level reflects a periodicity or non-randomness actually present in the data set.

There are two peaks that pass this strict test. The time series of Y1 shows a peak centered at a period of about six years. This is in the range of the period of the Southern Oscillation (Trenberth, 1976). Possible connections between the Northern Hemispheric circulation and the Southern Oscillation will therefore be considered later.

The time series for Y4 shows a highly significant peak centered on a 16-year period and the series for Y2 also shows a peak at the same period which does not quite pass the a posteriori significance test. Although the linear trends were small, both these peaks will be slightly affected (lowered) by the detrending process. We therefore have good evidence for low-frequency oscillations at periods of 16 years or longer. We had expected this result from an examination of the time series.

Although the quasi-biennial peak in Y5 is not sig-

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**Table 1. Variance (mb²) of the seasonal and annual fields, and percentage of variance explained by the first 10 seasonal and annual EOFs.**

<table>
<thead>
<tr>
<th>Season Variance</th>
<th>Winter 929.1</th>
<th>Spring 397.0</th>
<th>Summer 163.2</th>
<th>Autumn 318.1</th>
<th>Annual 140.9</th>
</tr>
</thead>
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<tr>
<td>EO1</td>
<td>Percent</td>
<td>Cumulative</td>
<td>Percent</td>
<td>Cumulative</td>
<td>Percent</td>
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<tr>
<td></td>
<td>variance</td>
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<tr>
<td>1</td>
<td>28.5</td>
<td>23.0</td>
<td>15.9</td>
<td>17.9</td>
<td>20.3</td>
</tr>
<tr>
<td>2</td>
<td>16.0</td>
<td>15.5</td>
<td>12.0</td>
<td>12.6</td>
<td>15.0</td>
</tr>
<tr>
<td>3</td>
<td>10.2</td>
<td>8.6</td>
<td>8.2</td>
<td>9.5</td>
<td>11.0</td>
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<tr>
<td>4</td>
<td>8.1</td>
<td>8.1</td>
<td>7.0</td>
<td>9.0</td>
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<td>5</td>
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<td>5.7</td>
<td>5.1</td>
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</tr>
<tr>
<td>7</td>
<td>5.0</td>
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<td>4.9</td>
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<tr>
<td>8</td>
<td>3.2</td>
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<td>4.2</td>
<td>4.0</td>
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<tr>
<td>9</td>
<td>2.8</td>
<td>3.1</td>
<td>3.9</td>
<td>3.5</td>
<td>3.1</td>
</tr>
<tr>
<td>10</td>
<td>1.9</td>
<td>2.9</td>
<td>3.8</td>
<td>2.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>
significant according to the above criteria, it does include five points, at periods from 2.1 to 2.9 years, above the 95% a priori significance level. This increases the likelihood that the QBO peak can be considered stable and may be part of the worldwide QBO, which appears in many phenomena. A quasi-biennial peak also occurs in Y1 significant at the 99% a priori significance level, and is worthy of further consideration.

In order to assess the amount of variance present in each of these quasi-periodicities, we estimated the area contained under each peak using the width at the half-peak power as the width of the peak. The variance associated with these peaks is given in Table 5. The expected variance of each peak, associated with the white noise continuum, is also given in Table 5, along with the difference between the expected and actual variances. This difference is a rough indication of the variance that may potentially be explained if we could accurately forecast the fluctuations associated with these quasi-periodicities.

Fig. 4. The first three empirical orthogonal functions for each season.
In order to assess the predictability further, the continuous, detrended time series were subjected to an autoregressive analysis. Such analyses make use of only the past values of a time series to predict the future, and we expect some skill to show up because of the quasi-periodicities. Based on the correlograms, autoregressive schemes most appropriate were of order 7 for Y1 and Y5, and order 6 for Y4 (Chatfield, 1975). Autoregression coefficients at all lags up to these were included in the prediction equations although some coefficients at intermediate lags were not significant and may contribute to negative skill in prediction of independent data. The reduction of variance \( \rho \), the expected population reduction of variance \( \rho_0 \) and the expected reduction of variance when the scheme is applied to independent data \( \rho_1 \) (Lorenz, 1977) are given in Table 6. The reductions of variance approach the values on the bottom line of Table 5. However, when the schemes are applied to independent data we
expect two of them to be useless. There is skill in predicting the coefficient of Y4, but Y4 explains only 8.5\% of the total variance (Table 1) and we can therefore hope to predict only about 1\% of the total variance by this means.

The above autoregressive schemes are certainly not the best prediction schemes that can be designed but they do give an indication of the magnitude of the problem of predictability. Even the best schemes can only hope to explain small fractions of the total variance. For example, if the full reductions of variance given in the bottom line of Table 5 could be achieved on independent data, the total variance explained would still be only 4.9\%. However, better schemes which make use of other predictors or pay more attention to seasonal differences, may also be possible (Davis, 1978). Similarly, local areas may be more predictable than the entire hemisphere.
4. Southern Oscillation

Bjerknes (1966) suggests that conditions in the tropical Pacific Ocean are related to the Northern Hemispheric circulation and postulated that anomalously warm sea surface temperatures in the tropical Pacific intensify the Hadley circulation which, in turn, transports increased momentum poleward to intensify midlatitude westerlies. In a subsequent work, Bjerknes (1969) related these anomalous ocean temperatures with the Southern Oscillation of Sir Gilbert Walker (Walker and Bliss, 1932). The Southern Oscillation (SO) is a term used to describe a large-scale exchange of mass, chiefly in the tropics and subtropics, between recognized centers of action over the Indonesian area and the South Pacific. Higher than normal pressures over one center tend to be concurrent with lower than normal pressures over the other.

Kidson (1975b), in an EOF analysis of the tropical regions, found that the Southern Oscillation could be represented by the first EOF of the normalized monthly departure fields of sea level pressure, temperature and rainfall. His analysis also showed a secondary center of action of the SO, in phase with that in the Indonesian area, over Northeast Brazil.

Trenberth (1976) showed that the time scale of fluctuations in the SO is 2–10 years. He used the pressure at Darwin, Australia (12.5°S, 130.9°E) as an index of the SO since it is near one center of action and has a long, reliable record. It has the advantage over other indices that have been suggested in that it is continuous and homogeneous.

In view of the QBO and 6-year spectral peaks found in Y1 (Fig. 7), we have computed correlations between time series at each grid point and Darwin in order to give the teleconnection patterns. These are shown for the 53-year period 1925–77 in Fig. 8. Contours of $r = \pm 0.18, \pm 0.27, \pm 0.35, \pm 0.44, \pm 0.55$ corresponding to the 80, 95, 99, 99.9 and 99.999% significance levels are plotted. The latter are appropriate for a two-tailed test of significance assuming independent data.

There seems to be some consistency in regard to the sign of correlation, but the only area where statistical significance is present in all seasons and in the annual patterns is in the eastern Pacific. Especially interesting with respect to prospects for seasonal forecasting over the United States are the large, and for the most part, statistically significant regions of negative correlation off the eastern and western coasts of the United States, with positive correlations in between. Only in autumn is this pattern poorly defined. As a result of the contrasts in sign in the correlations, these patterns should be reflected in anomalous winds and thus have an impact on temperatures. This is the case in winter (Wright, 1977; van Loon and Madden, 1981).

Correlation fields were also computed using running series of seasonal anomalies of length 212 (winter 1925–autumn 1977), as shown in Fig. 9. The contours of $\pm 0.14, \pm 0.18, \pm 0.22$ and $\pm 0.30$ correspond to significance levels of 95, 99, 99.9 and 99.999% respectively. If we compare this
map with the correlations derived from the annual averages they match very well, with the former retaining the area of high statistical significance off the eastern United States.

5. Discussion

a. EOF patterns

A comparison of our EOF patterns with those published in previous studies shows some significant differences and provides a more general perspective since EOF's have not been previously presented for spring, autumn and annual mean analyses.

Y1 resembles Kidson's (1975 a) EOF 1 for the departures from monthly mean SLP except that he did not show a center of action in the vicinity of the Aleutian low. Not surprisingly, in view of his short data record and since all months were combined in his analyses, Kidson's higher order patterns do not correspond very well to any of our analyses.
The first two EOF’s of Kutzbach’s (1970) analysis for July have features in common with S1 but none of the EOF’s correspond on a one-to-one basis. This is to be expected because S1 contains the major part of its variance over the polar region where Kutzbach had no data and since the orthogonality of the EOF’s puts a constraint on the higher order patterns.

The main features of W1 are very similar to those of Kutzbach’s (1970) EOF 1 for January, in spite of the lack of data north of 70°N in his analyses. Wallace and Gutzler (1981) and Rogers (1979) have recently performed an EOF analysis on winter SLP fields, including the polar regions, and find a similar pattern to W1 in their dominant EOF.

By defining a “seesaw” in winter temperatures between Greenland and Northern Europe, van Loon and Rogers (1978) produced anomalous SLP patterns for winters when a seesaw was present (high temperatures on one side of the Atlantic, low on the

| Table 3. Correlations (×100) among the first three EOF coefficient time series 1925–77 in the sequence W–P–S–A. Single and double underlines correspond to significance levels of 95 and 99%, respectively. |
|---|---|---|---|---|---|---|---|---|---|
| | P1 | P2 | P3 | S1 | S2 | S3 | A1 | A2 | A3 |
| W1 | −06 | 07 | −07 | 17 | 01 | −19 | 16 | 09 | −11 |
| W2 | −03 | −14 | 03 | −09 | 19 | −05 | 04 | 08 | −27 |
| W3 | 07 | 11 | 08 | 05 | 32 | −03 | 00 | −14 | 03 |
| Y1 | 78 | 02 | 05 | Y1 | Y2 | Y3 |
| Y1 | 03 | −16 | −17 | −11 | 18 | 03 | −50 | −03 | −09 |
| Y2 | 12 | −17 | 05 | −27 | 04 | −06 | 10 | −61 | 16 |
| Y3 | 08 | 12 | 01 | −21 | −19 | −18 | 09 | −13 | −21 |
| S1 | −03 | 09 | 08 | Y1 | Y2 | Y3 |
| S2 | 09 | −13 | −10 | 15 | 41 | 51 |
| S3 | −05 | −03 | 21 | −08 | −03 | −16 |
| A1 | 08 | 44 | 35 |
| A2 | −31 | −14 | 11 |
| A3 | −08 | −07 | 11 |
Fig. 6. Coefficient time series of the first three EOF's in each season and the first six EOF's of the annual fields. Units are in millibars.
Fig. 7. Spectra of the 212 continuous seasonal time series values obtained from the annual EOF patterns. The spectra are normalized by the total variance so that the total area under the curve = 1. The null hypothesis of white noise has a value of 2 and is labeled 50%. The 5, 95, 99, and 99.9% a priori significance levels of the spectra, corresponding to 8.8 df, are plotted. The spectra were calculated with 64 lags and the band width is plotted.

other) and winters when a seesaw was not present. The anomalous SLP pattern for the case of a seesaw present in winter also is remarkably similar to W1. The pattern when the seesaw was not operating is very similar to W2 and Kutzbach's (1970) EOF 2 for January.

The seesaw also was identified with the so-called North Atlantic Oscillation (NAO), originally defined by Walker and Bliss (1932). The NAO is a teleconnection pattern with centers of action of opposing sign in the regions of the Icelandic low and the Azores high. Both Kidson (1975a), and Kutzbach (1970) for his January analysis, related their EOF 1 patterns to the NAO.

However, W1 clearly involves much more than the NAO. There is a major center of action in the North Pacific (Kutzbach, 1970) which also was found to be related to the seesaw (van Loon and Rogers, 1978). Further, when the polar regions are fully included in the analysis, the northern center
of the NAO near Iceland is not limited to that area but extends across the pole (see Fig. 4). Wallace and Gutzler (1981) found a similar result and suggest that EOF 1 for winter should not be viewed as a one-to-one correspondence with the NAO. W1 therefore corresponds to a more general high-latitude zonal index pattern. North-south fluctuations in mass occur not only in the Atlantic, but also in the Pacific and, to a lesser extent, elsewhere.

Kutzbach’s (1970) EOF 2 for January differs slightly from W2 in that his pattern shows opposing centers of action in the Pacific. He suggested that this was part of a north-south fluctuation between the Aleutian low and the subtropical high, similar to the NAO, which was classified by Walker and Bliss (1932) as the North Pacific Oscillation. In W2 this compensation in mass occurs mainly south of 20°N. The major centers of action on W3 and Kutzbach’s (1970) EOF 3 for January again are similar, but W3 exhibits aspects of the North Pacific Oscillation. The North Pacific Oscillation recently has been considered in more detail by Rogers (1979).

As shown in the previous section, P1 and A2 have

Fig. 8. Correlations (×100) between the anomalies in sea level pressure at Darwin and grid points in the Northern Hemisphere for each season and the annual fields. Contours of 18, 27, 35, 44 and 55 correspond to the 80, 95, 99, 99.9 and 99.999% significance levels. Correlations significant at the 95% level are shaded.
very similar characteristics to W1, and even S1 has many features in common with these. Viewed in this perspective, it seems that the primary mode of variation in the atmosphere in all seasons, and on an annual scale (cf. Y1), is that of a high-latitude zonal pattern corresponding to fluctuations in mass over the polar regions. In each case, the polar regions are balanced by anomalies of opposite sign in the region south of ~50°N, although in summer part of the mass compensation apparently occurs south of 20°N. In the other seasons there tends to be dominant areas of mass compensation over the oceans in the vicinity of the Aleutian and Icelandic lows, but perhaps these should be considered as seasonally dependent embellishments. Thus, in this context, the NAO is but part of a hemispheric or even larger scale mode of the atmospheric circulation.

The above interpretation is supported by a parallel analysis of zonal mean pressures which shows that there is a strong tendency for changes in pressure in one latitudinal belt to be compensated for elsewhere in the hemisphere 30–40° latitude further north or south (see, also, Brier, 1968). However, there also is a residual such that significant changes occur in the entire area averaged pressure north of 20°N. These results will be reported in more detail elsewhere, following global analysis of seasonal variations in pressure (Trenberth, 1981).

b. EOF time series

Kutzbach (1970) noted that long-term fluctuations were present in his EOF time series, which he suggested reflected changes in the hemispheric circulation. These fluctuations consisted of fairly abrupt changes in the time series in the early to mid-1920’s and the early to mid-1950’s. Although our EOF analysis begins with the winter of 1925, we also have noted a change in circulation in the 1920’s in connection with the time series for Y2. The change in the 1950’s is found only in S3. However, the spectral analyses confirm that long term fluctuations of 16 years or longer are prominent in the Northern Hemisphere SLP distribution. Wagner (1971), in a spectral analysis over the seasonal Northern Hemisphere SLP fields, also noted the

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Table 4. Correlations (×100) between spring, summer, autumn and annual EOF coefficient time series with winter the following year. Single and double underlines correspond to 95 and 99% significance levels.
Table 5. Percentage variance associated with the significant spectral peaks for EOFs 1, 4 and 5. The white noise continuum value is given for comparison, along with the difference.

<table>
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existence of significant long-term fluctuations with a period of about 21 years but parts of his analysis may have been affected by spurious discontinuities in the SLP time series over the Asian region (Trenberth and Paolino, 1980).

Wagner (1971) also found significant power at QBO frequencies, particularly in winter. We have found evidence for a QBO in the power spectra for Y1 and Y5 of our continuous seasonal series (Fig. 7). The only published patterns of the QBO, to our knowledge, are those of Ebdon (1975). He composited SLP patterns for mid-season months corresponding to strong easterly and westerly phases of the QBO in the 30 mb zonal wind at Canton Island, and found significant differences in only January and July. The composited for each month were quite different.

Ebdon’s anomalous SLP pattern in January is somewhat similar to the high-latitude zonal pattern displayed by Y1 and the time series for W1, in particular, exhibits a sawtooth character indicative of QBO character. We have therefore taken the same 10 years used by Ebdon in his January composites and computed the mean values of Y1 and W1 corresponding to the different phases of the QBO. In the westerly phase, both Y1 and W1 are positive and in the easterly phase they are negative. Using a Student t-test on the differences between the means we obtain values of t = 2.04 for Y1 and 2.49 for W1 with eight degrees of freedom. The latter is significant at the 95% level and the former at the 90% level. Note that whereas Ebdon’s composites were for January, our composites are for the 3-month winter season in the case of W1, and for the entire year December through to the following November in the case of Y1. It therefore appears that Ebdon’s QBO in January and that in W1 and Y1 are part of the same phenomenon.

Ebdon’s July pattern is less distinctive and cannot be identified with either Y1 or Y5. Although Y1 and Y5 are orthogonal, their patterns are similar but displaced relative to one another, indicating perhaps that they are but part of an overall progressive pattern. Since the spectral analysis used time series of all seasonal values together, as represented by the annual EOF’s, seasonal differences in patterns are not properly allowed for. It therefore seems that further analysis is required to make a definitive study of the QBO in the surface circulation of the Northern Hemisphere.

Wagner (1971) also found a 5–6 year periodicity in the SLP data over the North Pacific Ocean, which may be related to that found in Y1 (Fig. 7). Along with the Southern Oscillation, this will now be considered further.

c. The Southern Oscillation

Kidson’s (1975b) pattern for the SO in the Northern Hemisphere, as represented by EOF 1 of his global SLP analysis, is similar to the patterns on our correlation maps between annual mean anomalies of SLP at Darwin and both the Northern Hemisphere annual mean SLP anomaly fields (Fig. 8) and the running seasonal SLP anomaly fields (Fig. 9). Wright (1977, 1978) presents a global mapping of correlation coefficients for seasonal SLP

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\text{Table 6. For the autoregressive schemes, the percentage variance explained } \rho, \text{ population reduction of variance } \rho_0, \text{ and expected reduction of variance if applied to an independent sample } \rho_0.
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Fig. 9. Correlations (x 100) between the anomalies at Darwin and in the Northern Hemisphere for the 212 continuous seasonal time series values. Contours of 14, 18, 22 and 30 correspond to the 95, 99, 99.9 and 99.9999% significance levels. Correlations significant at the 99% level are shaded.
fields corresponding to his SO index. These patterns are fairly similar to ours in all seasons.

Fig. 7 revealed that a quasi-periodicity of about 6 years, the approximate time scale of the SO, was present in the continuous seasonal time series for Y1. If we compare the pattern for Y1 (Fig. 5) with the departure pattern corresponding to the correlations between the annual mean SLP anomalies at Darwin and those over the Northern Hemisphere, given in Fig. 10, we see that the patterns have many features in common. They are very highly significantly correlated $-0.74$ over the 137 point grid. The correlation coefficient between the coefficient time series for Y1 and the series of anomalies from the annual mean of SLP at Darwin for 1925–77 is equal to $-0.39$, which is above the 99% significance level.

These results suggest that the SO contributes strongly to the high-latitude zonal pattern present in all seasons of our EOF analysis. It also suggests a possible association of the SO to the other factors contributing to this pattern, including the NAO. However, there is no one-to-one correspondence. We have previously noted that Y1 also contains a QBO, which raises the question of the relationship of the QBO to the SO. Trenberth (1976, 1980) points out that they appear to be different phenomena but perhaps not independent. For instance, no QBO is present at Easter Island (Trenberth, 1976) near one center of the SO. Another complicating factor is the existence of more than one QBO (Trenberth, 1980).

The SO pattern shown in Fig. 10 is very interesting when considered with respect to the climate over the United States. Dickson (1978) made a composite analysis of SLP patterns for five winters (1960–61, 1962–63, 1967–68, 1969–70, 1976–77) which were colder than normal in the eastern United States. The resulting pattern at sea level is very similar to that corresponding to the SO, viz., a low in the Pacific, high over the western United States, and a weak low over eastern Canada. It is also related to the North Pacific–North American teleconnection where anomaly patterns in the Pacific Ocean are related to those downstream over the United States, as extensively investigated by Namias (1951, 1978) and Dickson and Namias (1976).

Clearly the phenomenon of the SO is a global mode of the atmospheric circulation, and it is related to large-scale SLP anomalies in the Northern Hemisphere. Therefore, it seems that a global perspective is essential before the source of these large-scale anomalies can be fully understood.

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Fig. 10. Departure pattern of pressures in the Northern Hemisphere corresponding to the correlations in Fig. 8e. Values have been unnormalized by multiplying by the standard deviation, given in Fig. 3e, and correspond to the departure in $10^{-2}$ mb associated with a 1 standard deviation departure ($=0.64$ mb) in pressure at Darwin.

6. Conclusions

The Northern Hemisphere SLP data set from January 1899–December 1977, as refined by Trenberth and Paolino (1980), has been reanalyzed onto a 137 point polar stereographic grid covering the Northern Hemisphere to about $20^\circ$N. Seasonal and annual mean anomaly fields for the period winter 1925–autumn 1977 were then subjected to various statistical analyses.

Results of an EOF analysis showed that a pattern which explained a large fraction of the variance for all seasons and the annual means consisted of a basically zonal circulation at high latitudes. Departures in pressure at high latitudes correspond to anomalies of opposite sign at lower latitudes. A prominent part of this pattern is related to the NAO, but it involves much more than the NAO, since north-south fluctuations in mass occur not only in the Atlantic but also in the Pacific and, to a lesser extent, elsewhere. Although this was recognized by Kutzbach (1970) and others for winter, very similar patterns occur in every season.

The second EOF for winter and spring displays a pattern which seems to involve an exchange of mass with the region south of $20^\circ$N. Spatial correlation coefficients among the first six EOF's in each season confirmed the similarity of several
seasonal EOF's to the annual EOF's. As a result, spectral analysis of the time series was limited to a set of continuous seasonal coefficient time series generated using the annual EOFs for winter 1925–autumn 1977. Results revealed that a highly significant long term fluctuation with a period of about 16 years was present in Y4. A QBO was found in Y5 and Y1, and the latter is similar to the Northern Hemisphere QBO pattern presented by Ebdon (1975) at the surface for winter. However, further investigation into the QBO is warranted in order to consider in more detail the relationship of Y1 to Y5, and it also seems desirable to take further account of seasonal character.

The SO patterns resemble those of Kidson (1975b) and Wright (1977, 1978), and the departure pattern corresponding to the correlations between annual mean SLP anomalies at Darwin and those over the Northern Hemisphere (Fig. 10) has many features related to the Y1 pattern. The spectral analysis of the time series of Y1 revealed a significant quasi-6-year oscillation which further suggests an association between the Southern Oscillation and the high-latitude zonal pattern present in all seasons of our EOF analysis. Fig. 10 also resembles a composite SLP pattern produced by Dickson (1978) for winters where colder than normal temperatures were experienced in the eastern United States. This suggests that the SO also is related to the North Pacific—North American teleconnection pattern.

The phenomenon of the Southern Oscillation is evidently a global mode of the atmospheric circulation. From the relationships outlined above, we infer that anomalies in the Northern Hemisphere circulation north of 20°N are at least partly coupled to influences in the tropics and the Southern Hemisphere. It therefore seems that a global perspective is essential before we can hope to fully understand their source. Trenberth (1981) has provided a background for such a perspective.

The coefficient time series of each season were generally uncorrelated with the time series of other seasons, indicating no significant relationships between the seasonal EOF's at lag, with the possible exception of persistence from autumn to winter. Autoregressive schemes were also fit to the time series in order to further investigate predictability but with disappointing results. It appears that the prediction of future seasonal SLP anomaly patterns from present anomaly patterns will show limited skill, although further possibilities may exist through utilization of lag relationships in the Southern Oscillation.

Acknowledgments. This research was sponsored by the Climate Dynamics Program, Division of Atmospheric Science, National Science Foundation under Grants ATM78-19318 and ATM79-16485.

APPENDIX

Method of Reanalysis

We consider the original analyses as constituting the data points for the new analyses. Missing data were given zero weight and grid points with no available data for a particular month had their analyzed value set to missing. The Cressman weighting scheme was adopted initially and only data within a scan radius $R$ of each gridpoint are considered. The scan radius used was $R = 0.866$ grid lengths and only one scan of the data is made. This provides a method of interpolating to the new grid while still including some smoothing. Fig. A1 gives the number of "observations" within this radius $R$ at each new grid point. Owing to the convergence of meridians, there are more data points per area at high latitudes. Therefore, this method would bias the new analyses towards higher latitude values unless the Cressman weights are modified. An additional factor is therefore applied to the Cressman weights so that each latitude is equally represented. To further avoid any possible systematic bias from the distribution of data points, it was also desirable to first subtract out a mean field and perform the analyses on the anomalies. Since the anomalies are random in sign and location, any bias remaining in our analysis should be extremely small. The means used were the monthly means for the period January 1899—December 1977. The mean fields were interpolated, without smoothing, to the new grid and added onto the anomaly fields to produce the new pressure analyses.

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Fig. A1. The number of observations within the scan radius $R = 0.866$ grid lengths at each grid point.
REFERENCES


