Relationships Among the Stratospheric and Tropospheric Zonal Flows and the Southern Oscillation

RODERICK S. QUIROZ

Climate Analysis Center, NMC, NWS, NOAA, Washington, DC 20233

(Manuscript received 29 March 1982, in final form 28 September 1982)

ABSTRACT

Relationships among the high-latitude stratospheric zonal wind, the tropospheric zonal wind in the region of the subtropical jet and over the equator, the Southern Oscillation, and the stratospheric tropical quasi-biennial oscillation (QBO) were examined from monthly anomaly data for 13 years (1968–80). Patterns of correlation were found which are broadly consistent with the theory on vertical and latitudinal Rossby wave propagation, with high correlations diminishing rapidly in association with easterly basic flow. Lag correlations as high as 0.8–0.9 were found for leads of ~1–7 months, based on three-month average anomalies for successive months. The simplified lead path is from Southern Oscillation to equatorial winds to subtropical winds to stratospheric high-latitude winds. Relationships involving the QBO appear weak compared to those involving the extratropical flows, the tropospheric equatorial flow of the east Pacific, and the Southern Oscillation. Even so, the structure of correlation found between the stratospheric high-latitude winds (or height gradients) and the QBO is consistent with “compositing” results of Holton and Tan (1980, 1982); moreover, the correlations found between the stratospheric high-latitude flow and the Southern Oscillation are consistent with compositing results of van Loon et al. (1982). Spectra for the variables examined all show a quasi-biennial signal, but coherences involving the QBO at periods 20–30 months were found to be weak to moderate, whereas coherences involving other pairs of variables were moderate to strong.

1. Introduction

Interest in the stratospheric circulation has heightened because of its role in determining the ozone distribution (Garcia and Hartmann, 1980) and because large changes in the high-level circulation could possibly influence tropospheric wave properties on climatic time-scales. The second effect has been deduced from modeling experiments designed to assess the influence on vertically propagating planetary waves attributable to large changes in the stratospheric mean zonal flow (Bates, 1977; Geller and Alpert, 1980; Schmitz and Greiger, 1980). In these experiments the tropospheric zonal wind was usually held fixed. In this paper, we will show that Northern Hemisphere stratospheric wind variations are closely linked not only to variations in the troposphere of the same hemisphere, but also to surface pressure variations in the Southern Hemisphere.

From data for only four winters, Quiroz (1980) reported the appearance of a strong negative correlation between the zonal mean flow in the stratospheric polar-night jet (at 65°N, 10 mb) and the flow in the tropospheric subtropical jet (at 33°N, 200 mb). One purpose of this paper is to show that this relationship is supported by data for a longer period of years (1968–80), using data for all months. The broader purpose, however, is to show the pattern of correlation among five stratospheric and tropospheric variables, including an index of the “Southern Oscillation,” and to indicate the relation of this pattern to the basic background flow. It will be shown that, among certain pairs of variables, a high correlation is sustained during several months of the year and then the correlation breaks down abruptly in association with the change from westerly to easterly basic flow, in a manner consistent with the theory of Rossby wave propagation.

The role of the Southern Oscillation (SO) is especially intriguing. Our computations show that variations in the SO lead anomalies in the Northern Hemisphere 200 mb jet wind at 33°N by 2–6 months, depending on time of year, consistent with recent findings by Arkin (1982); the 200 mb wind in turn leads the high-latitude stratospheric wind by ~1–2 months. The SO is a global phenomenon (Horell and Wallace, 1981; van Loon and Rogers, 1981; Rasmussen and Carpenter, 1982) characterized by, among other things, a large-scale fluctuation in the low-latitude surface pressure of the South Pacific and the region of the Indian Ocean, Australia and Indonesia; and by major changes in the sea surface temperature (SST) of the equatorial east Pacific. As has been shown by many authors (e.g., Rasmussen and Carpenter, 1982), when there is strong, sustained warming of the equatorial east Pacific ocean surface, the
pressure at a station such as Tahiti (18°S, 150°W) tends to be low and the pressure at a station such as Darwin, Australia (12°S, 131°E) tends to be high. For this study, a Southern Oscillation Index (SOI) was constructed from the difference between the normalized monthly pressure anomalies for these stations (Tahiti minus Darwin). See Trenberth (1976) and Chen (1982) for a detailed discussion of Southern Oscillation indices.

The relevance of the Southern Oscillation to the Northern Hemisphere processes lies especially in the possibility that anomalous atmospheric heating linked to the SST field near the equator could trigger trains of large-scale waves propagating, under favorable basic flows, into middle and high latitudes (see, e.g., Hoskins and Karoly, 1981). Extra-tropical response to tropical thermal forcing has been modeled in approximately twelve papers since 1972. The results, obtained mainly from general circulation models (e.g., Julian and Chervin, 1978) and relatively simple steady-state models (e.g., Osterheg and van den Dool, 1980; Webster, 1982), indicate a wide range of response.

Meanwhile, observational studies (e.g., Chiu and Lo, 1979; Horel and Wallace, 1981; van Loon and Rogers, 1981, Arkin, 1982; Chen, 1982) have revealed various extratropical upper air relationships with the SO. Van Loon et al. (1982) have provided evidence of a stratospheric link with the SO, and Holton and Tan (1980, 1982) have investigated relations between the high-latitude stratosphere and the equatorial (stratospheric) quasi-biennial oscillation (QBO). These authors, however, have mainly looked at the winter months or have dealt with conventionally-defined calendar seasons (Arkin; Chen). In this paper, we consider various time stratifications, but emphasize three-month average values centered on each successive month. This choice allows a meaningful comparison with the basic mean zonal flow, which becomes easterly in May in the high-latitude stratosphere and in July in the subtropical upper troposphere.

Away from the equator, we shall deal with anomalies in the latitudinally averaged mean zonal flow, i.e., the zonal flow averaged around a latitude circle. A brief comparison will be provided, however, between latitudinal and regional means at the same latitude (Section 6). This distinction is especially important at the equator, where the east Pacific has a dominantly westerly 200 mb flow in nine months of the year, making this a preferred region for the propagation of Rossby waves to extratropical latitudes. One of the most interesting results to come out of the steady-state models cited above is the finding (e.g., Hoskins and Karoly, 1981; Simmons, 1982) that in response to tropical thermal forcing, large-scale waves could be generated which 1) in the upper troposphere possessed basic properties of barotropic Rossby waves, and 2) therefore could propagate to higher latitudes only under conditions of local westerly basic flow (see also Webster and Holton, 1982).

The theoretical principle for 2) is worth noting. Planetary waves may generally propagate both vertically and horizontally. For vertical propagation, Charney and Drazin (1961) showed the transmissivity of the upper atmosphere to be exceedingly sensitive to the mean zonal wind structure; specifically, stationary waves would propagate upward only if the wind was westerly and less than the modified critical velocity \(U_c\). An inverse dependence of \(U_c\) on zonal wavenumber further indicated that only the ultralong waves (small wavenumbers) would likely reach the stratosphere. For horizontal propagation, Simmons (1982) has shown, by extension of the Charney and Drazin analysis and for an idealized flow situation, that stationary waves generated in the tropics will be trapped in a basic easterly flow, but will propagate to higher latitudes for a basic westerly flow and small zonal wavenumber. If stationary wave propagation is a vital link in the set of processes explaining relationships between the extratropical tropospheric flow and tropical states, and between the flows in the stratosphere and troposphere, then one may expect these relationships to break down in association with an easterly basic flow. These relationships will be examined in Section 4, from data described in Section 3. The nature of the climatological basic flow, whether easterly or westerly, etc., is examined first in Section 2.

2. Background climatology and latitudinal correlation structure

a. Climatology

Various features of the tropospheric and stratospheric mean zonal wind climatology are depicted in Fig. 1. These include: 1) the occurrence of maximum 200 mb tropospheric wind at 30–35°N during seven months of the year (November–May), the maximum wind shifting to near 45°N in late summer; 2) the occurrence of maximum 30 mb stratospheric wind near 65°N during seven months (September–March); 3) easterlies in the stratosphere May–August at 65°N, their strength and duration increasing equatorward; and 4) easterlies in the tropospheric subtropics in July–September, two months later than in the stratosphere north of 30°N. Winds at the equator are discussed below.

Fig. 2, constructed from winter data (December–February) emphasizes the latitudinal structure of the tropospheric and stratospheric jet flows. The polar night jet, centered near 65°N, increases in speed from the mid-stratosphere (30–10 mb) to the lower mesosphere and is inclined toward midlatitudes with increasing height (Quiriouz, 1981a).

Also shown in Fig. 2 are map-analyzed values of
observed 200 mb winds from 40°N to the equator. Differences between observed, \([U_0]\), and geostrophic, \([U_g]\), zonal mean winds are appreciable in subtropical latitudes, as discussed by Quiroz (1981a). In the context of this paper, it is important to note that consistency of choice must be maintained in calculating the anomalous part of the wind (departure from long-period mean); i.e., \(\Delta[U_0] = [U_0] - [U_g]\), and \(\Delta[U_g] = [U_g] - [U_g]\), where the overbar refers to long-period means. Hereafter, zonal means, denoted by a bracket, will refer to winds averaged around a latitude circle. Regional zonal means will refer to specific longitudes or ranges of longitude.

At the equator, tropospheric zonal mean winds may have little practical meaning. Fig. 3 (upper) shows 200 mb zonal mean winds which are easterly in the annual mean, with weak westerlies in four months. However, the character of the winds changes drastically from region to region. Fig. 3 (bottom) shows no westerlies in Regions 1–3, whereas Region 4 (east Pacific) has westerlies in nine months of the year, making this a preferred region for wave propagation from a tropical heat source to higher latitude. Regional wind differences in extratropical latitudes are discussed in Section 6.

**b. Latitudinal correlation structure**

Our main analysis, which focuses on winds in the jet stream regions and at the equator, will be based on 13 years of data. Data available for all latitudes for six recent winters meanwhile provide an approximation to the pattern of cross-correlation between tropospheric and stratospheric winds over a wide range of latitude, and between the SOI and the tropospheric and stratospheric winds with latitude. "Winds," as used here, are anomalies in zonal mean winds. Fig. 4a gives the simultaneous correlation between 30 mb stratospheric and 200 mb tropospheric winds, based on a sample of 18 winter months (December–February, 1975–76 to 1980–81). Fig. 4b shows the correlation between the tropospheric winds in December–February and the SOI four months earlier, and between the stratospheric winds in February–April and the SOI six months earlier (\(N = 18\) for each correlation). Lags of four and six months (SOI leading) were chosen on the basis of results to be presented later in this report. These figures are intended merely to give some idea of the spatial scale of regions of positive and negative correlation during winter. Fig. 4a is consistent with the 2–3 cell structure of wind anomalies depicted by the author (1981a) in

---

**Fig. 1.** Climatological zonal mean geostrophic wind at 30 and 200 mb, the former based on data (1958–71) published by Berlin University and the latter based on long-period data derived at the National Climatic Center.

**Fig. 2.** Latitudinal traces of zonal mean geostrophic wind illustrating tropospheric 200-mb jet and stratospheric "polar-night" jet maxima, along with the trace of analyzed values of observed zonal mean wind at 200 mb at latitudes south of 40°N.

**Fig. 3.** Top: monthly zonal mean analyzed wind at the equator, 200 mb. Bottom: months with westerly wind in six longitudinal sectors along the equator, 200 mb, based on NMC data for 1968–80.
The variability minimum in zonal mean 200 mb wind at the equator, relative to other latitudes, obscures the fact that there are strong contrasts along the equator. Data for the six winters show that the east Pacific, the region of maximum westerlies (Fig. 3), is also the longitudinal region of greatest variability.

These factors, therefore, have guided our choice of variables for further examination.

3. Data sources and method of analysis

a. Data

The basic data used were monthly means for each year, 1968–80. Table 1 lists the five variables to be examined, together with symbols for denoting any smoothing performed. Variable (1), the geostrophic wind anomaly in the high-latitude stratosphere, was computed from zonal mean height data for 50 and 80°N from publications of Berlin Free University (e.g., Just et al., 1969); closer finite differencing, e.g., for 60 and 70°N, does not significantly alter the derived winds. Variable (2), the tropospheric jet-region wind anomaly, is from unpublished tabulations based on daily maps of the National Meteorological Center (NMC), Washington, DC (Arkin, 1982). The curious choice of latitude, 33°N, corresponds to the latitude array in those tabulations; data for 35°N should give basically the same results. These tabulations were also the source for data on Variable (3), the 200 mb wind anomaly above the equator, for the eastern Pacific.

For the SOI, monthly pressure anomalies were first determined through subtraction of long-period station pressures from the observed data for two stations, Tahiti (18°S, 150°W) and Darwin (12°S, 131°E) (Chen, 1982). It is the difference of the monthly normalized pressure anomaly at these stations (Tahiti

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbols</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) uSTRAT65</td>
<td>Anomaly in $U_g$ at 65°N, 30 mb, determined from anomalies in mean zonal height at 80 and 50°N</td>
<td></td>
</tr>
<tr>
<td>(2) uTROP33</td>
<td>Anomaly in $U_g$ at 33°N, 200 mb</td>
<td></td>
</tr>
<tr>
<td>(3) uTROPeq</td>
<td>Anomaly in $U_g$ at equator, 165–110°W, 200 mb</td>
<td></td>
</tr>
<tr>
<td>(4) SOI</td>
<td>Southern Oscillation Index, defined in text</td>
<td></td>
</tr>
<tr>
<td>(5) QBO</td>
<td>Anomaly in $U_g$ at Balboa, C.Z., 30 mb, to represent Quasi-biennial Oscillation</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Unsmoothed monthly values</td>
<td></td>
</tr>
<tr>
<td>3M, 5M</td>
<td>Three-, five-month averages of monthly values, with equal weighting</td>
<td></td>
</tr>
</tbody>
</table>

* Binomial smoothing applied
minus Darwin) that has been used to define the SOI, the unsmoothed monthly index ranging usually between −4.0 and 4.0. The inclusion of the QBO in this investigation was motivated by evidence of an association with the high-latitude troposphere (Ebdon, 1975) and stratosphere (Holton and Tan, 1980, 1982), and by the possibility of a link with the Southern Oscillation. (See Quiróz, 1981b, for a detailed description of the QBO since 1951.)

To give the reader an appreciation for the overall structure of the variables of interest, Fig. 5 shows continuous traces of 5M* (defined in Table 1) for 1968–80. The same basic structure is evident in traces of 5M (Table 1) and those with less drastic smoothing. For the latter, more detail and greater amplitude of the fluctuations are usually to be found. The ordinate scale has been reversed in Fig. 5 for uTROP33. Some similarity of structure will be evident among the traces, especially in the first two pairs of variables. The most regularly repeating structure is obviously in the stratospheric QBO.

b. Method of analysis

Possible relationships among the variables described were examined in two ways, through “time-dependent” cross-lag correlations and through cross-spectrum analysis.

By “time-dependent” we mean the fixing of lag 0 in successive months of the calendar, in order to perceive any seasonal dependence in the correlation structure. Thus, for example, we might correlate variable Y at lags −6, −5, · · · +6 months with variable X in January (lag 0); then repeat this for X in February (new lag 0), · · · December. For the observational record used, 1968–80, the sample size is 12 or 13 for each correlation. Statistical significance will be discussed later. Note that seasonal dependence as used here does not refer to ordinary inter-seasonal dependence, since we are dealing with anomalies, but rather to a calendar variation of the correlations which might be linked to the seasonally-variable background flow. Most of the cross-lag correlations were carried out with 3M data (three-month average anomaly), but in the monthly marching pattern described above.

The cross-spectrum analysis was carried out for all possible pairs of the five stratospheric and tropospheric variables listed above, using complete unsmoothed monthly data for February 1968–November 1980 (N = 154); for the SOI and QBO, further analysis based on 30 years of data (1951–80) was possible.

4. Time-dependent correlation results

a. Correlation patterns

Before showing the detailed correlation results, it is helpful to examine a small sub-set which illustrates the influence of time stratification. Fig. 6 compares uTROP33 (the tropospheric jet wind anomaly) at lags −7 to +4 months with uSTRAT65 (the stratospheric high-latitude wind anomaly) in January. Negative lag means troposphere leads. The correlations are given according to whether five-month average, three-month average, or one-month anomaly values were used in each sample. Although it is evident from this figure and from other computations that moderately high correlations may be encountered if unsmoothed monthly data (M, Table 1) are used, the correlations normally increase with the use of 3M or 5M data. This would be due to the averaging out of some short time-scale changes in the category of “noise.” (Sample size is the same for all computations in Fig. 6.) On the other hand, 5M or 5M* data may give ex-
cessive smoothing, from a diagnostic viewpoint. Thus, our main results in this section will be based on three-month average anomalies, determined for successive months.

Figs. 7a–g give correlation patterns found for several pairs of tropospheric and stratospheric variables. In these figures, the first variable is fixed at the month indicated, and the second variable is allowed to “float” between lags −9 to +3 months. Actual time series underlying some of the higher correlations are shown in Figs. 8a–g. As discussed in Section 4b, individual correlation coefficients in these figures may be judged significant at the 95% level if greater than \( \sim 0.65 \) (absolute value).

Fig. 7a, relating the stratospheric and tropospheric jet-region winds, shows some remarkable features:

1) The correlations at lag 0 break down precipitously between April and May, changing from \(-0.58\) to \(+0.32\). This is precisely the time of transition from westerly to easterly background flow in the stratosphere (Fig. 1). The correlations remain weakly negative or positive (at lag 0) until September, when there is a sudden increase to a moderate (−0.47) correlation. September is the first month of westerly flow in middle to high latitudes (Fig. 1, for 30 mb level).

2) Maximum correlation in the fall to spring months is for lag −1 (September) to lag −2 months (troposphere leading), except that as spring approaches, the maximum appears again at or near lag 0.

3) An unexpected moderate positive correlation appears for June and July (stratosphere) at lags −2 to −3, which merits further examination.

4) The slopes of the zero and −0.5 correlation isolines to January, together with the correlations at lag 0, indicate that the tropospheric signal is not transmitted to the stratosphere in summer (when its winds are easterly), but evidently some tropospheric memory is retained and transmitted later. Thus a correlation of −0.64, verging on significance at the 95% level, was found between January stratospheric winds and tropospheric winds in the preceding July (lag −6). Fig. 8a shows actual data underlying the January lag −2 correlation (−0.85).

The fact that the tropospheric wind was examined at constant latitude (33°N) for these correlations, although the maximum wind shifts to near 45°N in summer, does not alter our overall results, as the correlation between the stratospheric wind (65°N) and tropospheric wind at 45°N in summer was similarly low (+0.35 at lag 0, July).

Fig. 7b shows relations between the tropospheric jet flow (33°N) and the Southern Oscillation Index. Note:

1) High negative correlations are sustained from November, the SO leading by 1–2 months; to February \((r = -0.91)\), SO leading by five months; with high correlations as late as June, SO leading diffusely by 2–8 months.

2) From June to July, the correlations change abruptly from values near −0.7 to very weak values. This is precisely the time of changeover to easterly background flow in the equatorial east Pacific, 165–110°W (Fig. 3) and in the subtropical zonal mean flow for 200 mb (Fig. 1). Certain details of the summertime correlation, such as the change of sign in August from lag −5 to −6, are hard to explain; but in any case, these correlations are not likely significant even at the 90% level.

3) As in the tropospheric–stratospheric relationship, some summertime “memory” appears to be retained as late as March, in view of a persistent high correlation between the SO at lag −8 (July data) to lag 0 with March tropospheric wind (33°N).

As above, taking the tropospheric wind at constant latitude (33°N) for these correlations, in spite of a shift of the maximum wind to nearly 45°N in summer, does not seem to have a significant bearing on our results, as the correlation of the SO with summertime wind data for 45°N was not found to be significant (+0.34 at lag 0).

Fig. 8b shows the extraordinary relationship \((r = -0.91)\) between the SO in September and the tropospheric 200 mb wind anomaly (33°N) in February, five months later.

Fig. 7c, relating the SO and the 200 mb Equatorial wind in the eastern Pacific, shows, in contrast to the extratropical wind comparisons, a uniform field of positive correlation in all months of the year. Coefficients expected to be significant at the 95% level (>0.65) are found for equatorial winds from October to March, with the SO leading by approximately one month in October to three months in March. The strong relationship \((r = 0.89)\) between the SO in September and the equatorial winds in November is shown in Fig. 8c.

The general sense of correlation among the SO, the equatorial high-altitude winds, and winds in the extratropical jet region of the North Pacific, has previously been established by Arkin (1982). He found, for example, a correlation of +0.60 between the SO and the equatorial 200 mb winds at grid-points near 160°W, and a correlation of −0.40 between the SO and the extratropical 200 mb winds at grid-points near 25°N, 150°W, at lag 0. The lesser magnitude of these coefficients, as compared with the wintertime values in our figures, is explainable by Arkin’s use of all seasons combined. In Section 7 we will consider further the relationship between the SO and the regional extratropical winds of the east Pacific.

Figs. 7d–e show correlations between the equatorial and extratropical (33°N) winds and between the 200 mb equatorial and 30 mb stratospheric (65°N) winds.

The positive correlation between the high altitude
FIG. 7a–g. Cross-lag correlations between pairs of variables shown in upper left of each figure. For each month, the correlation is between the value of the first variable (uSTRAT65 in Fig. 7a) in that month and the second variable (uTROP33 in Fig. 7a) several months earlier to one or more months later. Negative lag means second variable leads. All “monthly” values here refer to three-month average anomalies centered on the month indicated.
stratospheric winds and the SOI is seen in Fig. 7f, which includes the result that the SOI leads the March stratospheric winds by ~7–8 months ($r > 0.80$). Note, as between the stratospheric and tropospheric winds, the abrupt breakdown of the correlations from April to May. Note the delay of high correlations ($>0.6$) until January in contrast to October for the stratospheric–tropospheric relationship (Fig. 7a). The timing of maximum correlation between the stratospheric and equatorial tropospheric winds is also of interest. Figs. 7d–e show correlations exceeding 0.80 not until February, with the equatorial winds leading by two or more months. Since the stratospheric–tropospheric jet wind correlation decreases after January (Fig. 7a) there is a suggestion here that some “signal” is carried directly to the stratosphere via the equatorial winds.

Fig. 8f shows traces underlying one of the highest uSTRAT–SOI correlations.

The results in Fig. 7f are consistent with recent findings by van Loon et al. (1982), who obtained “composites” of stratospheric height and wind fields for high and low values of a similar Southern Oscillation index, using a 15-year observational series (1963/64 to 1977/78). Their composites are for the combined winter months, December–February, and,
in agreement with our results, show positive anomalous height gradient between middle and polar latitudes of the stratosphere (height increasing poleward, giving weaker geostrophic winds), in association with low SOI.

Our final figures in this series are Figs. 7g and 8g, relating the high-latitude and equatorial stratospheric winds, the latter representing the well-defined QBO. Surprisingly, in view of recent results obtained by “compositing” Northern Hemispheric stratospheric height fields according to whether the QBO was in easterly or westerly phase (Holton and Tan, 1980, 1982), the highest correlations obtained by us are near +0.70, probably only weakly significant. Moreover, these are maximum around October–November, with no well defined lead or lag. It is evident from Fig. 8g, that given a longer series of observations, compositing high latitude wind (or height) patterns for cases of extreme westerly phase of the tropical QBO should give important differences from patterns compositing for easterly phase, as Holton and Tan (1980) found. (These authors used data for a 16-year period, 1962–77.)

Diagrams similar to Figs. 7a–g were prepared showing the correlation between the QBO and 1) uTROP33; 2) uTROPeq; and 3) SOI, respectively. Maximum correlations found were near 0.65 (absolute values) for 1 and 2 and near 0.50 for 3; in other words, weaker than all the maximum correlations in Figs. 7a–g. These results are consistent with cross-spectral coherence data to be presented in Section 5. It is well known that the phase of the QBO near the equator is delayed downward at the rate of approximately one month per kilometer, between ~5–50 mb. Accordingly, leads and lags cannot be well determined from diagrams comparing other data with the QBO at a single level. Further investigation of QBO relationships based on a more comprehensive framework of QBO wind data is needed.

In Figs. 7a–f, highest correlations (absolute values) were obtained for lags of one or more months. The time-dependent model results cited in the Introduction (those from general circulation models and from a barotropic spectral model used by Hoskins and Karoly, 1981; and Simmons, 1982) indicated that the extratropical circulation response was essentially well-defined by ~10 days after the introduction of tropical thermal forcing. However, the GCM results also indicated great persistence of the response patterns, to ~90 days. A further consideration in regard to lag effects is the morphology of SST anomaly in the east equatorial Pacific, which involves a spreading westward of warm water over a period of several months (Fig. 22 of Rasmusson and Carpenter, 1982). Thus, we may suspect that the appearance of a strong lag at remote latitudes is somehow related to the morphology of the thermal forcing. The lag effect also merits investigation.

b. Statistical significance

Although the sample size for each correlation in Figs. 7a–g was 12 or 13, the effective number of degrees of freedom \( N_r \), calculated by using a modified form of the technique suggested by Davis (1976), ranged typically from 7 to 11. Correlation coefficients required for 95%-level significance are 0.75 to 0.60, respectively. As an approximate guide, one might use a value of 0.67 (for \( N_r = 9 \)), for judging the significance of the individual correlations in these figures.

If enough correlations are computed, 5% of them may be expected to be significant at the 95% level even if no relation exists. Binomial theory provides further guidance in evaluating the significance of collections of coefficients such as those in Figs. 7a–g (Livezey and Chen, 1982). These figures are based on collections of ~120 coefficients (72 coefficients in Fig. 7c). Because the coefficients were computed from overlapping data (three-month averages centered on each month) only every third value may be independent. For a conservative estimate of 10 effective degrees of freedom for the collections of coefficients and from binomial distribution considerations (Livezey and Chen, 1982), the odds are less than 1 in 20 that a given collection of correlation coefficients occurred by chance if more than ~23% of the individual correlations are significant at the 95% level. The area represented by individually significant coefficients \( r \geq 0.67 \) in Figs. 7a–e is 25, 36, 43, 23 and 21%, respectively, indicating overall significance of these correlation patterns. For Figs. 7f–g the corresponding areas were only 12 and 13%, but our confidence in the significance of these results is enhanced by their consistency with independent analyses by van Loon et al. (1982), and Holton and Tan (1980) based on longer observational records, as noted above.

It is possible that our results reflect characteristics of the 1970’s especially well and not so well for some other decade. To provide an indirect check, use was made of mean zonal heights at 500 mb available back to 1951. Geostrophic wind anomalies at 35°N for February were compared with the SOI in the preceding September for 1968–80, as in Fig. 8b, and additionally for 1951–80. Correlations were ~0.66 and ~0.55, respectively. This result indeed suggests that the high correlations based on 200-mb winds presented in this paper might diminish somewhat if computed for a 30-year period.

5. Spectral and cross-spectrum analysis

The length of record (13 years) is perhaps too short to yield well-defined spectra. A feature worth noting, nevertheless, is a spectral peak near 30 months in all five variables listed in Table 1. For variables (3) and (5), the QBO and uTROPeq, the peak near 30 months is clearly significant at the 95% confidence level, ac-
Table 2. Squared-coherence (x100) for period 20–30 months for indicated pairs of variables. Based on monthly unsmoothed data for 1968–80 (N = 154, 5 DOF). SOI–QBO also shown based on data 1951–80 (N = 360, 10 DOF).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Squared coherence</th>
</tr>
</thead>
<tbody>
<tr>
<td>uSTRAT65–uTROP33</td>
<td>[93]*</td>
</tr>
<tr>
<td>uSTRAT65–uTROPeq</td>
<td>[92]</td>
</tr>
<tr>
<td>uSTRAT65–SOI</td>
<td>[85]</td>
</tr>
<tr>
<td>uSTRAT65–QBO</td>
<td>56</td>
</tr>
<tr>
<td>uTROP33–uTROPeq</td>
<td>[86]</td>
</tr>
<tr>
<td>uTROP33–SOI</td>
<td>[79]</td>
</tr>
<tr>
<td>uTROP33–QBO</td>
<td>55</td>
</tr>
<tr>
<td>uTROPeq–SOI</td>
<td>[94]</td>
</tr>
<tr>
<td>uTROPeq–QBO</td>
<td>36</td>
</tr>
<tr>
<td>SOI–QBO (68–80)</td>
<td>20</td>
</tr>
<tr>
<td>SOI–QBO (51–80)</td>
<td>25</td>
</tr>
</tbody>
</table>

* [ ]: Significant at 95% level (Koopmans, 1974); ( ) : significant at 90% level.

According to confidence limits given by Jenkins and Watts (1968) (N = 154, unsmoothed data, five spectral degrees of freedom, bandwidth 0.2 cpy). For the SOI, the strongest signal spreads to a longer period, 30–60 months, in agreement with other determinations of SOI spectra based on longer records (e.g., Rasmussen and Carpenter, 1982).

Graphs of the coherence squared (not shown) were prepared for all possible pairs of variables. All pairs except SOI–QBO and uTROPeq–QBO showed moderate to high coherence at 20–30 months. For this range of period the maximum values of the coherence squared are tabulated in Table 2. Significance is noted at the 95% and 90% levels, for five spectral degrees of freedom, based on required coherence as given by Koopmans (1974).

Coherences significant at the 95% or 90% level appear for all pairs of variables which do not involve the QBO. The lowest coherence found was for the QBO and the Southern Oscillation Index (0.20). As data for these variables were jointly available back to 1951, further analysis based on the 30-year period 1951–80 was made, with a similar result (Table 2). Since data at only one level, 30 mb, were used here to represent the QBO, any further investigation should probably take altitude and QBO phase and period variations (Quieroz, 1981b) into account, as well as regional components of the Southern Oscillation.

6. Regional and latitudinal zonal mean winds

Except for the equator, the analysis has concerned latitudinally-averaged zonal winds. Zonal mean winds are important in modeling and dynamical interpretation, but they may be of little use in the interpretation of regional climatic anomalies. Accordingly, it is of interest to examine possible relations between regional and latitudinal zonal mean winds (and between regional winds and long-wave phase-amplitude behavior).

The second and bottom curves of Fig. 9 give the longitudinal variation of the long-period average zonal wind, based on data for 13 Januarys, in the stratospheric and tropospheric jet regions. Note at 200 mb the much stronger winds corresponding to the “Far East” or “West Pacific” jet stream, relative to those of the North American jet. Do interannual fluctuations in regional winds bear any resemblance to fluctuations in zonal mean winds? The regional and zonal mean winds are, of course, not independent quantities; correlations between the two merely indicate the degree of similarity of the time-traces.

The first and third curves of Fig. 9 indicate a high correlation at all longitudes in the stratosphere and a moderate to high correlation at some longitudes of the troposphere, at the given latitudes and pressure levels. The best relationships appear to be with stratospheric winds near 130°E and, surprisingly perhaps, with tropospheric winds at 165–110°W, in the region between the West Pacific and North American jets.

In view of the high correlation between east Pacific subtropical tropospheric winds and the latitudinal zonal means, and in view of the previously shown

![Fig. 9](image_url)
high SOI–uTROP33 correlation (Fig. 7b), one might expect a good relationship between the SOI and the uTROP33 (165–110°W). Earlier we noted that Arkin (1982) had found a correlation of −0.4 with winds at 25°N, 150°W, at lag 0, using all seasons combined and data for 11 years (March 1968–February 1979). Fig. 10 shows the much higher correlations obtained with three-month averages at a lag of five months (SOI leading). Moreover, a strong signal is still present ($r = −0.84$) for correlations based on unsmoothed monthly data.

7. Summary and remarks

1) Patterns of correlation among the high-latitude stratospheric flow, the subtropical tropospheric jet flow, the equatorial 200 mb flow and the Southern Oscillation were found which are broadly consistent with the theory on Rossby wave propagation. As easterly basic flow is encountered in intervening regions, correlations involving the extratropical flow break down precipitously.

2) Lag correlations as high as 0.8–0.9 (absolute values), significant at the 95% level, were found for leads of ~1–7 months, with possible predictive value. Some of the highest correlations involved the state of the Southern Oscillation in August–October.

3) The pattern of correlation found between the high-latitude stratospheric wind and the subtropical tropospheric jet wind, based on data for 1968–80, confirms the earlier results of the author (1980) based on a shorter observational record.

4) The pattern of correlation found between the high-latitude stratospheric winds and the Southern Oscillation is consistent with compositing results of van Loon et al. (1982), who used a 15-year wintertime observational series beginning in 1963–64.

5) The pattern of correlation found between the high-latitude stratospheric winds and the tropical stratospheric QBO (wind) is consistent with compositing results of Holton and Tan (1980, 1982), based on data for 1962–77.

6) Although the spectra for the five variables examined all showed a quasi-biennial signal, only moderate correlations (~0.7 at best) and coherences not significant even at the 90% level were found in comparisons involving the stratospheric tropical QBO. A low SOI–QBO coherence was confirmed from the use of 30 years of data (1951–80).

7) Because only one level of data (30 mb) was used for the tropical QBO, further study is needed to sort out relationships with the QBO. The determination of leads and lags, in particular, is sensitive to the QBO phase structure with altitude.

8) A brief examination of the relation between regional zonal winds and latitudinally-averaged zonal winds showed, for January, generally high correlation in the stratosphere (at 65°N), and high correlation in restricted longitudes of the troposphere (at 33°N).

These results indicate promise for interpreting latitudinal zonal means in terms of regional means or vice versa, but of course thorough study of this problem is needed. It should be stressed that here, as for all findings listed above, the relationships concern anomalies in the wind (departure from the monthly long-period mean).

The number of years (13) used for the main part of this investigation seems small for definitive climatological diagnosis. Further analysis based on a longer observational record is no doubt desirable. Of greater urgency, perhaps, is increased understanding of the atmospheric processes underlying the observed relationships. A framework of potentially-relevant physical processes has been outlined which may serve as a basis for further study. An essential task, already in progress, is the thorough investigation of relations between the Southern Oscillation and regional winds in extratropical latitudes.

Acknowledgments. I am very grateful to Dr. Richard Reynolds for extensive help on the co-spectrum analyses and to Thomas Carpenter and John Kopman for programming and technical assistance. This work was partially supported by the Equatorial Pacific Ocean Climate Studies (EPOCS), as EPOCS Contribution No. 16.

REFERENCES


Charney, J. G., and P. G. Drazin, 1961: Propagation of planetary-
scale disturbances from the lower into the upper atmosphere. 

Chen, W. Y., 1982: Fluctuations in Northern Hemisphere 700 mb 
height field associated with the Southern Oscillation. *Mon. 

Chiu, W.-C., and A. Lo, 1979: A preliminary study of the possible 
statistical relationship between the tropical Pacific sea surface 
107, 18–25.

Davis, R. E., 1976: Predictability of sea surface temperature and 
sea level pressure anomalies over the Pacific Ocean. *J. Phys. 
Oceanogr.*, 6, 249–266.

Ebdon, R. A., 1975: The quasi-biennial oscillation and its 
association with tropospheric circulation patterns. *Meteor. Mag.*, 
104, 282–297.

Garcia, R. R., and D. L. Hartmann, 1980: The role of planetary 
waves in the maintenance of the zonally averaged ozone 
distribution of the upper stratosphere. *J. Atmos. Sci.*, 37, 2248– 
2264.

between the troposphere and middle atmosphere as a possible 
sun–weather mechanism. *J. Atmos. Sci.*, 37, 1197–1215.

Holton, J. R., and H.-C. Tan, 1980: The influence of the equatorial 
quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, 
37, 2200–2208.

—, 1982: The quasi-biennial oscillation in the Northern Hemi-

phenomena associated with the Southern Oscillation. *Mon. 

Hoskins, B. J., and D. J. Karoly, 1981: The steady linear response 
of a spherical atmosphere to thermal and orographic forcing. 


Julian, P. R., and R. M. Chervin, 1978: A study of the Southern 

Just, D., B. Kriester, K. Labitzke, R. Lenschow, K. Petzold, R. 
Scherhag and K. Sietland, 1969: Daily and monthly Northern 
Hemisphere 30-millibar synoptic weather maps of the year 


Livezey, R. E., and W. Y. Chen, 1983: Statistical field significance 

Opsteegh, J. D., and H. M. van den Dool, 1980: Seasonal differ-
ences in the stationary response of a linearized primitive equa-
tion model: Prospects for long-range weather forecasting? *J. 
Atmos. Sci.*, 37, 2169–2185.

Quiroz, R. S., 1980: Variations in zonal mean and planetary wave 
properties of the stratosphere and links with the troposphere. 

——, 1981a: The tropospheric–stratospheric mean zonal flow in 

——, 1981b: Period modulation of the stratospheric quasi-biennial 

Rasmussen, E. M., and T. H. Carpenter, 1982: Variations in tropi-

cal sea surface temperature and surface wind fields associated 
with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, 110, 
354–384.

Schmitz, G., and N. Grieger, 1980: Model calculations on the structure 
of planetary waves in the upper troposphere and lower stratosphere 
as a function of the wind field in the upper strato-

Simmons, A. J., 1982: The forcing of stationary wave motion by 
503–534.

Trenberth, K. E., 1976: Spatial and temporal variations of the 
654.

Part II: Associations with changes in the middle troposphere 

——, C. S. Zerefos and C. C. Repapis, 1982: The Southern 

Webster, P. J., 1982: Seasonality in the local and remote response 

——, and J. R. Holton, 1982: Cross-equatorial response to middle-
latitude forcing in a zonally varying basic state. *J. Atmos. Sci.*, 
39, 722–733.