Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation

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ABSTRACT

Atmospheric phenomena associated with the Southern Oscillation are examined, with emphasis on vertical structure and teleconnections to middle latitudes. This paper is specifically concerned with the interannual variability of seasonal means for the Northern Hemisphere winter during the period 1951–78. Among the variables considered are sea surface temperature in the equatorial Pacific, precipitation at selected equatorial Pacific stations, a “Southern Oscillation Index” of sea level pressure, 200 mb height and tropospheric mean temperature at stations throughout the tropics, and Northern Hemisphere geopotential height fields. Selected statistics derived from surface data also are examined for the period 1910–45. Results are presented in the form of time series and correlation statistics for the variables listed above.

Results concerning the relationships between sea surface temperature, sea level pressure and rainfall are consistent with the major conclusions of previous studies by J. Bjerknes and others. Fluctuations in mean tropospheric temperature and 200 mb height are shown to vary simultaneously with equatorial Pacific sea surface temperature fluctuations, not only in the Pacific sector, but at stations throughout the tropics. The zonally symmetric component of these 200 mb height fluctuations is considerably larger than the Southern Oscillation in 1000 mb height, and the corresponding fluctuations in the mean temperature of the tropical troposphere are on the order of nearly 1 K.

The correlations between the tropical time series and Northern Hemisphere geopotential height fields exhibit well-defined teleconnection patterns. Warm episodes in equatorial Pacific sea surface temperature tend to be accompanied by below-normal heights in the North Pacific and the southeastern United States and above-normal heights over western Canada.

Recent theoretical work by Opsteegh and Van den Dool (1980), Hoskins and Karoly (1981) and Webster (1981) on Rossby wave propagation on a sphere provides a basis for understanding the teleconnection in terms of the distribution of sea surface temperature and rainfall in the equatorial Pacific. The theory successfully explains several characteristics of the observed teleconnection patterns, including their horizontal scale and shape, their vertical structure and their seasonal dependence.

1. Introduction

In a remarkable series of research papers, Sir Gilbert Walker described year-to-year fluctuations in sea level pressure, surface air temperature, and precipitation which exhibited a distinctive global-scale teleconnection pattern extending over the Southern Hemisphere and a large part of the Northern Hemisphere (Walker [1923, 1924, 1928], Walker and Bliss [1932, 1937]; for a thorough review of the papers by Walker, see Montgomery [1940]). In this so-called Southern Oscillation, sea level pressure anomalies in the low-pressure belt over Australia and Indonesia tend to be of opposite sign compared to the pressure anomalies in the South Pacific anticyclone. The reality of the Southern Oscillation has been confirmed in more recent studies by Troup (1965), Berlage (1966), Trenberth (1976), and many others. Extratropical meteorological variables that Walker believed to be influenced by the Southern Oscillation during the Northern Hemisphere winter season include rainfall in the Hawaiian Islands, temperature in western Canada, and sea level pressure over the southeastern United States. These relationships have been verified by Wright (1977, 1978) using a large set of more recent data.

Walker and Bliss (1932) noted that the sign of the pressure anomalies associated with the Southern Oscillation is remarkably persistent over several seasons, but they were unable to identify the physical processes responsible for this long-term memory. It wasn’t until nearly 40 years later that Bjerknes (1969) showed that the Southern Oscillation is linked to low-frequency temporal fluctuations in sea surface temperature in the
equatorial Pacific Ocean, from which it presumably derives its memory.

As a result of the work of Bjerknes and others [for a recent review see Julian and Chervin (1978)] the Southern Oscillation has come to be viewed as but one of a number of manifestations of atmospheric fluctuations associated with alternating episodes of warm and cool sea surface temperature in the equatorial Pacific. The warm episodes which have occurred at irregular intervals and lasted typically from one to two years, tend to be characterized by the following atmospheric conditions:

1) Above-normal sea level pressure in the Australia-Indonesia trough region together with the weakening of the subtropical high in the Southeast Pacific. These conditions correspond to the negative phase of the Southern Oscillation as defined by Walker (Bjerknes, 1969; Quinn, 1974; Julian and Chervin, 1978).

2) Weakening or reversal of the easterly winds in the equatorial central Pacific, which constitutes an interruption of the climatological mean east-west circulation cell in this sector (Ichiy and Peterson, 1963; Wyrtki, 1975).

3) Sharply enhanced precipitation at equatorial stations to the east of 160°E (Dobrytz, 1968; Quinn and Burt, 1972; Flohn and Fleer, 1975).


5) Teleconnections to extratropical latitudes including a deepening and southward displacement of the Aleutian low during the Northern Hemisphere winter season (Bjerknes, 1966, 1969, 1972; Rowntree, 1972; White and Walker, 1973; Namas, 1976).

As a matter of convenience, throughout the remainder of this paper, we will refer to the time periods in which the above conditions prevail as "warm episodes".

In the present work we will review the seven major warm episodes that have occurred since 1950, emphasizing anomalies in the upper air circulation, both in the tropics and in the Northern Hemisphere extratropics during the Northern Hemisphere winter season. By placing the temporal correlations noted by Walker and Bliss (1932) and Wright (1977) in the context of the upper air patterns we hope to lay the groundwork for a dynamical interpretation of teleconnections between tropical and extratropical latitudes on these long time scales. Throughout the paper we will tend to emphasize simultaneous relationships between seasonally averaged statistics. However, we will have occasion to mention some of the more important non-simultaneous relationships that have been pointed out in other papers.

Our analysis strategy is based on the view that the atmospheric fluctuations on the seasonal time scale are a (virtually) simultaneous response to the boundary forcing from the sea surface temperature field. It is this same perception of the phenomenon that motivated the general circulation model sensitivity experiments of Rowntree (1972, 1976, 1979) and Julian and Chervin (1978). We believe that this approach has merit for elucidating the dynamical relationships between those atmospheric and oceanic fluctuations which are essentially simultaneous on the seasonal time scale. Of course, it does not allow us to address the cause of the sea surface temperature fluctuations or the nature and causes of non-simultaneous relationships.

2. Preliminary data processing

This study is primarily based on monthly mean statistics for the 28-year period 1951-78. Data sources are listed in the Appendix. Missing or obviously misreported monthly means were replaced by the average values of the means for the previous and following months. Monthly means for December, January and February (DJF) were averaged to obtain seasonal means: for example, the 1970 DJF seasonal mean consists of an average of the monthly means for December 1969, and January and February 1970. If two or more consecutive months of data were missing (as it was in three cases for the 200 mb height records) no interpolation was done and the season was considered missing. None of the time series used in this study were filtered or detrended.

3. Sea surface temperature

Fig. 1a shows the spatial pattern associated with the first eigenvector of monthly mean sea-surface temperature (SST) anomalies for the Pacific Ocean, based on the analysis of Weare et al. (1976). This pattern explains 23% of the total SST variance. The large amplitudes along the equatorial belt are a reflection of the large interannual variability of SST and the large east–west spatial coherence of

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3 The following exchange between R. Montgomery and Sir Gilbert Walker is of interest (Montgomery, 1940). Montgomery wrote, "It is difficult to find any suggestion of an explanation for a close connection of temperature and pressure in North America with the Southern Oscillation, so it seems to me a mistake to include these, as well as Hawaii rain, in the definition of the oscillation." Walker replied, "I think the relationships of world weather are so complex that our only chance of explaining them is to accumulate the facts empirically; there is a strong presumption that when we have data of the pressure and temperature at 10 and 20 km, we shall find a number of new relations that are of vital importance." The empirical evidence of the relationships of North American temperature and Hawaii rain seem to me satisfactory and I regard myself as logically bound to include them as factors in the oscillation."
anomalies in that region. The time series of the amplitude of this spatial pattern is shown in Fig. 1b, where positive values are indicative of a warm equatorial Pacific and a cold central North Pacific. The product of the ordinate in Fig. 1b times the amplitude contours in Fig. 1a gives the local value of the temperature anomalies associated with this coherent standing wave pattern. For example, during the period of large positive excursions during 1957–58 temperature anomalies associated with this pattern reached about +1.5°C in the eastern equatorial Pacific and −0.4°C in the central North Pacific. (Actual anomalies in these regions are somewhat different, since they also depend on the amplitudes of the higher numbered modes.)

Although the time series in Fig. 1b has not been subjected to any smoothing, it shows remarkably strong month-to-month autocorrelation with distinctive warm episodes in 1951–53, 1957–59, 1963–64, 1965–66, 1969–70, 1972–73 and 1977–78, separated by colder periods. Allison et al. (1971) have obtained a very similar time series by averaging sea surface temperature in the belt extending from 5°N to 5°S and 80°W to the Date Line.

Fig. 2 shows an abridged version of the time series of the same eigenvector pattern (the solid curve), formed by plotting only the mean values for the Northern Hemisphere winter season (DJF) and assigning them to the calendar year in which January and February fall. The time series shown in Fig. 2 has been normalized by subtracting the long-term mean from each seasonal mean, and dividing by the corresponding standard deviations. Also shown in this figure, for the sake of com-

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parison, are values of SST averaged over the region bounded by 5°N–5°S and 180–140°W, based on the analysis of F. Miller of the U.S. National Marine Fisheries Service and kindly provided by K. Wyrski. It can be seen that the two time series are very similar. The shading, which constitutes our subjective definition of the warm episodes, is repeated in some of the subsequent figures in this paper.

It should be noted that there is nearly (but not quite) a one-to-one correspondence between the "warm episodes" defined in Fig. 2 and the so-called El Niño events consisting of anomalously warm sea surface temperatures along the South American coast. The onsets of the El Niño episodes have occurred close to the Januaries of 1951, 1953, 1957, 1965, 1969, 1972 and 1976 (Quinn et al., 1978; Rasmusson and Carpenter, 1981). The peaks of the El Niño events along the South American coast are observed to occur about 3–6 months after their onset. The region of anomalously warm SST expands and propagates westward, reaching the central Pacific by the following fall or winter (Hickey, 1975; Barnett, 1977; Rasmusson and Carpenter, 1981). Hence the peaks in Fig. 1b lag the maximum temperatures along the South American coast by 4–8 months, and the warm episodes defined in Fig. 2 lag one calendar year behind the calendar years of the corresponding El Niño events.

4. Rainfall at equatorial Pacific stations

In order to demonstrate the strength of the relationship between episodes of warm sea surface temperature and rainfall at equatorial Pacific island stations during the Northern Hemisphere winter season, in Fig. 3 we have shown time series of rainfall at Tarawa, Canton, Christmas and Fanning. The locations of these island stations are indicated in Fig. 1a. All four time series show a tendency for enhanced precipitation during the warm episodes. However, on close inspection the series exhibit some marked differences. For example, the first warm episode, which took place during the early 1950's, was accompanied by enhanced precipitation at Tarawa and other stations located to the west of the dateline during three consecutive winters. A similar enhancement was observed at Fanning, although it was not as pronounced. At Christmas the enhancement was limited to the later part of the winter of 1952–53, and at Canton, no enhancement was observed at all during this warm episode. As expected from a comparison of Figs. 2 and 3 the time series of equatorial island rainfall are all well correlated with one another and with the SST Index (see Table 1).

The spatial structure of the precipitation anomalies has been described by Doberitz (1968) and Wright (1977). Changes in equatorial rainfall during warm episodes may also be inferred from the changes in satellite-derived brightness and outgoing infrared data shown by Krueger and Gray (1969), Krueger and Winston (1974, 1979), Murakami (1975), Sadler (1980) and Heddinghaus and Krueger (1981). The region of enhanced cloudiness and precipitation during the warm episodes as inferred from these works, will be related to other variables in Fig. 11.

It is interesting to note that the Galapagos Island stations, such as San Cristobal (0°54'S, 90°W), showed a strong enhancement of precipitation in March, April and May of 1953, 1957, 1965, 1969 and 1972; close to the times of the maximum sea surface temperature anomalies near the South American coast (Taylor, 1973; Donguy and Henin, 1980). These stations showed no appreciable enhancement of precipitation during the subsequent DJF season, in contrast to the stations further to the west.

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5. Tropical sea level pressures

As mentioned in the Introduction, the sea level pressure fluctuations associated with the fluctuations in sea surface temperature have a structure suggestive of an east-west standing wave; sea level pressure anomalies in the Indonesian region are negatively correlated with those in the southeast Pacific high pressure belt. To document the changes in sea level pressure near the two antinodes or “centers of action” of this standing wave, time series of DJF seasonal mean sea level pressure at Darwin and Tahiti will be used. The correlation between the Darwin and Tahiti time series is −0.67 during the period 1951–78. [Trenberth (1976) obtained a similar value using data for the entire year and a somewhat different period of record.] For our purposes it will be convenient to define as a Southern Oscillation Index the difference between the normalized sea level pressure anomalies at Tahiti and Darwin as suggested by Trenberth (1976). A positive value of the Index is indicative of a strong South Pacific trade wind circulation and equatorial easterlies. To allow easy comparisons between the time series of Figs. 2 and 3 and the Southern Oscillation Index, the Index has been normalized, inverted and plotted in Fig. 4. The correlations between the Southern Oscillation Index and the time series of Figs. 2 and 3 are shown in Table 1.

It is apparent from a comparison of Figs. 2, 3 and 4 and from an inspection of the correlation coefficients listed in Table 1 that the fluctuations in the Southern Oscillations are strongly related to variations in sea surface temperature but are not quite as directly associated with the equatorial rainfall fluctuations described in the previous section. There is a one-to-one correspondence between the minima in the Southern Oscillation Index and the warm episodes indicated by the shading, except for the fact that the 1964 and 1966 episodes are not separated in this abridged time series. (The Index did actually exhibit a distinct maximum between these two episodes with positive values from February through November 1964.)

Trenberth (1976) has noted that changes in sea level pressure in the two centers of actions of the Southern Oscillation do not occur simultaneously, i.e., pressures in the Australian-Indonesian region usually rise a season or two later than the weakening of the anticyclone in the southeast Pacific. Recent work by Quinn (1974, 1978), E. Rasmusson and ourselves suggests that when the sea surface temperatures are beginning their sharp rise along the coast (usually in January) prior to a major El Niño event, sea level pressures at Rapa (27°S, 144°W) and Easter (27°S, 109°W) are already below normal while pressures at Tahiti are falling but are still near normal. Our Tahiti minus Darwin Southern Oscillation Index doesn’t reach its minimum value until the following September by which time sea surface temperatures may already be falling along the coast of South America.

6. Tropical 200 mb height

Fig. 5 shows the locations and lengths of record for 10 stations which constitute our primary set of 200 mb height data. These stations were chosen because they are widely separated and have relatively long records. The primary data set was augmented by shorter records for another 22 tropical stations. Time series of normalized seasonal anomalies were calculated for each of the primary stations using the

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7 Personal communication.
same procedure that was outlined in Section 3 for
the sea surface temperature index. Station means
and standard deviations are based on the periods of
record starting with the years indicated in Fig. 5
and ending in 1978.

The first column of Table 2 shows the mean 200
mb height at each of the stations in our primary
data set. The corresponding standard deviations,
presented in the second column of Table 2, give an
indication of the interannual variability of DJF
seasonal (Northern Hemisphere winter) mean 200
mb height. The standard deviations are much larger
than the “noise” resulting from random errors in
the temperature sensors of the radiosondes. 8 The
interannual variability appears to be considerably
larger at the mid-Pacific stations (Hilo and Tahiti)
than at the other stations listed in Table 2. The
Australian region exhibits the smallest variability.

Since the fluctuations in sea level pressure at
Darwin and Tahiti are roughly equivalent to 8 m
changes of 1000 mb geopotential height (see Tren-
berth, 1976), it is evident that the 200 mb height
fluctuations at all the stations listed in Table 2 are
at least twice as large as the 1000 mb height fluc-
tuations near the centers of action of the Southern
Oscillation. Hence, there must exist a strong
temporal correlation between 200 mb height and
1000–200 mb thickness at tropical stations; i.e.,
above-normal 200 mb height is indicative of a warm
troposphere (locally).

Fig. 6 shows the time series of normalized DJF
seasonal 200 mb height anomalies for each of
the ten primary tropical stations. Immediately ap-
parent is the similarity between most 200 mb height
time series with a tendency for high values during
the warm episodes and lower values in between.
This tendency is apparent even at stations far from
the Pacific.

Widespread spatial coherence in the upper
tropospheric geopotential height field has been

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8 Typical rms errors in the temperature sensors of radiosondes
are on the order of 0.3°C. The corresponding rms error in
individual determinations of 200 mb height should be on the order
of 15 m. At stations which take one sounding per day, up to 90
individual soundings enter into the determination of seasonal
means. Hence the rms error in seasonal means should not be
more than a few meters. A potentially more important source
of uncertainty are any systematic biases in temperature sensors
which might have been present during the earlier part of the
record at some stations. The records for Abidjan and Tahiti are
particularly suspect in this regard because the French
radiosondes are known to have exhibited large biases during the
earlier part of the record.

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| Table 2. Matrix of contemporaneous correlation coefficients (×100) between time series consisting of Northern Hemisphere
| wintertime (DJF) seasonal means of 200 mb height at our ten primary stations. The mean (€) and standard deviation (σ) for every
time series are also given (gpm). The numbers of Northern Hemisphere winter seasons used in these calculations are shown in Table 3. |
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shown to exist within short time intervals by previous studies. Monthly mean 200 mb heights for three consecutive Novembers (1963–65) were compared by Bjerknes (1972) who was surprised to find year-to-year differences of the same sign throughout the tropics with 1964 heights being lower than those in 1963 and 1965. This “dip” is prominent in nearly all the curves in our Fig. 6. (Note that November 1964 would be considered part of our 1965 winter.) Kraus (1977) found that 52 out of 55 radiosonde stations between 30°S and the equator which he examined exhibited negative 500 mb height anomalies during the 1972 Northern Hemisphere winter season. Negative anomalies are also evident in our Fig. 6 for that season.

The contemporaneous correlation coefficients between the 200 mb time series for all possible pairs of stations in the primary data set are all positive as shown in Table 2. (The number of seasons used in computing each of the correlations in Table 2 is listed separately in Table 3.) Although it is apparent from Fig. 6 that the data from the 1970’s makes a strong contribution to these positive correlations, the similarity between some of the longer and possibly more reliable time series such as Hilo and Nandi or Darwin and San Juan is quite impressive.

A time series representative of these simultaneous fluctuations in the tropical 200 mb height field was generated by determining the first principal com-

Fig. 6. Time series of normalized 200 mb height for the Northern Hemisphere winter (DJF) seasonal means at each of the primary tropical stations. Gaps in the time series indicate a season with 2 or more months of missing data. Shading as in Fig. 2.
TABLE 3. The number of Northern Hemisphere winter (DJF) seasonal means used in determining the contemporaneous correlation coefficients shown in Table 2.

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The component of DJF seasonal mean 200 mb height at Nairobi, Darwin, Hilo, Nandi and San Juan for the period 1951–78. (These five stations were chosen because of their location and their complete and reliable records.) The procedure involves diagonalizing the temporal correlation matrix generated from the normalized time series for these five stations. The same procedure was used by Wright (1977)² for generating a sea level pressure Index for studying the Southern Oscillation. Our 200 mb Index, after normalization to unit variance, is given by

\[ Z_{200} = 0.20z^* \text{ (Nairobi)} + 0.23z^* \text{ (Darwin)} + 0.23z^* \text{ (Nandi)} + 0.25z^* \text{ (Hilo)} + 0.27z^* \text{ (San Juan)}, \]

where, for example, \( z^* \) (Nairobi) represents a normalized departure of a particular DJF season from the mean 200 mb height at Nairobi, averaged over the 28 Northern Hemisphere winter seasons. This particular linear combination explains 71% of the total normalized variance of 200 mb height for the five stations, which is the most that any single linear combination can explain. Inspection of (1) reveals that the stations are weighted almost equally. The correlation coefficients between \( Z_{200} \) and 200 mb height at each of the stations in our primary data set are listed in Table 2. It is evident that the Index is highly correlated with 200 mb height, not only at the stations used in computing it, but also at Cocos Island, Guam and Lima. The correlations with the French stations (Abidjan and Tahiti) are much lower, but still positive (were it not for the spurious trends in these two records, the correlations might be much higher; note in Table 2 that these stations are more highly correlated with each other than with any of the other stations, even though they are halfway around the world from one another).

The time series of our 200 mb Index is shown in Fig. 7. It is clear that the 200 mb height Index tends to be above normal during the warm episodes, denoted by the shading in Fig. 7. The correlation coefficient between the 200 mb height and sea surface temperature Indices is +0.80 as shown in Table 1.

The Index defined in (1) was used as a basis for compositing 200 mb height data at 32 radiosonde stations between 30°N and 30°S. Tropical radiosonde stations with data from 1958 through 1978 (and some in selected locations with shorter records) were used to provide better spatial coverage than that provided by our primary 200 mb height data set. Seasonal mean 200 mb heights averaged for the four Northern Hemisphere winters which exhibited the largest positive values of the 200 mb Index (1958, 1964, 1973, 1978) are shown in Fig. 8a; while corresponding values for the four winters with the largest negative values of the Index (1965, 1972, 1974 and 1976) are shown in Fig. 8b. The differences in average 200 mb heights between the two sets of winters, which gives a rough indication of the peak-to-peak amplitude of these fluctuations, is shown separately in Fig. 8c. From an inspection of these figures it is evident that the largest differences in average 200 mb heights are observed at the central Pacific stations (Hilo and Tahiti); the small differences at the Australian stations should be regarded as reliable, since the Darwin time series was shown to be strongly correlated with the 200 mb Index.

Since the 200 mb height anomalies are indicative of thickness anomalies in the 1000–200 mb layer, it follows that the episodes of above-normal sea surface temperatures in the equatorial Pacific are characterized by above-normal temperatures throughout the tropics and throughout the depth of
the troposphere. This conclusion is consistent with the results of Walker and Bliss (1932), Kidson (1975) and Wright (1977) relating the Southern Oscillation with surface temperature fluctuations. If we assume that the difference in 200 mb height, averaged over the tropics, between “high and low 200 mb Index” Northern Hemisphere winters (the contrasting conditions in Fig. 8) is on the order of 50 m, then the corresponding difference between the mean temperature of the tropical troposphere should be on the order of 1 K. (This estimate is based on the assumption that sea level pressure, averaged over the entire tropics is almost the same for the “high and low 200 mb Index” winters, so that 200 mb height and 1000–200 mb thickness changes are synonymous).

Angell and Korshover (1978; their Fig. 7) have provided direct evidence of fluctuations in the mean temperature of the tropical troposphere with warm episodes being slightly less than 1 K warmer than cool episodes. Their time series of tropical temperature, derived from surface-to-100-mb thickness, averaged for six stations between 10°N and 10°S, bears a strong similarity to the time series of 200 mb height shown in this paper. Newell and Weare (1976) and Newell (1979) obtained similar results based on data for 700–300 mb thickness. Time series of 700–200 mb thickness at selected tropical stations for the winters from 1955 through 1968 also closely resemble the time series shown in Fig. 6 (Rowntree, 1979).

7. Teleconnections with Northern Hemisphere extratropical latitudes

Several of the time series described in the previous sections were correlated with gridded DJF seasonal mean sea level pressure, 700 mb and 300 mb geopotential height and 1000–700 mb thickness data for the Northern Hemisphere poleward of 20°N, for the 28-year period 1951–78. The data source is listed in the Appendix. Results are presented in Fig. 9 for 700 mb height correlated with (a) Weare’s sea surface temperature Index (Fig. 2), (b) Fanning rainfall (Fig. 3), (c) the Southern Oscillation Index (Fig. 4), and (d) the 200 mb height Index (Fig. 7). All four maps are characterized by similar patterns, which indicate that conditions in the tropics associated with warm SST episodes in the equatorial Pacific are usually accompanied by negative 700 mb height anomalies in a broad belt across the North Pacific extending westward into Siberia, positive anomalies over western Canada, and negative anomalies over the south-
eastern United States. The correlation patterns in Fig. 9 resemble the pattern derived by Wright (1977, 1978) on the basis of correlations between his Southern Oscillation Index and surface temperature at Northern Hemisphere stations. Since mid-latitude, wintertime climatic anomalies tend to have an equivalent barotropic structure, with positive correlations between 700 mb height and surface temperature, the similarity between Wright's patterns and the patterns in Fig. 9 is not surprising.

The shapes of the patterns derived by correlating the tropical Indices used in this section with the Northern Hemisphere sea level pressure, 300 mb height and 1000–700 mb thickness fields are, for
the most part, quite similar to the correlation patterns shown in Fig. 9. These figures will not be shown here, but are available from the authors on request. The correlations near the centers of action are generally stronger at the 700 and 300 mb levels than at the surface. Correlations between the tropical Indices and the 1000–700 mb thickness are rather weak for the subtropical center of action in the west Pacific but of comparable strength to the 700 mb height correlations in the vicinity of the higher latitude centers of action.

The pattern in Fig. 9 contains elements of the Pacific/North American (PNA) and west Pacific (WP) teleconnection patterns described by Wallace and Gutzler (1981). The former pattern has long been recognized as being of importance in long-range forecasting because of its influence on winter temperatures over the eastern United States (e.g., see Namias, 1969; Dickson and Namias, 1976). As a basis for documenting the year-to-year variability of these patterns we have generated Indices similar to those used by Wallace and Gutzler but having the reverse polarity in order to be compatible with Fig. 9:

**PNA Index** = \( z^* \) (55°N, 115°W) – \( \frac{1}{2}(z^* \) (45°N, 165°W) + \( z^* \) (30°N, 85°W)),

**WP Index** = \( \frac{1}{2}(z^* \) (30°N, 155°E) – \( z^* \) (60°N, 155°E)),

where \( z^* \) represents a normalized departure of a particular winter season from the 1951–78 mean 700 mb height for that particular grid point. The locations of the centers of action in these formulas are indicated in Fig. 9d (heavy dots for the PNA Index and open circles for the WP Index). The PNA Index defined in Wallace and Gutzler’s paper includes a fourth center of action (20°N, 160°W) near Hilo; we have purposely eliminated that grid point from the Index used in this paper in order to avoid “building in” a correlation between the PNA Index and the 200 mb height Index defined in (1), which includes data for Hilo. Time series of the two extratropical Indices are displayed in Fig. 10 and correlation coefficients between them and the various Indices described in previous sections are listed in Table 1.

Arkin et al. (1980)9 have recently undertaken a more comprehensive study of correlations between seasonal mean values of the Southern Oscillation Index (Tahiti minus Darwin sea level pressure) and the Northern Hemisphere 700 mb height field, including lag correlations as well as simultaneous

correlation between sea surface temperature averaged over the region 10°N–10°S and 180°W–90°W and Hawaiian rainfall (Wright, 1979).

2) There are negative mid-tropospheric geopotential height anomalies over the North Pacific, which should be reflected in the sea level pressure field, since low-frequency fluctuations in this region tend to be highly barotropic (Blackmon et al., 1979); hence the pattern in Fig. 11 is consistent with Bjerknes' (1966, 1969) and Namias' (1976) observations concerning the Aleutian low.

3) There are positive mid-tropospheric geopotential height anomalies over western Canada, which should be more strongly reflected in surface temperature than in sea level pressure since low-frequency fluctuations in this region tend to be highly baroclinic (Blackmon et al., 1979). This result is consistent with the teleconnection patterns of Walker and Bliss (1932) and Wright (1978).

4) There is a negative anomaly center over the southeastern United States which should be reflected in both surface temperatures and sea-level pressures, since Blackmon et al. found that sea level pressure, 500 mb height and 1000–500 mb thickness are all positively correlated with one another in this region. Hence the pattern in Fig. 11 is consistent with the inclusion of Charleston, South Carolina sea level pressure in the Southern Oscillation Index of Walker and Bliss and with the surface temperature correlations reported by Wright (1978).

As a further confirmation of these relationships we have composited selected meteorological surface data for 12 winter seasons within warm episodes which took place during the period 1910–45, as determined from the rainfall record at Fanning and substantiated by inspection of partial records for neighboring stations on Christmas, Malden and Washington Islands. The DJF seasonal rainfall totals for the 12 wettest winters at Fanning prior to 1957 are listed in the first column of Table 4, together with the mean and median for the period 1910–45. The time series of Darwin sea-level pressure displayed in Fig. 4 of Trenberth (1976) shows distinct maxima corresponding to each of these wet episodes at Fanning; however the 1924 and 1928 events show up only very weakly. Also, all the preceding calendar years have been identified as El Niño years by Quinn et al. (1978) with the exceptions of 1914 and 1928. Seasonal means for Honolulu (21°N, 158°W) rainfall, Dutch Harbor (54°N, 167°W) sea level pressure, Edmonton (54°N, 113°W) temperature, and Jacksonville (30°N, 82°W) temperature for each wet episode are listed in subsequent columns of Table 4. These stations are indicated as dots in Fig. 11.

The resulting composite anomalies are all statistically significant at probability levels well in excess

8. Relation to wintertime climate anomalies at the earth's surface

The pattern of anomalies shown in Fig. 11 is consistent with the Northern Hemisphere wintertime teleconnections reported by Walker and Bliss (1932), Wright (1977, 1978), and Bjerknes (1966, 1969). During Northern Hemisphere winters which fall within warm episodes, the following conditions prevail:

1) The Pacific jet stream is stronger and further to the south than normal so that Hawaii is situated along its anticyclonic flank, in a region of subsidence; this relationship is reflected in the correlation between Hawaiian rainfall and the Southern Oscillation Index of Walker and Bliss (1932), the negative correlation between Hawaiian and Line Island rainfall (Meisner, 1976), and the negative

Table 4. Composites of selected surface data for the period 1910–45 based on Fanning seasonal precipitation. Values of Honolulu seasonal rainfall, Dutch Harbor sea level pressure, Edmonton temperature and Jacksonville temperature for each of the 12 wettest Northern Hemisphere winter seasons at Fanning are shown, together with the mean and standard deviation for the entire 46-year period, the mean for the 12 wettest years at Fanning, and the mean for the other 34 years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fanning season precipitation (cm)</th>
<th>Honolulu season precipitation (cm)</th>
<th>Dutch Harbor sea level pressure (mb)</th>
<th>Edmonton temperature (°C)</th>
<th>Jacksonville temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1912</td>
<td>215.9</td>
<td>16.8</td>
<td>-9.0</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>1914</td>
<td>139.2</td>
<td>13.4</td>
<td>-10.7</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>1915</td>
<td>136.9</td>
<td>14.1</td>
<td>-11.3</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>1919</td>
<td>137.7</td>
<td>17.1</td>
<td>-8.9</td>
<td>13.9</td>
<td></td>
</tr>
<tr>
<td>1920</td>
<td>88.4</td>
<td>14.0</td>
<td>-11.0</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td>76.0</td>
<td>24.3</td>
<td>1000.0</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>1926</td>
<td>146.6</td>
<td>9.0</td>
<td>992.4</td>
<td>13.0</td>
<td></td>
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<tr>
<td>1928</td>
<td>113.0</td>
<td>49.0</td>
<td>996.6</td>
<td>12.8</td>
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</tr>
<tr>
<td>1931</td>
<td>132.3</td>
<td>4.7</td>
<td>988.1</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>1940</td>
<td>146.8</td>
<td>10.9</td>
<td>994.2</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>1941</td>
<td>145.3</td>
<td>3.4</td>
<td>991.8</td>
<td>13.3</td>
<td></td>
</tr>
<tr>
<td>1942</td>
<td>71.6</td>
<td>11.2</td>
<td>989.5</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>46-winter mean</td>
<td>59.1</td>
<td>26.1</td>
<td>999.1</td>
<td>-11.8</td>
<td></td>
</tr>
<tr>
<td>Mean for 12 wettest winters at Fanning</td>
<td>129.1</td>
<td>15.8</td>
<td>993.3</td>
<td>-9.4</td>
<td></td>
</tr>
<tr>
<td>Mean for other 34 winters</td>
<td>22.6</td>
<td>31.2</td>
<td>1002.0</td>
<td>-13.0</td>
<td></td>
</tr>
<tr>
<td>46-winter standard deviation</td>
<td>56.4</td>
<td>16.8</td>
<td>6.2</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

of 99% (as judged from the conventional t test applied to the differences between wet and dry winters at Fanning, with 17 independent data points, i.e., the number of non-consecutive wet winters (9) plus the number of intervening dry years (8)). The results for Edmonton are typical of stations in western Canada. Even stronger anomalies and t values were observed at Dawson (64°N, 139°W). Likewise, the results for Jacksonville are representative of stations in the southeastern United States and Bermuda (32°N, 65°W).

9. Dynamical interpretation of the global teleconnection pattern

The distribution of geopotential height anomalies illustrated in Fig. 11 bears a strong qualitative resemblance to steady-state solutions of the linearized primitive equations on a sphere, forced by a tropical heat source, as obtained in theoretical studies by Egger (1977), Opepeh and Van den Dool (1980), Hoskins and Karoly (1981) and Webster (1981). The resemblance is particularly evident in the solutions of the latter two papers in which trains of alternating positive and negative geopotential height anomalies, spaced ~2000 km apart, emanate from the region of forcing. The most prominent of these wave trains is oriented such that the ray path connecting the anomaly centers is directed first poleward, then curves eastward, and finally equatorward along a "great circle route", as in Fig. 11. If the heat source is centered on or very near the equator, the primary centers in the streamfunction anomaly pattern at upper tropospheric levels are anticyclones located at subtropical latitudes, poleward of the heat source, as in Fig. 11. Although the largest perturbations in the vorticity and streamfunction fields are associated with these primary centers in the sub-tropics, the largest geopotential height anomalies in the theoretical patterns occur in connection with the secondary and tertiary anomaly centers in the wave pattern (the analogues of the centers over the North Pacific and western Canada in Fig. 11). Results obtained by Hoskins and Karoly (1981) using a five-layer model indicate that away from the region of the forcing the vertical structure of the anomaly fields is equivalent barotropic, with largest amplitude in the upper troposphere, in agreement with the observed patterns.

The theoretical results indicate that strong teleconnections to middle latitudes are possible only when the westerlies extend from middle latitudes into the equatorial troposphere over the region of the heat source. For the Northern Hemisphere this condition is fulfilled only during the winter half of the year equatorward of the upper tropospheric mid-Pacific and Atlantic troughs. Hence the theoretical results provide a possible explanation for the fact that the teleconnections to high latitudes appear to be present only during the winter half of the year.
These three-dimensional wavetrains and their associated vertical velocity patterns provide a more substantive dynamical interpretation of the atmospheric response to tropical SST anomalies than the two-dimensional Walker and Hadley circulation response postulated by Bjerknes (1969). Still lacking is a satisfactory theoretical explanation of the large zonally symmetric response in the tropical temperature and upper level geopotential height fields.

10. Time evolution of a typical warm episode

Throughout this paper, we have concentrated on the Northern Hemisphere winter season when sea surface temperatures are above normal in the central equatorial Pacific as inferred from the time series of Figs. 1b and 2. In this section we will attempt to look at these seasons in the context of the life cycle of a typical warm episode. Table 5 summarizes the changes in selected parameters during the evolution of a warm episode such as 1957–58 or 1972–73, as inferred from the works of Quinn and Burt (1972), Quinn et al. (1978), Hickey (1975), Trenberth (1976) and Reiter (1978b), and the unpublished research results cited in previous sections. Most of the material contained in Table 5 has been mentioned in previous sections, particularly Sections 3, 5 and 7.

The second Northern Hemisphere winter season of a warm episode is the time of the heaviest equatorial rainfall, the warmest tropical tropospheric temperatures (and highest 200 mb heights), and the strongest Northern Hemisphere extratropical teleconnections as shown in Table 5. As mentioned in the previous section, it is only during these warm episode winters that the dynamical conditions are favorable for the tropical anomalies to influence the Northern Hemisphere planetary waves.

The westward propagation of the warm sea surface temperatures is reflected in Table 5 as a 3–6 month lag between changes in sea surface temperature near the coast of South America and changes in the central equatorial Pacific (i.e., the equatorial belt near Canton Island). Note that the conditions during year 2 of the time sequence have not always been characterized by a return to normal, as indicated in Table 5. The warm episodes of 1957–58 and 1976–77 were marked by successive years of above-normal temperatures.
along the South American coast in the March through July period, both of which were followed by wet winters in the equatorial central Pacific.

As mentioned in Section 5 and shown in Table 5, the weakening of the South Pacific anticyclone precedes all the other changes which occur in association with the warm episodes. Quinn and Burt (1972) have used falling sea level pressures at Easter Island as predictors of increased rainfall at equatorial island stations one and two seasons later; similar forecasts of warmer sea surface temperatures along the coast of South America have been attempted by Quinn (1974) and Wyrtki et al. (1976). Both the intensity of the south Pacific anticyclone and changes in sea surface temperatures near the South American coast should be considered as useful long-range predictors of not only equatorial rainfall but temperatures over western Canada and the southeastern United States as well. Such a prediction scheme was first suggested and attempted by Walker and Bliss (1932) after they noted the strong correlation between their Southern Oscillation Index for the Northern Hemisphere summer season and temperatures over western Canada of the following winter season. Harnack (1979), among others, has recently used a Southern Oscillation Index based on sea level pressures during the Northern Hemisphere fall season as one member of a set of predictors of winter temperatures in the eastern United States.

11. Concluding remarks

In this article we have emphasized those aspects of the Southern Oscillation which are most directly related to climate anomalies at extratropical latitudes of the Northern Hemisphere. We have purposely passed over a number of other equally important aspects of the phenomenon:

1) Teleconnections to the Southern Hemisphere extratropics. Studies by Pittock (1973), Streten (1975), Nicholls (1977) and Trenberth (1975, 1976, 1980), among others, have linked tropical fluctuations with changes in the Southern Hemisphere circulation. A detailed analysis of Southern Hemisphere sea level pressure and 700 mb height anomalies by van Loon (1980)\(^\text{11}\) has revealed the existence of teleconnections comparable in strength and qualitatively similar, in terms of spatial patterns, to those in the Northern Hemisphere. The analysis of Rasmusson and Carpenter (1981) indicates that the earliest indications of the onset of El Niño events are the changes in sea surface temperature, surface winds and sea level pressures across a broad belt of the South Pacific near 30°S.

2) Surface wind changes in the equatorial Pacific. Recent analyses by Meyers and Pazan (1980)\(^\text{12}\) and Rasmusson and Carpenter (1981) have revealed a remarkable pattern of surface wind anomalies during the autumn-winter period when sea surface temperatures are warm and rainfall is enhanced in the equatorial central Pacific. A knowledge of the time evolution of these anomaly patterns is an essential prerequisite for an understanding of the coupled air-sea interactions which give rise to the El Niño/Southern Oscillation phenomenon.

3) Anomalies in the currents, thermocline structure, salinity and sea level slope in the equatorial Pacific and along the west coast of the Americas. Wyrtki (1975, 77, 79) has documented large sea-level changes over large areas of the tropical Pacific at the time of the onset of El Niño episodes, with falls in the western Pacific and rises near the South American coast. These changes indicate that the temperature of the entire mixed layer and the depth of the thermocline may be undergoing substantial interannual variability in association with the Southern Oscillation. A comprehensive theory of the Southern Oscillation must await a more complete documentation of the oceanic variability and a better understanding of the dynamical and thermodynamical processes which initiate and maintain the sea-surface temperature anomalies.

It is evident from the foregoing sections that it may not be necessary to fully understand the nature and causes of the Southern Oscillation in order to derive some predictability from it. However, lest the case for such predictability be overstated, it should be noted that the influence of conditions in the equatorial Pacific on North American climate appears to be important only during the winter half of the year and only over the northwestern and southeastern parts of the continent. Even for these regions the Southern Oscillation accounts for less than half the variance of wintertime mean surface temperatures as reflected in the correlation statistics of Wright (1977)\(^\text{2}\). We suspect that the relationships reviewed in this paper, in fact, are already implicit in some of the lag correlation statistics used in the preparation of operational long-range forecasts.

What, then, are the prospects of utilizing information on equatorial sea surface temperature anomalies and related rainfall patterns to improve the quality of long-range forecasts for middle lati-
tudes? The answer depends, in large part, upon the nature of the teleconnection patterns in Figs. 9 and 11. If the strength of the correlations in those patterns and in Table 4 is essentially limited by the high noise level inherent in seasonal averages due to the presence of weather fluctuations, as suggested by Leith (1973), Madden (1976) and Madden and Shea (1978), then the prospects are not encouraging. On the other hand, if these patterns constitute blurred images resulting from our inadvertent superposition of an ensemble of sharper patterns, corresponding to the various states of the equatorial atmosphere that have existed under the general category of "warm episodes", then there is hope that given a more specific and detailed prediction of tropical sea surface temperature and rainfall patterns, it might be possible to use the simplified numerical models described in Section 9 to infer midlatitude climate anomalies with a higher degree of detail and accuracy than is now possible.

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APPENDIX

Data Sources

The 200 mb geopotential heights at the 32 stations used in this study were obtained from the Monthly Climatic Data for the World, published by the U.S. Department of Commerce and the National Climatic Center, Asheville, NC 28801. Sea level pressure records were also obtained from the same source for Darwin and Tahiti.

The rainfall time series were extracted from Taylor (1973) and updated from data kindly supplied by E. M. Rasmusson. Sea level pressure, 700 and 300 mb geopotential heights for a regularly spaced array of gridpoints poleward of 20°N for the winter months are based on analyses made by the U.S. National Meteorological Center and obtained from the National Center for Atmospheric Research (NCAR) Data Library. Selected monthly mean station data for rainfall, temperature and sea level pressure for the period 1910–45 were also obtained from the NCAR Data Library.

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