NOTES AND CORRESPONDENCE

A Possible Link of the QBOs Between the Stratosphere, Troposphere and Sea Surface Temperature in the Tropics

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Abstract

Some evidence is presented on the interaction of the QBOs between the stratospheric and the tropospheric zonal wind in the tropics. Zonal winds over some stations (Singapore, Koror, Ponape) in the equatorial Pacific clearly show the coherent vertical phase structure between the downward propagation of zonal wind anomalies in the stratosphere and the zonal wind anomalies in the lower and the upper troposphere. The QBOs in the tropospheric zonal wind are also proved to be coupled with that in the SST anomalies in the equatorial Pacific.

These results suggest a possible dynamical link of the QBO in the large-scale coupled atmosphere/ocean system over the Asian monsoon region through the equatorial Pacific with that in the equatorial stratosphere.

1. Introduction

The quasi-biennial oscillation (QBO) in the zonal wind is a predominant phenomenon in the tropical stratosphere. Lindzen and Holton (1968) and Holton and Lindzen (1972) presented a confirmative theory of this oscillation.

On the other hand, many observations have suggested similar QBO-like oscillations in the troposphere (Trenberth, 1975; 1980; Ebdon, 1975; Angell and Korshover, 1974; 1975; Gordon and Wells, 1975; Yasunari, 1981 *etc.*). Some studies also focused on the problem of the inter-relation of QBOs between the troposphere in the mid latitudes and the stratosphere in the tropics (Trenberth, 1980; Gray, 1984). However, there has been so far no certain evidence of coupling of the QBOs between the troposphere and stratosphere. Some theoretical studies presented a somewhat different mechanism of the tropospheric QBO (Brier, 1978; Nicholls, 1978).

The previous studies on the coupling of the QBOs have dealt with the correlation of some specific parameters in the higher-latitude troposphere and the QBO in the tropical stratosphere. The present study, however, will present some evidence of the *in situ* association of the QBOs between the stratosphere and the troposphere in the tropics. This approach may be important, since the stratospheric QBO is based on forcing in the tropical troposphere (Holton, 1972).

2. Data

Monthly mean zonal winds at 850 mb through 30 mb over Singapore, Koror, Truk and Ponape for 18 years (1964–1981) are adopted. Additionally, monthly mean zonal winds at 200 mb and 700 mb (10°×10°) from NMC operational wind field analysis for 18 years (1968–1985) were utilized. Monthly mean sea surface temperatures (SST) for 173 months (Jan. 1964 to May 1978) were also adopted, which were originally compiled by NOAA (Reynolds, 1983).

3. Stratosphere-troposphere coupling of QBOs in the zonal wind

a. QBOs in the equatorial Pacific

Holton and Lindzen's theory on the QBO in the stratospheric zonal wind in the tropics assumes a random forcing by wave energy of the eastward-moving Kelvin waves and the westward-moving Rossby-gravity waves from the lower boundary (*i.e.*, from the troposphere), which interact with the zonal mean flow in the stratosphere. However, the ac-

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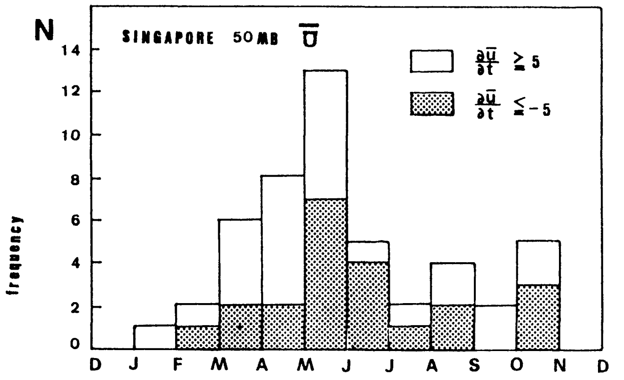

Fig. 1. Frequency distribution of zonal wind acceleration at 50 mb over Singapore which exceeds +5 ms^{-1} month for each month of year. Period for the statistics 23 years (1961–1983).

tual forcing by the waves for the stratospheric QBO seems to have a strong seasonality. Fig. 1, for example, shows the frequency of westerly (easterly) acceleration of the zonal wind at 50 mb over Singapore that exceeds +5 ms^{-1} month. The timings of maximum westerly (or easterly) acceleration appear mostly during March through July. That is, the upward wave-energy propagation from the lower stratosphere through the upper troposphere apparently shows seasonal phase-locking, which suggests the influence of the seasonal change of the wave energy activity in the troposphere on the stratospheric QBO.

The dominant periodicities of zonal wind at each level are examined from the stratosphere down to the lower troposphere. Fig. 2 shows the results of MEM (Maximum Entropy Method) power spectra for 9 levels from 30 mb through 850 mb. At 30 mb and 50 mb the QBO is shown as a single dominant peak, while at the tropopause level (100 mb) both the QBO and the annual cycle (12–month period), show maximum power. In contrast, in the upper troposphere (150 mb, 200 mb and 300 mb) the peaks associated with the annual cycle (12–month and 6–month period) predominantly appear. The peak with a period range from 35 to 55 months also exists as a dominant interannual mode, which is associated with the El Niño/Southern Oscillation (ENSO) cycle (Yasunari, 1987). It is interesting to note that in the lower troposphere (700 mb and 850 mb) excepting the annual cycle the period with QBO time scale again appear as a dominant interannual mode.

Cross-spectral analysis was then applied to the zonal wind at 50 mb and 700 mb, to examine the coherence of two QBOs in the stratosphere and in the lower troposphere. Fig. 3 shows the coherence spectra between the 50 mb and 700 mb zonal wind by using FFT cross-spectral analysis for the period of 173 months (Jan. 1964–May 1978). High coherence values of more than 0.9 are noted in the QBO period range. To see the phase relationships among each level for the QBO mode, the time-height section of the filtered zonal wind anomalies is composed as shown in Fig. 4. The Butterworth recursive filter (M. Murakami, 1981) with the maximum response of 22 to 32 months centered at 27 months is adopted for the filtered series. This figure surprisingly shows a possibility of coupling of the QBO in the stratospheric zonal wind with that in the troposphere. The downward propagation of the anomalies in the stratosphere are well synchronized with the upward propagation of anomalies at the tropopause through the upper troposphere. In the troposphere, the phase of anomalies show an upward propagation from the surface level to the upper troposphere, and the easterly (westerly) anomalies in the upper level are simultaneously coupled with the westerly (easterly) anomalies in the lower troposphere, which suggests the existence of the QBO mode in the large-scale convective activity.

The non-existence of the QBO signal in the upper troposphere at Singapore may be, at least partly, related to its location in the zonal structure of the tropospheric QBO. As shown in Yasunari (1985), the tropospheric QBO in the zonal wind has a zonally-standing component with some quasi-standing nodes, though it totally shows an eastward propagation with a structure of zonal wavenumber one and/or two. For example, Fig. 5 shows the longitude-time section of the QBO mode in the zonal wind at 200 mb with easterly and westerly maxima at 700 mb. This diagram shows that the time-mean amplitude of this mode differs considerably from place to place along the longitudes. Singapore seems to be located near a node of this mode, or in the area of smaller amplitudes. In fact, the result of the MEM spectral analysis of zonal winds at three stations (Koror; Truk; Ponape) in the equatorial western and central Pacific (Fig. 6) shows a very large power in the QBO mode (20–30 months) in the upper and the lower troposphere ,even compared to the ENSO mode (40–60 months).

b. Phase structures in vertical-zonal plane

The QBO in the stratosphere has no zonal structure (*i.e.*, the dominance of wavenumber zero) while that in the troposphere has a zonal structure of wavenumber one and/or two with the eastward phase propagation as shown in Fig. 5. The feature of vertical coupling between these two QBOs should, therefore, be different from place to place along the equatorial longitudes.

To examine the vertical phase structure of these QBO modes along the equatorial Pacific, the vertical-timelag section of the correlations (from

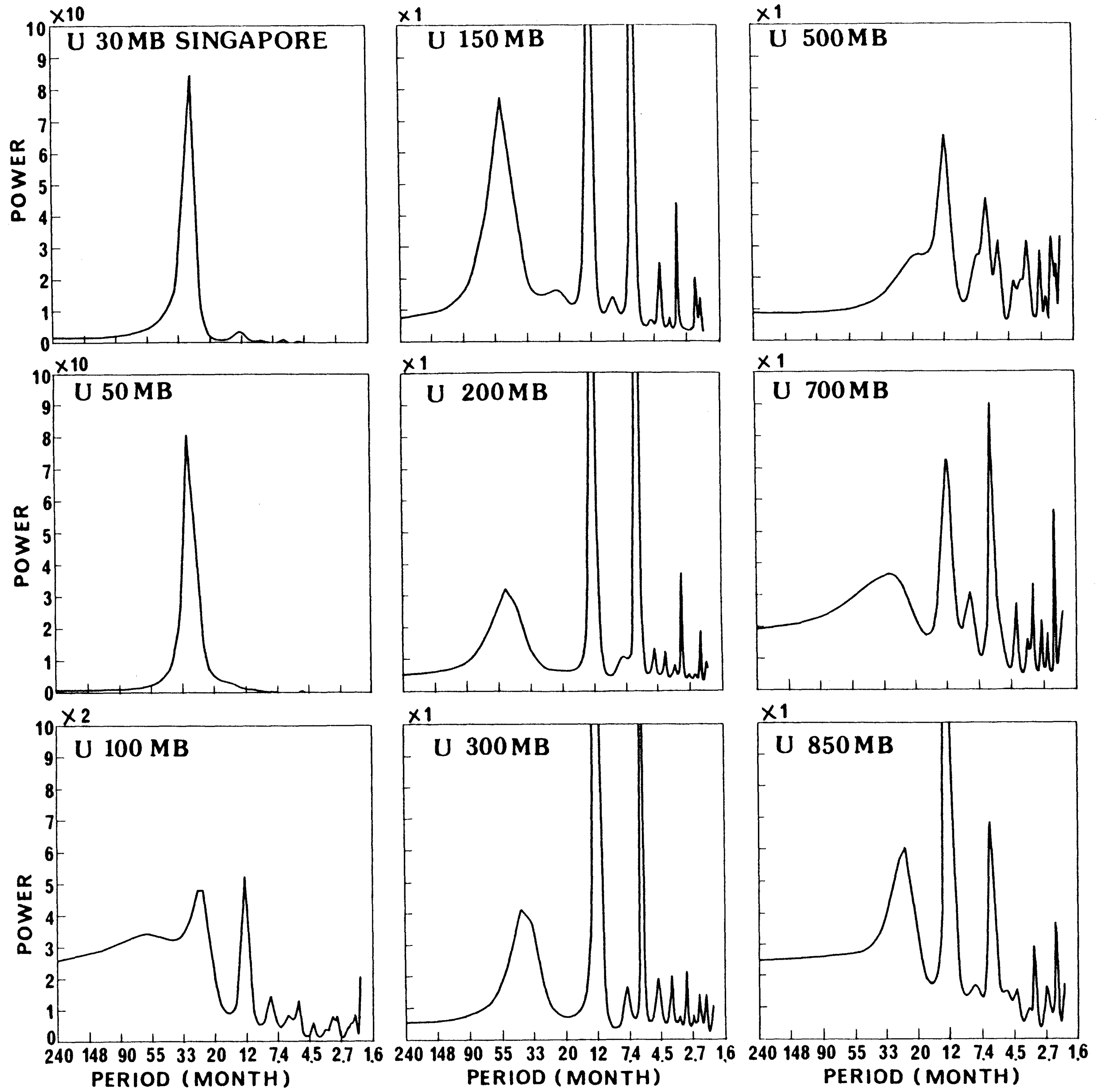

Fig. 2. MEM Power spectra of monthly mean zonal wind at each level (30 mb through 850 mb) over Singapore for the period of 18 years (1963–1981). Units are ms^{-1} month. Maximum lag number of 40 is adopted.

lag=−13 to +13 months) between the 700 mb zonal wind and that of each height level are composed for Singapore, Koror and Ponape, as shown in Fig. 7. Although the band-pass filtered data were adopted for this computation to see more clearly the phase relation of the QBOs, the results from the low-pass filtered data containing the components of broader frequency band show fundamentally the same correlation structures.

The vertical structure of Singapore in this diagram has confirmed the anomaly structure in Fig. 4. That is, the downward propagation of positive (negative) correlations are combined together with the positive (negative) correlations in the upper troposphere. In the extreme phases, the zonal wind anomalies in the lower troposphere are negatively correlated with those in the upper troposphere, and positively correlated with those at 50 mb.

At Koror and Ponape, although the phase structures in the troposphere are nearly the same as that at Singapore, the phase relations of the upper (or lower) troposphere to the stratosphere show the systematic time lags from the west (Singapore) to the east (Ponape). This implies the systematic eastward propagation of tropospheric QBO anomalies relative to the stratospheric QBO, since the anomalies in the stratosphere change nearly simultaneously along the whole equatorial belt.

If we take the phase of maximum correlation of, say, 30 mb as a reference of simultaneity, the correlation patterns in the upper (and the lower) troposphere show a systematic phase change between the maritime continent (Singapore) and the central/western Pacific (Koror and Ponape). They show nearly the opposite signs to each other, which indicates the Walker-type cell structure in the zonal wind along the equatorial central/western Pacific. These features in the tropospheric QBO are consistent with the results by Yasunari (1985, 1989), and Gutzler and Harrison (1987). For example, when the zonal wind at 50 mb is changing from the east to the west, that in the upper (lower) troposphere over Singapore is nearly the maximum in the easterly (westerly), while that in the upper (lower) troposphere over Koror or Ponape is near the end of the westerly (easterly) phase.

c. Phase lock to the annual cycle

As mentioned earlier (Fig. 1), the stratospheric QBO shows a strong phase lock to the annual cycle. The phase structure of the QBO in the stratosphere through the troposphere may, if so, be more distinctly exhibited in the composites stratified for the typical phase of the QBO cycle in the stratosphere.

Fig. 8, for example, shows the composite structure of the zonal wind anomalies for the 7 years (1966, 1969, 1971, 1973, 1975, 1978, 1980) over Ponape when the QBO at 50 mb changes from the east to the west (Year-1) and the next years (Year-2). The diagram of stratospheric zonal wind in Maruyama (1988) is adopted for selection of the years. This diagram clearly shows that the westerly maximum in the stratosphere is phase-locked to the winter season, while the westerly (easterly) maxima both in the upper and the lower troposphere are phase-locked to the summer through autumn season. Here, we should bear in mind that the seasonal convection center is located over South Asia through the western Pacific in these seasons, and the westerly (easterly) maximum in the upper (lower) troposphere over this region is associated with the strong convection over the convection center to the west. Over Singapore, in contrast, the westerly (easterly) maximum in the lower (upper) troposphere also appears in the winter season in phase with the westerly maximum in the stratosphere, as is easily deduced from Fig. 7. In other words, a strong winter monsoon over this region is in phase with the westerly maximum in the lower stratosphere. In the summer of Year-2, in contrast, weak convection over the Asian monsoon region is suggested by the zonal wind anomalies in the troposphere. At this phase

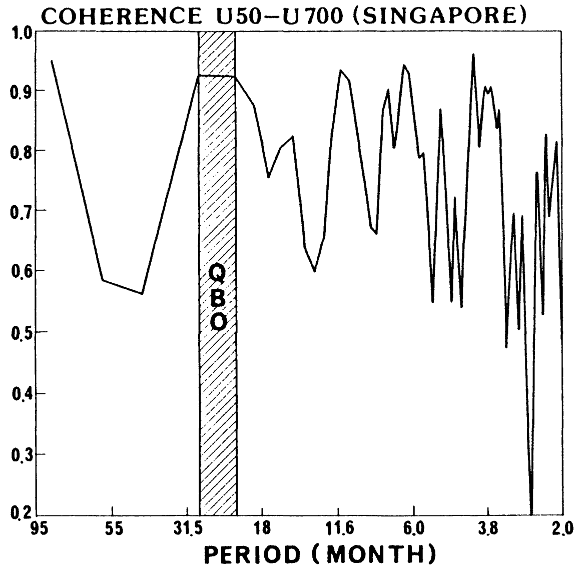

Fig. 3. Coherence spectra of monthly mean zonal wind between 50 mb and 700 mb over Singapore. Period of QBO time scale are shaded.

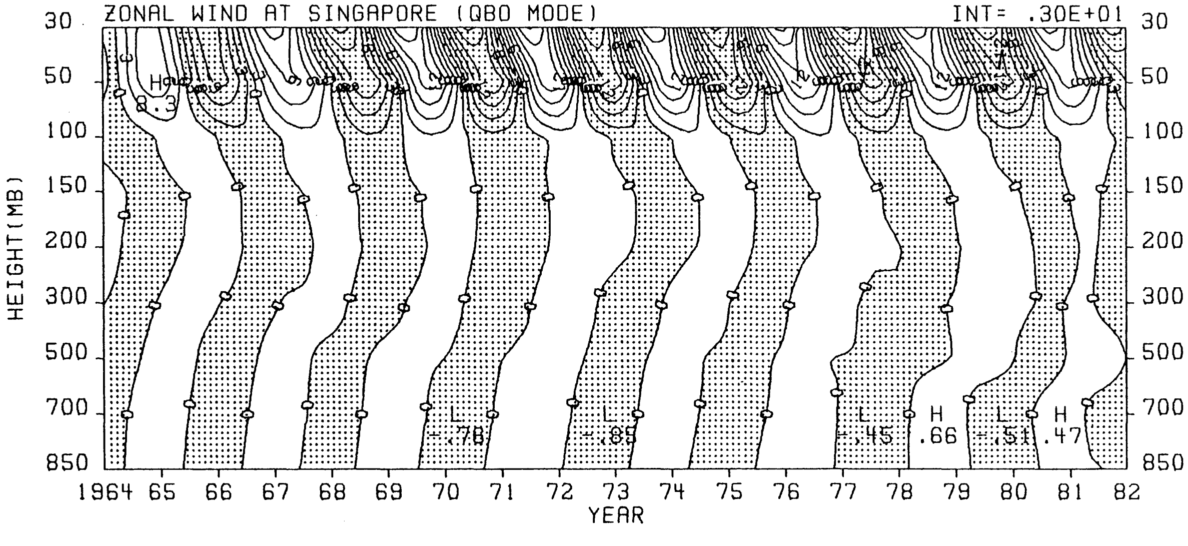

Fig. 4. Height-time section of filtered zonal wind (QBO mode) over Singapore. Units are 3 ms^{-1} and negative (easterly) anomalies are shaded.

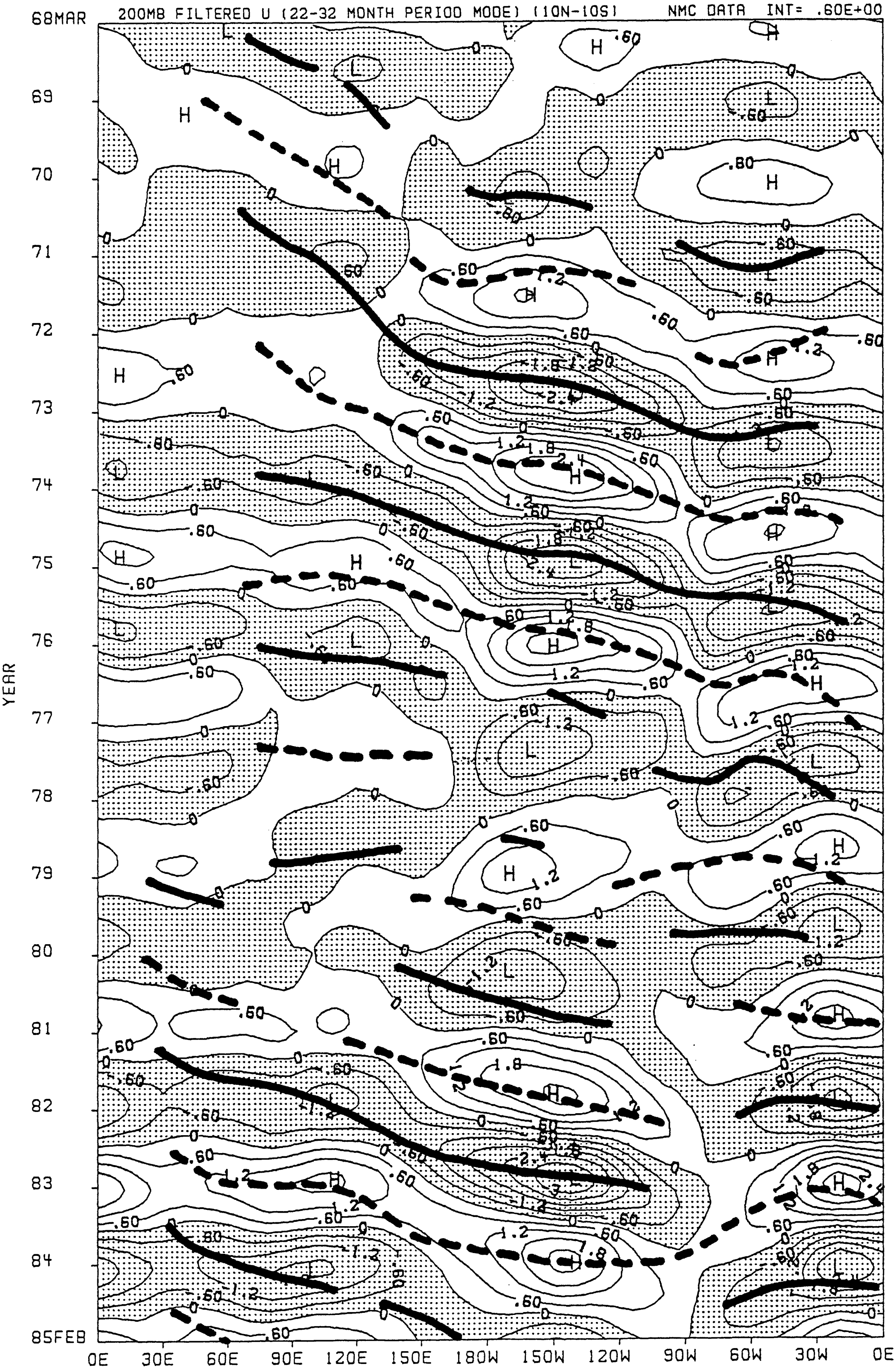

Fig. 5. Longitude-time section of filtered zonal wind (QBO mode) at 200 mb along the equatorial belt (10°N–10°S). Units are 0.6 ms^{-1} and negative (easterly) anomalies are shaded. Phases of westerly (easterly) maxima of filtered zonal wind (QBO mode) at 700 mb are also indicated with thick solid (dashed) lines.

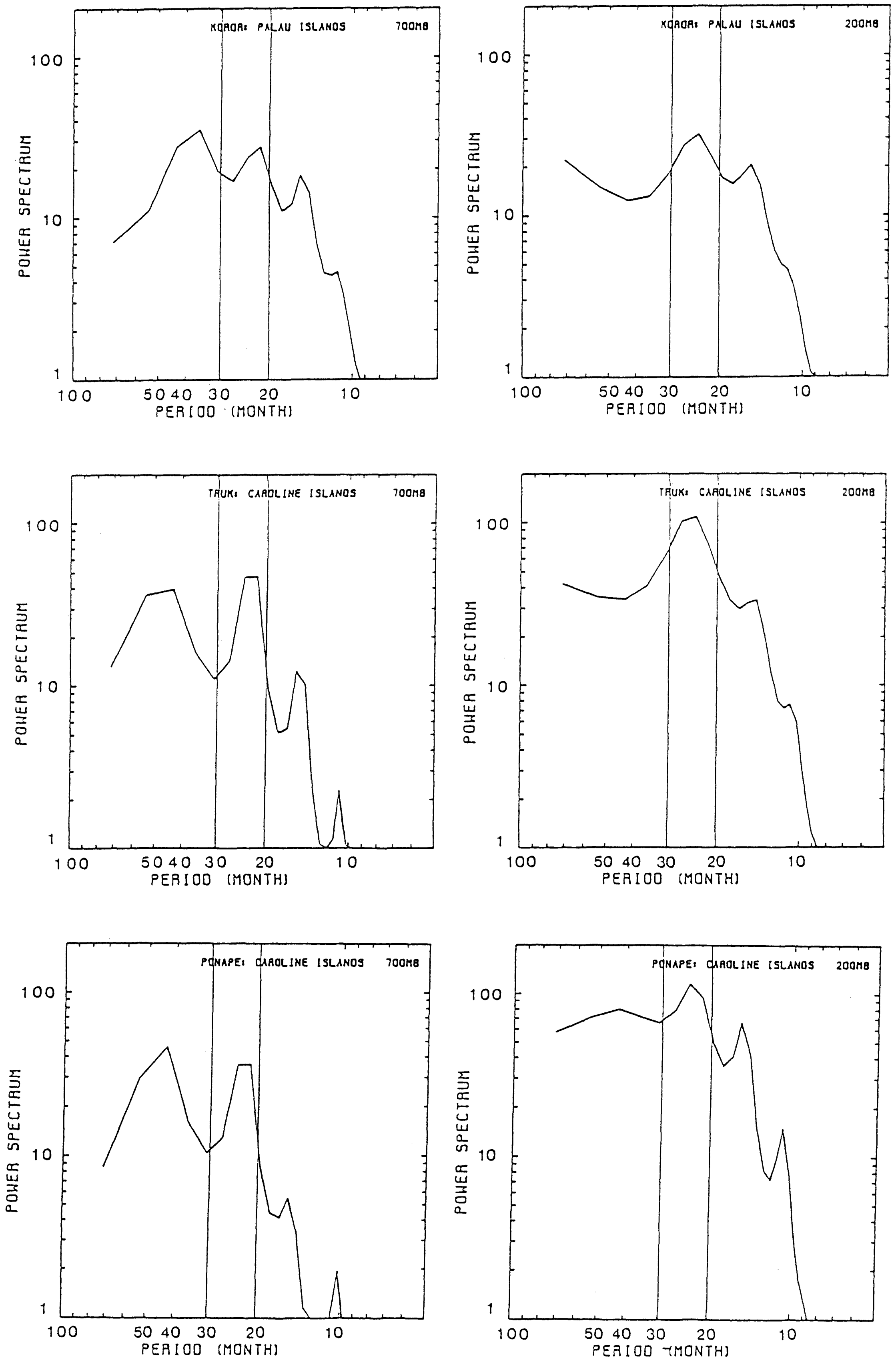

Fig. 6. MEM power spectra of zonal wind at 700 mb and 200 mb over Koror (7.3°N, 134.5°E), Truk (7.5°N, 151.9°E) and Ponape (7.0°N, 158.2°E) for 18 years (1964–1981). The power of annual cycle and period band with less than 6 months are filtered out of time series. Maximum lag number of 40 is adopted. QBO time scale (20–30 month period) is shown in each diagram.

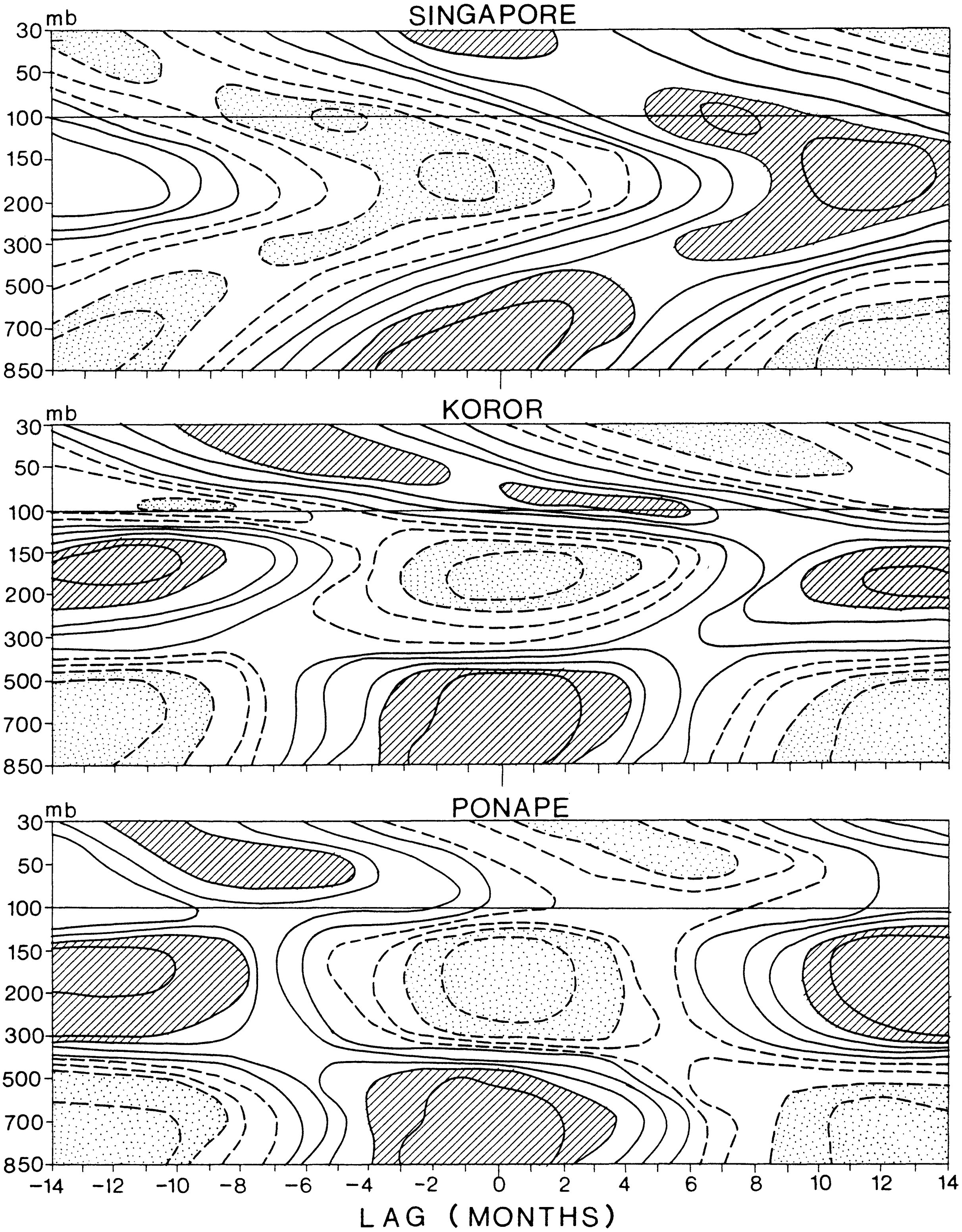

Fig. 7. Vertical-timelag section of correlation between zonal wind at 700 mb and that of each level (850 mb to 30 mb) for Singapore, Koror and Ponape. The contour interval is 0.2 with positive contours solid (negative contours dashed). Values above 0.6 (below −0.6) are hatched (dotted). The thin solid line at 100 mb shows the approximate tropopause level.

the zonal wind in the lower stratosphere appears to be a strong easterly, which was consistent with the former finding by Mukherjee *et al.* (1985). These results suggest some plausible role of seasonal convective activity from summer through winter over the Asian monsoon region through the western Pacific on the QBO in the stratosphere. This aspect will be discussed further later.

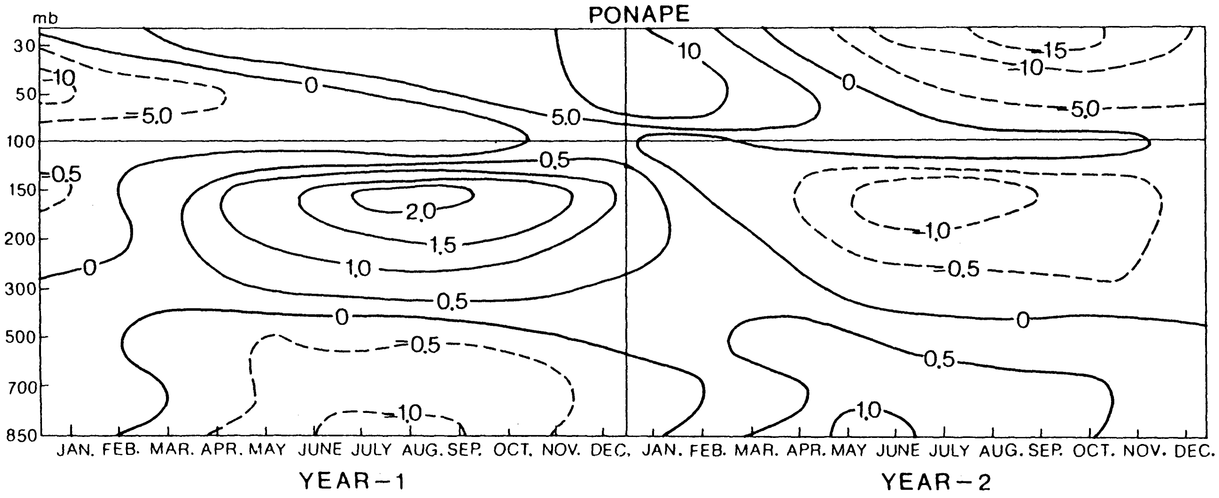

Fig. 8. Vertical-time section of zonal wind anomalies over Ponape composited for 7 years when easterly changes to westerly at 50 mb (Year-1) and for the next years (Year-2). Contour interval is 5.0 ms^{-1} at 30 mb and 50 mb and 0.5 ms^{-1} below 100 mb levels.

4. QBOs in the tropical troposphere and SST

The results deduced for the troposphere in the previous section have proved to be part of the tropospheric QBO along the equatorial belt detected by Yasunari (1985), Gutzler and Harrison (1987) and Kawamura (1988). That is, in addition to the ENSO mode (40–60 month period), the zonal wind in the tropical troposphere has a component of transient east-west circulation with the QBO time-scale, which shows a totally eastward propagation (Fig. 5). The eastward propagation seems to be partly due to the seasonal migration of an anomalous wind in the western through the eastern Pacific (Meehl, 1987), as has also been suggested here (Fig. 7 and Fig. 8).

This anomalous east-west circulation should be associated with the anomalous convection, which may, in turn, be connected with the sea-surface temperature (SST) anomalies of the same time scale along the equatorial Pacific. In fact, it was noted that the SST anomalies along the equatorial Pacific have the QBO mode as well as the ENSO mode (Rasmusson and Carpenter, 1982; Yoshino and Kawamura, 1987). Fig. 9 shows the time-longitude section of the QBO mode in the SST along the equatorial belt. In this diagram the phases of westerly and easterly maximum of the QBO in the zonal wind at 850 mb and 50 mb over Singapore are also shown, to see whether both QBOs in the tropical atmosphere and that in the SST coherently fluctuate or not. The westerly (easterly) maxima at 700 mb for the period from 1968 to 1978 (Fig. 5) over the eastern Pacific (180°–90°W) correspond well to the SST maxima (minima) over there. Fundamentally the same feature has been noted by Kawamura (1988). Although the SST anomalies in the western Pacific (100°–150°E) are small compared to the eastern Pacific, these are highly coherent with the zonal wind anomalies at 850 mb over Singapore. That is, the maximum (minimum) SST appear just in the intermediate stage from the easterly (westerly) to the westerly (easterly) maximum at 850 mb. It is also interesting to note that the westerly (easterly) maxima at 50 mb, for example, are nearly in phase with the minimum (maximum) SST anomalies over the central through the eastern Pacific through the whole analysis period (1964–78), which is expected from the vertical coupling of zonal winds as shown in Fig. 4.

These coherent phase relations between the SST and the lower tropospheric zonal wind suggest that the ENSO-like atmosphere ocean coupling via convection do exist for the QBO mode over the equatorial Pacific. Very recently, the dynamical coupling of the tropical east-west circulation and the SST with the QBO time $\frac{1}{N}$ scale along the equatorial belt has been comprehensively discussed by Yasunari (1989).

5. Summary and discussion

Some evidence has been presented for the coupling of the QBO in the stratospheric zonal wind with that in the tropospheric zonal wind in the tropics. In addition, this QBO in the troposphere has proved to be coupled with that of the SST anomalies in the equatorial Pacific. The QBOs in the tropospheric zonal wind and in the SST suggest an ENSO-like large-scale atmosphere-ocean coupling over the equatorial Pacific. The signals of the QBO in zonal wind are predominantly strong, even compared to the ENSO signals, over the Indonesian maritime continent through the western Pacific. Other surface elements over this region, such as surface wind

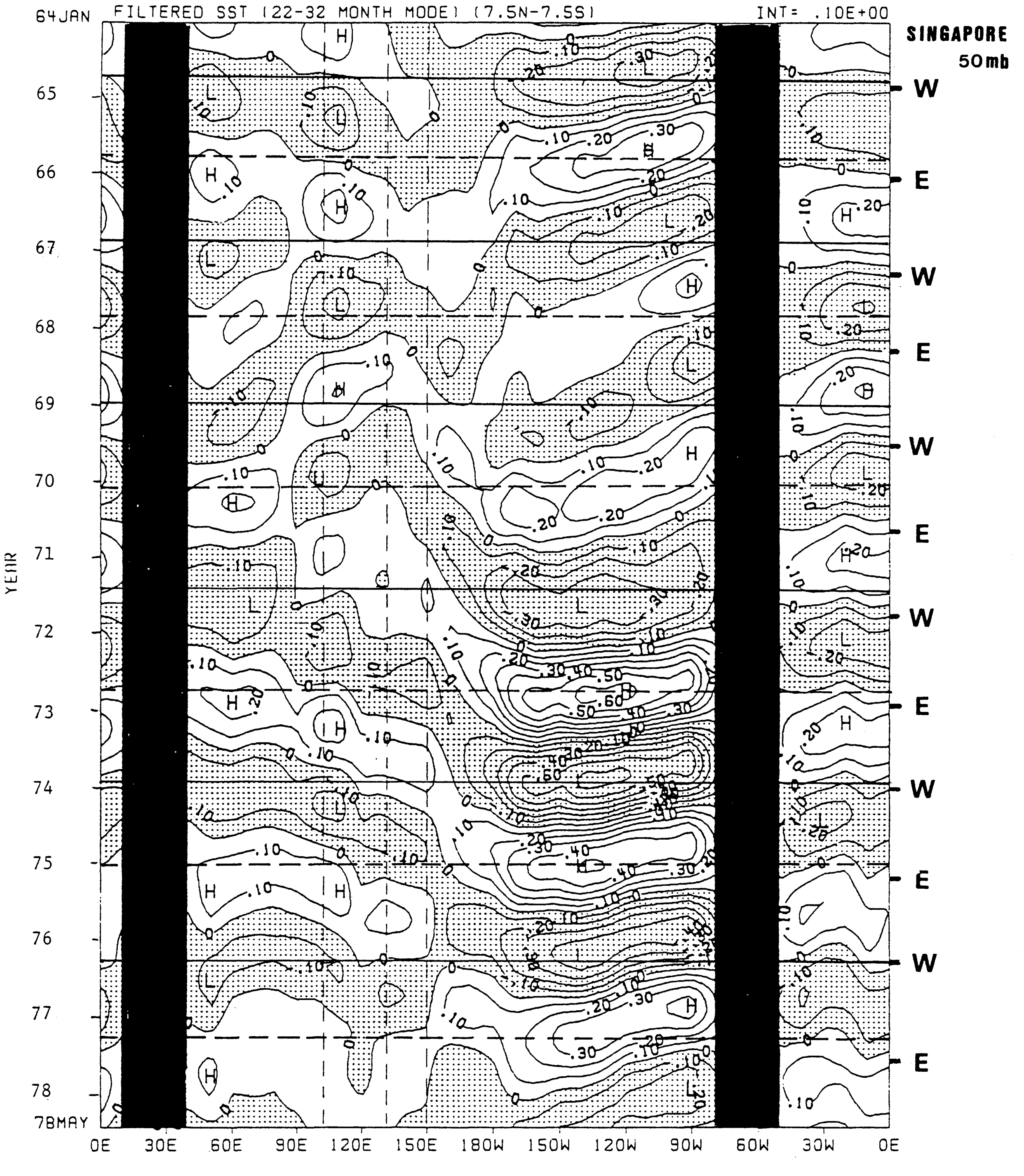

Fig. 9. Longitude-time section of filtered SST anomalies (QBO mode) along the equatorial belt (7.5°N–7.5°S). Units are 0.1°C and negative anomalies are shaded. Phases of westerly (easterly) maxima of filtered of zonal wind (QBO mode) at 850 mb over Singapore are shown with solid (dashed) lines. Phases of westerly (easterly) maxima of zonal wind at 50 mb are also plotted at the right-hand side of the diagram with capital letters of W (E).

stress (Kutsuwada, 1987) and rainfall (Yasunari, 1981: Yasunari and Suppiah, 1988) also show significant QBO in the interannual variation. In other words, the couple atmosphere/ocean system in the tropical Pacific with the QBO time $\frac{1}{N}$ scale centered in the western Pacific is suggested to be linked with the QBO in the stratosphere.

As earlier mentioned, these QBOs are strongly phase-locked to the seasonal cycle. As shown in Meehl (1987) and Yasunari (1989), the internannual anomalies in convection (rainfall) over Asian monsoon region through the tropical Pacific is strongly phase-locked to the northern summer through the northern winter season, associated with the seasonal migration of the convection center. It may be postulated, therefore, that the stronger than normal convection over this region from the northern summer to the winter season is closely related to the downward phase shift of westerlies in the lower stratosphere in the same seasons (Fig. 7) possibly via the stronger than normal Kelvin wave energy. Very recently, by using a simple one-dimensional model, Tanaka and Yoshizawa (personal communication) has shown that the periodicity of the stratospheric QBO is well synchronized with that of the tropospheric forcing of zonal mean flow. Their results suggest that although the stratospheric QBO may be undoubtedly interpreted as a typical wave-mean flow interaction (Holton and Lindzen, 1972: Lindzen, 1987), the tropospheric QBO may act as a pacemaker or frequency-modulator of the stratospheric QBO.

Another possibility may be that the QBO in the stratosphere modulates convective activity in the troposphere via some unknown mechanism. It is interesting to note in Fig. 8 that the tropospheric zonal wind anomalies (associated with the convection anomalies over the maritime continent) seems to change their signs when the westerlies in the stratosphere reach the tropopause level. In all events, the strong seasonal phase-lock of both the zonal wind acceleration in the stratosphere and the convection anomaly, particularly over the maritime continent, may provide some clue to the solution of these problems. Further observational and theoretical studies are apparently needed.

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熱帯の成層圏、対流圏および海面水温の準二年振動 (QBO) のあいだのリンクの可能性について

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熱帯の成層圏および対流圏の東西風に見られるQBOが、相互作用をしている証拠を提示する。赤道太平洋上のいくつかの地点における成層圏QBOの下方伝播と、対流圏QBOの間には、鉛直方向にコヒーレントな位相構造が見られる。対流圏QBOはまた、赤道太平洋上の海面水温のQBOと、対流活動を通じて結合していることも示された。

これらの結果は、アジアモンスーン地域から赤道太平洋にかけての大気・海洋結合系に見られるQBOが、熱帯成層圏のQBOと力学的にリンクしている可能性を示唆させる。