Three-Dimensional Structure of Low-Frequency Pressure Variations in the Tropical Atmosphere

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ABSTRACT

Results of a recent study show eastward propagation of information in the low-frequency variations of the tropical sea-level pressure (SLP) field. The current work extends that analysis to investigate the vertical structure of this signal. It is found that the propagating signal exists to a height of at least 850 mb. At 500 mb the signal is not so clear, while at 200 mb there is little evidence of propagation of information. Instead, the low-frequency variations in 200 mb height appear coherent for the tropical belt around the entire globe. The analysis suggests that the anomalies discussed here appear first at the surface and later at higher levels in the atmosphere.

1. Introduction

In a recent study Barnett (1985, hereafter called B) showed that there is a large-scale signal in the sea-level pressure field in the tropics that propagates from west to east. The signal is first apparent over the Indian region, moves eastward and loses its coherence by the time it reaches the Americas. It was shown that this large-scale signal included such well known features as the Southern Oscillation (SO), monsoon variations, tropical–midlatitude teleconnection patterns and other features of interannual climate variability.

It is known from the work of Bjerknes (1972), Horel and Wallace (1981), Newell and Weare (1976), Quiroz (1983a), and others that changes of geopotential height at 200 mb in the tropics are strongly correlated with El Niño phenomena, Southern Oscillation indices and other measures of large-scale, *surface* climate change. Horel and Wallace show that the changes in the 200 mb height were essentially coherent around the entire tropical belt, i.e., the signal is a monopole. However, it is equally clear from their work, as well as much earlier work dating from the time of Walker and Bliss (1932) that the surface manifestation of the Southern Oscillation signal is dipole, i.e., SLP anomalies of one sign in the Indo/Australian region associated with SLP anomalies of the opposite sign in the southeastern Pacific. It is this dipole signal that B showed to be part of a larger scale propagating feature in the SLP field.

Thus work to date has suggested the existence of a propagating dipole signal at the surface with monopole signal at 200 mb. The sign of this monopole is identical to the sign of the SLP anomaly in the Indo/Australian region. These facts raise several questions: What is the relationship between the propagating, near-surface dipole signal and upper troposphere monopole? At what altitude does the dipole become a monopole? Is there any propagation associated with the monopole signal? And finally, do changes at the surface appear to lead or lag those at altitude? These questions were answered by performing a complex empirical orthogonal function (CEOF) analysis of upper air data from a number of stations in the tropical belt.

2. Data analysis

The upper air station geopotential height data for the tropical belt (±30° of the equator) were obtained from NCAR. A time period 1960–80 was selected for analysis based on the fact that the best distribution of monthly mean data was available for this period. The data from the surface, 850, 500 and 200 mb were extracted as time series. Each of these time series was inspected for gaps, discontinuities, etc. Fifty-nine stations having less than 15% missing data were selected for analysis.

Gaps in the time series for the different heights were filled by simple linear interpolation. The time series for each height and station were passed through an 11-month Parzen filter and then normalized to have unit variance. The filter effectively eliminated the variability associated with periods of 18 months or less.

The filtered dataset was then submitted to CEOF analysis (see Barnett, 1983, for details). Denote by $h_{lj}(t)$ the anomalous height data for station "l" and level "j". Define the Hilbert transform of h_{lj} by $\hat{h}_{lj}$. Then form

$$H_k(t) = h_k(t) + i\hat{h}_k(t)$$

where the subscript double (l, j) has been compressed to a single subscript (k) and $i = \sqrt{-1}$. The H_k are normalized to have unit variance, so the associated correlation matrix is

$$C_{kk'} = \langle H_k^* H_{k'} \rangle,$$

where asterisks denote complex conjugate.

this mode.

the entire tropical belt, whereas SLP signal (Figs. 1 and 2) was confined mainly to the Indian

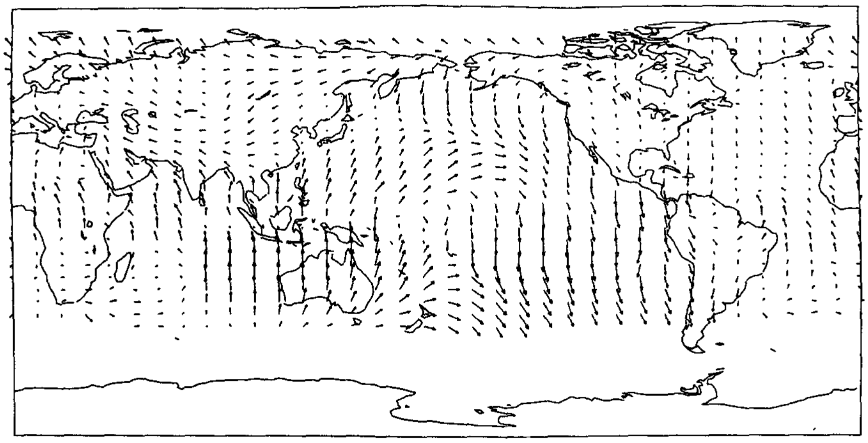

FIG. 1. Spatial phase vector resulting from a CEOF analysis of a near-global sea level pressure dataset (after Barnett, 1985).

The eigenvectors of **C**, denoted by B_{nk}, can be used to compute a "spatial phase vector." It is this quantity that will answer the questions posed before since it describes time averaged lead/lag relations between the h_k. In polar form the phase vector for the nth eigenmode is

$$V_{nk} = S_{nk}e^{i\theta_{nk}}$$

where

$$S_{nk} = [B_{nk}B^*_{nk}]^{1/2}$$

and

$$\theta_{nk} = \tan^{-1}\left[\frac{\mathrm{Im}B_{nk}}{\mathrm{Re}B_{nk}}\right]$$

The scaling is such that $\langle B_{nk}B_{mk}\rangle = \delta_{nm}$.

3. Results

The spatial phase vector for the full analysis of the near-global SLP field from B is shown in polar form in Fig. 1. The length of the vectors indicates the relative magnitude of the signal at each grid point, whereas the direction of the vectors gives information about lead and lag relative to an arbitrary reference point. In this case, as well as all of the rest of the diagrams to be shown, spatial phase is referenced to Darwin SLP, so the phase vector at Darwin points due north. Spatial vectors that point to the right (east) are associated with information that lags Darwin, whereas vectors oriented to the left (west) represent information that leads Darwin. The clockwise rotation of spatial phase vectors along the given latitudes suggests propagation of information from west to east.[1]

The surface phase vectors associated with mode 1 of CEOF analysis of the upper air stations are shown in Fig. 2. Note that the stations were generally placed relatively well to pick up the propagation of information in the Northern Hemisphere from the Indian Ocean across Australia and through the tropical Pacific. This is suggested by the clockwise rotation of the phase vectors as one moves from west to east. The dipole pattern involving the Indo/Australian region and the southeast Pacific is not well defined due to a lack of stations in the latter region. Intercomparison of Figs. 1 and 2 will be useful in relating the sparse upper air data network to the variations in the comparatively well sampled SLP field.

The spatial phase vectors at 850 mb are shown in Fig. 3. Note that these phase vectors look much like those seen at the surface. This fact is further verified in Fig. 4 which shows the SLP and 850 mb state vectors together. It is clear that the propagating signal exists at 850 mb as it does at the surface. As with SLP, the 850 mb signal seems to die out as it reaches the Americas (cf. B).

Figure 5 shows the 500 mb phase vector set. The propagation of information seen at the lower levels is harder to discern here, although there is a weak suggestion that it does exist. The main feature of the illustration is the monopole pattern mentioned earlier, i.e., all of the larger vectors point in essentially the same direction. Thus the transition between dipole and monopole appears to occur between 850 and 500 mb. The results of Horel (1981) and Chen (1982) hint that the transition occurs in the 600–700 mb level. Finally, note that the signal is still relatively strong and that it is now of nearly equal strength throughout the tropical belt, wherever data exists, i.e. no attenuation is seen over the Americas.

By the time one reaches 200 mb (Fig. 6) the monopole signal is even more clear. It is also obvious that the signal covers the entire tropical belt, whereas SLP signal (Figs. 1 and 2) was confined mainly to the Indian

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[1] Mode 1 captured 33% of the variance in the upper air dataset. The relative energy of each of the four levels was nearly equal for this mode.

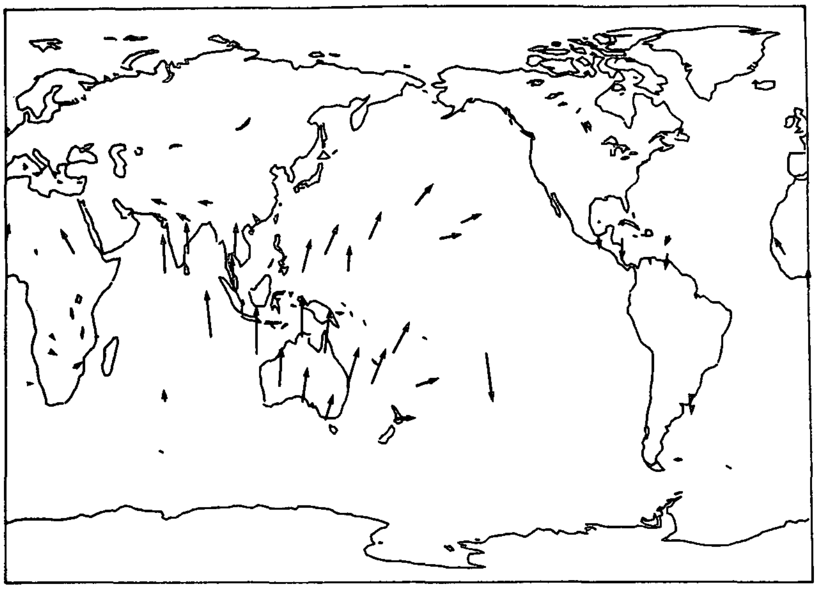

FIG. 2. Spatial phase vector derived from an analysis of near surface pressure at the upper air stations used in this study. All phases are measured relative to Darwin.

and the Pacific regions. There is virtually no sign of propagation. This contrasts with the observation of Quiroz (1983b) that eastward propagation of the zonal 200 mb wind anomaly occurred during the 1982–83 event, a time period not covered by the current analysis. However, the lowpass filtering of the data may have obscured this feature if it occurs only during part of the life cycle of the large scale near surface feature described by B. Mode 2 also did not show any propagation at the upper levels.

Comparison of the 850 and 200 mb phase vectors (Fig. 7) and the 850/500 vectors (not shown) suggests that the changes at 850 mb in the southeast Asia region appear to lead those at 500 and 200 mb, i.e., the spatial state vectors at the lower level generally point to the left of those at the higher levels. Thus, standard measures of the Southern Oscillation index would be expected to lead changes in the upper troposphere height field. Just such a relation was found by Quiroz (1983a) at 200 mb and Chen (1982) at 700 mb.

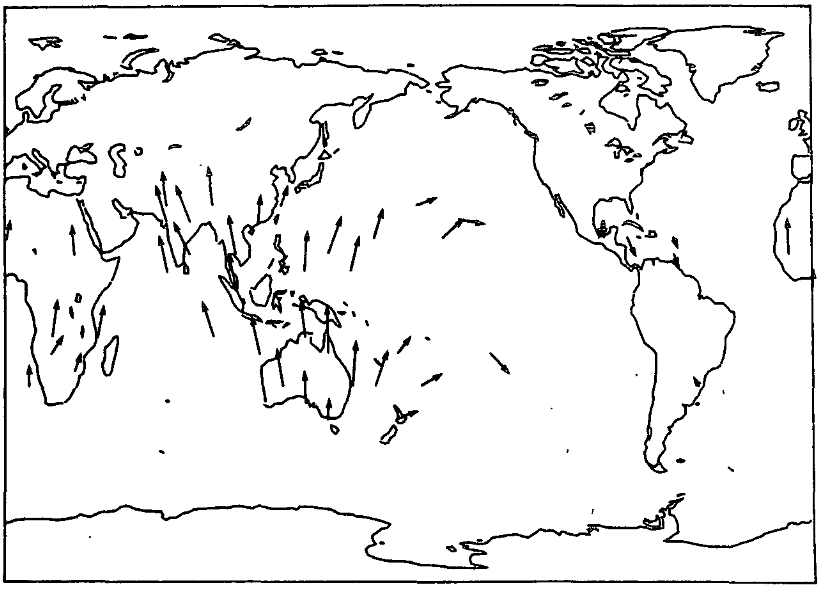

FIG. 3. As in Fig. 2 except for 850 mb.

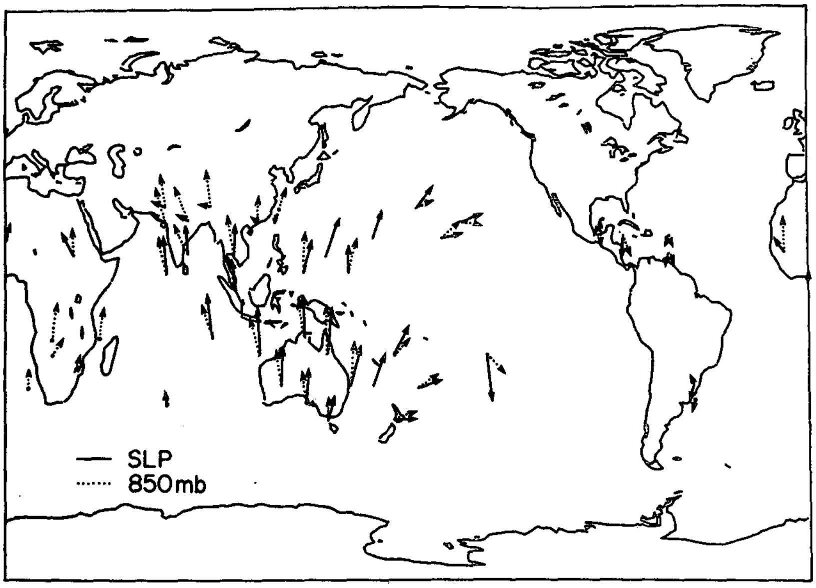

FIG. 4. Spatial phase vectors for sea-level pressure and 850 mb.

The region of near congruence of the 850/200 mb phase vectors appears to lie over Indonesia and the far western Pacific. This is where the forcing from the surface layers apparently reaches to the upper levels of the troposphere, i.e., a barotropic response is observed. Note that the response of the upper troposphere remains fixed as the anomaly at 850 mb moves out into the central Pacific. Thus the sign of the anomalies at the surface and 500/200 mb over the eastern Pacific are out of phase, i.e. a baroclinic response is observed. The preceding results suggest that it is anomalous forcing from the planet's surface that is driving the large scale signal (Southern Oscillation, etc.); the signal doesn't appear to start in the upper atmosphere.

4. Conclusions

A complex empirical orthogonal function analysis has been made of upper air data in the tropical belt. This analysis is similar to the one made for a near-global sea-level pressure data set by Barnett (1985). The results of the present study suggest:

1) The propagating signal found in the SLP field by Barnett (1985) is seen also at 850 mb. However, it does

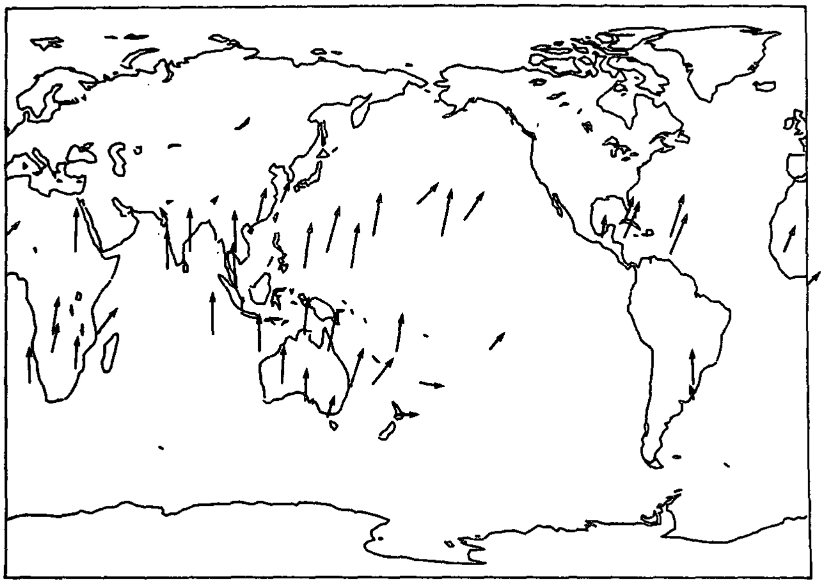

FIG. 5. As in Fig. 2 except for 500 mb.

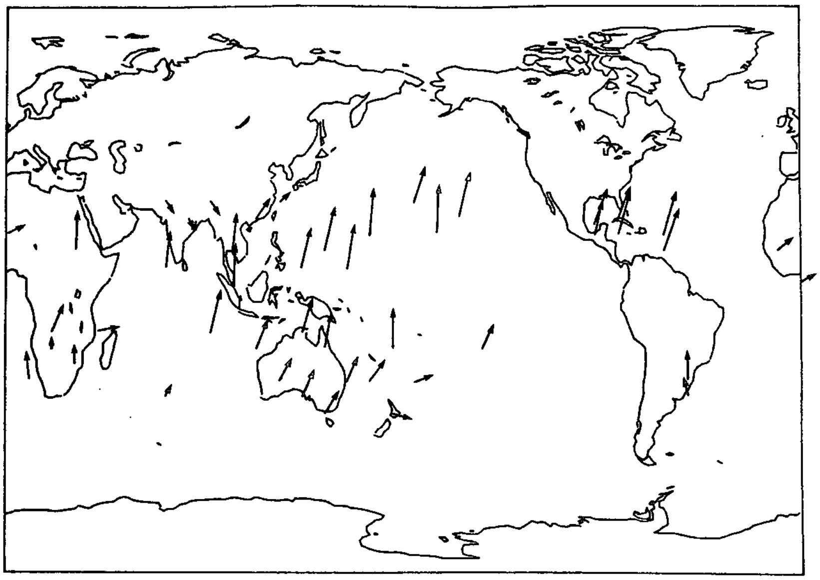

FIG. 6. As in Fig. 2 except for 200 mb.

not seem to appear above 500 mb. This suggests this signal is a creature of the lower atmosphere.

2) At higher levels in the troposphere the signal associated with the Southern Oscillation and large-scale SLP signal discussed by B is a monopole. This result is in agreement with previous findings by Bjerknes (1972), Horel and Wallace (1981) and others. There is little sign of propagation of information at these higher altitudes.

3) The transition from the surface dipole signature of the Southern Oscillation to the monopole signal characteristic of 200 mb appears to occur between the 850 and the 500 mb levels, a result in accord with the findings of Horel (1981). The mechanisms responsible for this transition and differential vertical response in the atmosphere are unknown.

4) It appears that the monopole signal at 200 mb lags slightly the surface signal as seen near India but is in phase with the surface signal over the far western Pacific. This suggests that interactions between the surface of the planet and the lower atmosphere are responsible for the large-scale variations seen at the upper levels of the troposphere. It also illustrates the obvious fact that the upper and lower levels of the troposphere

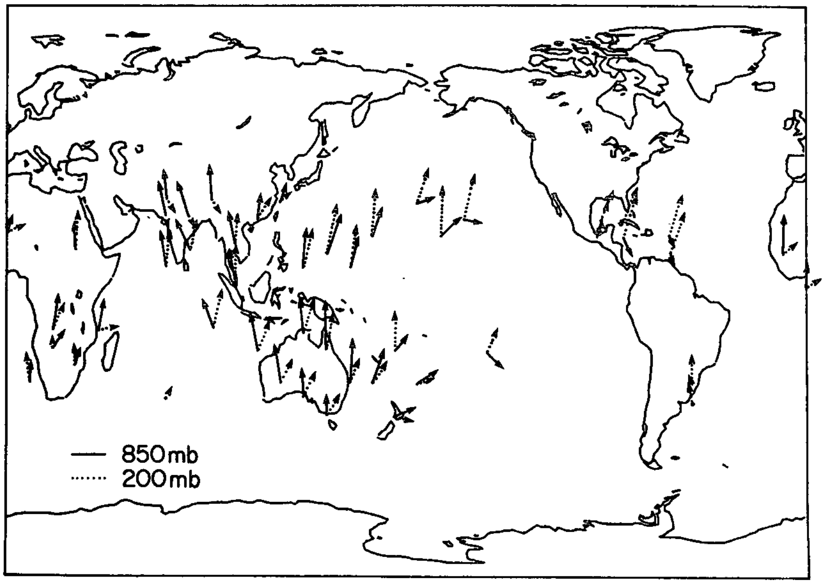

FIG. 7. As in Fig. 4 except for 850 and 200 mb.

communicate most effectively in the area of large convergence associated with the Indonesian Low.

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