Influence of the Stratospheric QBO on ENSO Variability

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Abstract

A hypothetical mechanism is described whereby the Quasi-Biennial Oscillation (QBO) of Zonal winds in the equatorial stratosphere actively modulates the timing of El Niño-Southern Oscillation (ENSO) events. The mechanism involves the meridional redistribution of deep convective activity throughout the tropical Pacific warm pool region in response to variable wind shear processes which are linked to the opposing phases of the QBO. Hydrostatic conditions favoring deep convective activity within approximately ±7° of the equator develop in response to the easterly shear phase of the QBO. At the same time, deep convection is inhibited in the monsoon-convergence zones farther off the equator (8–18° latitude) during the east phase of the QBO. The opposite trends occur during the westerly shear phase of the QBO wherein deep equatorial convection is suppressed while off-equator monsoon convection is enhanced. It is shown that during the east phase of the QBO, the Pacific regional pressure and circulation anomalies which arise in response to QBO-linked trends in convective activity are consistent with conditions leading to warm ENSO events (*i.e.*, El Niño). If the heat content of the warm pool is sufficient, a warm event will occur. Conversely, conditions favoring the development of cold (or La Niña) events tend to occur in association with the westerly phase of the QBO. Although several aspects of the hypothetical mechanism remain tentative, extensive empirical results present a compelling argument for the QBO as an active and fundamental component of ENSO variability.

1. Introduction: Problems of ENSO predictability

Reliable prediction of significant El Niño-Southern Oscillation (ENSO) events remains an important long term research goal for improved extended range weather forecasting. In this report, it is proposed that the ENSO cycle may be significantly influenced by subtle trends in tropical convective activity which occur in association with the Quasi-Biennial Oscillation (QBO) of zonal wind and temperature anomalies in the equatorial stratosphere. We present evidence that such convective trends occur in response to several QBO-linked processes. These processes include variations in: (1) the distribution of geopotential heights in the equatorial upper troposphere and lower stratosphere, (2) the horizontal ventilation of the lower stratosphere over deep tropical convective cells penetrating the tropopause and (3) the reflection versus absorption of upward propagating wave energy from these developing convective cells. Each of these processes varies in response to conditions linked to trends of QBO-induced vertical wind shear and likely feedback into intense convective activity.

The duration of full ENSO cycles typically varies from three to seven years, entailing the accumulation and comparatively rapid release of heat energy in the ocean surface layer of the western equatorial Pacific. Easterly trade winds in the tropical Pacific tend to move warm surface layer water westward. Ocean upwelling processes along the equator which are linked to the divergence of this westward drift maintain comparatively cold Sea Surface Temperatures (SST) throughout much of the central and eastern equatorial Pacific. The deep layer of comparatively warm (>28°C) surface water which accumulates in the West Pacific is the so called West Pacific "warm pool". The West Pacific warm pool is the principal area of tropospheric mass flux into the stratosphere, primarily through the concentrated effects of deep convective clouds penetrating the tropical tropopause. Termed the "stratospheric fountain" by Newell and Gould-Stuart (1981), this vast region is at the center of the ascending branch of the Pacific Walker circulation.

Any process which significantly alters deep convective activity in the warm pool must also influence the regional Walker and Hadley circulations and hence, the Southern Oscillation. Therefore, the proposed mechanism linking the QBO to ENSO is based on the contention that contrasting amounts of vertical wind shear and static stability imposed

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by the east and west phases of QBO act to significantly alter the regional scale distribution of deep convective activity over the warm pool region. If contrasting trends in the distribution of deep tropical convection are linked to the phase of the QBO, then the resulting tropospheric circulation anomalies which they promote will occur over large areas. These trends also persist over interannual time scales which should be more than adequate to force concurrent changes in the regional tropospheric circulation. As shown in the following section, the distribution of these effects varies such that the QBO east phase trends to promote the development of El Niños (warm SST events) whereas the QBO west phase promotes La Niña (cold) conditions.

Whereas progress is being made in numerical simulations of El Niño and of the ENSO cycle, important questions remain concerning the specific combination of oceanic and atmospheric conditions that actually initiate the transition between distinct ENSO modes (see Phillander, 1990). Many researchers believe that inadequate knowledge of both the structural and quantitative factors governing the ocean-atmosphere heat budgets of the warm pool region are primary obstacles to more successful numerical forecasts of ENSO variability. Others maintain that a more detailed understanding of the organization of atmospheric convective processes in the warm pool holds the key to ENSO variability. Efforts are now underway (*e.g.*, the forthcoming TOGA-COARE field program) to acquire extensive heat flux data for the warm pool area.

It is our opinion that additional processes (such as the QBO) which are not currently under serious consideration may be important components of ENSO variability. The mechanism for the QBO-linked modulation of ENSO variability which is outlined in this report is based on the interpretation of empirical data for several aspects of ENSO variability which are otherwise not well explained. It is important to note (and we shall re-emphasize throughout this report) that the stratospheric QBO-troposphere-ocean interaction which is proposed here is likely neither necessary nor sufficient, in and of itself, to either cause or to completely inhibit ENSO events; therefore, it is not proposed that the stratosphere drives the troposphere. Rather, it is suggested that the QBO is an important interactive component influencing the timing of the major ENSO events in the tropical ocean-atmosphere system. Consequently, we also argue for the inclusion of likely QBO-linked effects in ENSO forecasting schemes.

Note also that in our discussion, the term "QBO" will refer strictly to the QBO of lower stratospheric zonal winds, temperature and geopotential height. Other biennial or quasi-biennial oscillations which have been observed in the troposphere and ocean will be explicitly identified as they are discussed. The term "ENSO" will be used to refer to all aspects of the phenomenon although our primary ENSO index is anomalous variations of SSTs in the "Niño 3" (5°N to 5°S, 90 to 140°W) area of the equatorial East Pacific.

In the following section we briefly summarize prior related studies. The remainder of the report is organized as follows: In Section 2 we present a detailed discussion of physical mechanisms tying QBO-linked vertical wind shear, temperature and height fields to anomalous trends in tropical convection and ENSO variability. Empirical evidence of a QBO-tropical convection-ENSO association is presented in part 3. A summary which includes a review of questions related to ENSO variability which are better resolved by the proposed QBO modulation mechanism, is presented in part 4.

2. Related research

Studies of associations between the QBO and ENSO are relatively sparse. A few authors have suggested that variable, vertically propagating planetary wave energy flux linked to ENSO might affect the periodicity of the QBO (see Maruyama and Tsuneoka, 1988). However, the possibility that the QBO might somehow modulate ENSO variability has received little serious consideration (see Trenberth, 1976; Barnett, 1989, 1991; Enfield, 1990). Several recent studies have presented evidence of strong biennial components in ENSO linked data sets. Results presented by Lau and Sheu (1988), Barnett (1990, 1991), Rasmusson *et al.* (1990), Xu (1992), and Ropelewski *et al.* (1992), show biennial components in global data including precipitation, equatorial Pacific SSTs and broad scale tropical circulations. Most notably, Rasmusson *et al.* (1990) and Xu (1992) argue that these observed tropospheric biennial oscillations are distinct from the stratospheric QBO in that the tropospheric oscillations tend to be comparatively pure biennial signals (*i.e.*, 24 month periodicity), closely phase locked with the annual cycle, but occasionally reversing phase. Our view, as detailed below, is that when a quasi-biennial process (*i.e.*, the QBO) is actively modulating circulations with strong annual cycles (*i.e.*, the monsoons, intertropical convergence zones and tropical cyclone activity), then the characteristics of the resulting tropospheric "biennial" oscillations are precisely as those described by Rasmusson *et al.* (*i.e.*, 24 month oscillations, occasionally reversing phase). Consequently, the failure of rigorous spectra based comparative studies to find a clear QBO-ENSO tie is not surprising, especially in view of the additional complications of powerful ENSO feedback processes acting throughout the region on a highly variable interannual time scale.

Prior work by Gray (1984, 1988) and by Shapiro

(1989) demonstrated strong QBO-linked differences in the incidence of tropical cyclones. Earlier studies by Van Loon *et al.* (1981) suggested a link between ENSO and the sudden mid-winter polar stratospheric warming which often occurs in the Northern Hemisphere. Concurrently, Holton and Tan (1980, 1982) suggested a similar association between these polar stratospheric warmings and the QBO (see also Wallace and Chang, 1982). The conclusions of recent studies by Kuma (1990), Yasunari (1989), Enfield (1990), Gray and Sheaffer (1991), Knaff (1991), Knaff *et al.*, (1992), Gray *et al.*, (1991, 1992) and Angell (1992) argue for direct linkage between the stratospheric QBO and various tropospheric and oceanic data series. Van loon and Labitzke (1988), Barnston *et al.*, (1991), Barnston and Livezey (1991) and Sheaffer (1991) have also presented evidence of active modulation of ENSO-linked teleconnections into mid-latitude areas by the stratospheric QBO. A demonstrated link between the QBO and ENSO might help reconcile all of these issues.

In summary, the recurrent finding in most of the recent research related to ENSO-QBO interactions is that although quasi-biennial variability seems to be an intrinsic property of ENSO (*e.g.*, Rasmusson *et al.*, 1990; Barnett, 1991; Xu, 1992), the associations of ENSO with the QBO are at times weak and inconsistent and lack a reasonable plausible cause-effect mechanism. Some of these problems, in our view, may lie in a tendency for ENSO related research to emphasize the largely east-west zonal differences which are tied to variations of the Walker circulation. Moreover, the likely association requires that the warm pool be fully charged with heat energy before the QBO can act to discharge it in an El Niño event. Therefore, as we interpret it, the QBO-ENSO association should be rather inconsistent, akin to Angell's (1992) ideas, but with a strong seasonality factor. We argue that a notably different set of relationships emerges when these same tropical Pacific data are closely examined for QBO-linked meridionally varying conditions, in this case, following the distribution of strong meridional variations of vertical wind shear imposed by QBO zonal wind anomalies.

3. Hypothetical mechanism linking the QBO and ENSO

3.1 The ties between QBO and ENSO variability

The essential features of the proposed QBO-ENSO mechanism are summarized in Fig. 1 and are described in detail below. These include the following: (1) contrasting stratospheric temperature and pressure-height anomalies which accompany each phase (*i.e.*, easterly, westerly) of the QBO zonal wind (shear) anomalies, plus the contrasting ventilation effects of the zonal wind shear both exert distinct but complimentary influences on the distribution of deep tropical convective activity during each QBO phase; (2) the west phase and east phase distributions of QBO-linked anomalous convection each promote distinct regional pressure and circulation anomalies during each phase; (3) the pressure and circulation anomalies of the east phase QBO are favorable for initiating El Niño events whereas anomalous conditions associated with the west phase QBO promote the "La Niña" or cold ENSO mode.

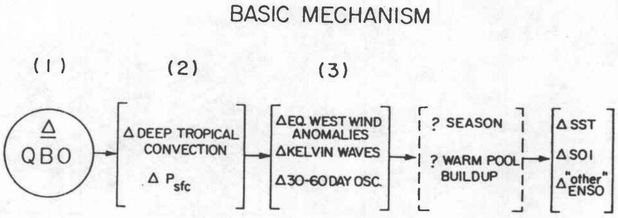

Fig. 1. Diagram showing the likely sequence of interactions in the proposed mechanism wherein a change in the QBO (Step 1) leads to regional changes in deep convection and surface pressure, thereby initiating processes culminating in a change in ENSO provided the season and the condition of the warm pool are favorable.

The time mean variation of QBO zonal wind anomalies in the equatorial stratosphere is shown in the top panel of Fig. 2 (after Naujokat, 1986). Periods of strong easterly and westerly wind shear are emphasized in this figure. The cyclic downward propagation of easterly (unshaded) then westerly (shaded) modes is attended by closely associated anomalies of relatively cold and warm stratospheric temperatures, respectively. The mean, approximately 28 to 29 month cycle of QBO-linked temperature anomalies is also illustrated in relation to the mean cycle of the zonal wind. Data which suggest an ENSO-QBO link are also depicted in the lower portion of Fig. 2 wherein the centroid of ENSO warming events tends to develop when the vertical shear of zonal winds in the lower stratosphere is either easterly or is rapidly becoming easterly. In the opposite sense, the centroid of cold ENSO events at the bottom of Fig. 2 suggests that La Niñas tend to develop and intensify as the vertical shear of QBO zonal wind becomes westerly.

During the full 40-year period (1951–1992) for which we have fairly reliable QBO data, there were 18 west-to-east QBO shifts but only 10 substantive ENSO warm periods (see Gray *et al.*, 1992; Angell, 1992). Most of these events are shown in the extended time series in Fig. 3 (redrawn from Holton, 1992 after Naujokat, 1986). The specific association for all 18 QBO cycles (except 1950–1952 and 1991–1992) are shown in Fig. 3 and are summarized in Table 1. The six QBO easterly periods in

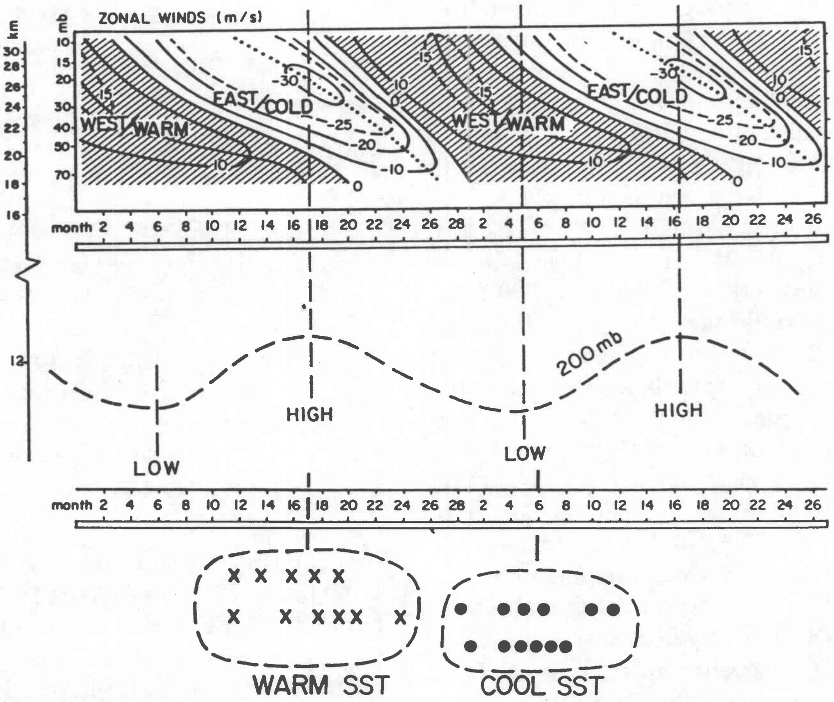

Fig. 2. Schematic rendering of the mean 28–29 month cycle of QBO zonal wind anomalies, beginning with the westerly (shaded) maximum and continuing through two cycles. Typical QBO zonal wind speed anomalies at the equator are also shown in the top panel, expressed in meters per second. Comparatively cold stratospheric temperature anomalies which typically accompany the QBO easterly shear and warm temperatures accompanying the westerly QBO are labeled as such (after Naujokat, 1986). Middle: Schematic rendering of the typical observed variations of 200 mb height (dashed line) associated with the east and westerly shear phases (also see Reid and Gage, 1985). Bottom: Approximate temporal position of the center of 11 ENSO warm periods and 12 cold periods between 1950 and 1991 in relation to QBO zonal winds. The vertical dashed lines in the upper panel delineate the phase maxima of the east-west-east QBO cycle of vertical wind shear. The two vertical dashed lines in the lower panel show the approximate centroid timing of warm and cold events.

Fig. 3 with no associated significant ENSO warming bear the following considerations: (1) 1954, which is at the end of the multi-year 1951–1953 warming event; (2) 1958–1959 and again in 1960, following the strong and extended warming event of 1957–1958; (3) 1970–1971, at the end of the 1969 warming event; (4) 1974–1975, at the end of the 1972–1973 warm event; (5) 1983–1984, at the end of the strong and persistent 1982–1983 warming event, and (6) 1989–1990, soon after the strong 1986–1987 warm event.

In the proposed interaction, the "discharged" and thus energy-depleted condition of the warm pool following the most recent prior warm event appears to preclude significant ENSO warming attending the onset of the subsequent east phase of the QBO. Hence, the "No" cases listed in Table 1 are primary examples of times wherein an El Niño had only recently ended, thereby disallowing substantial redevelopment of warm SSTs. The time scale of warm pool heat dissipation process varies for each warm event and thus determines the extent to which any trends associated with each new QBO east phase may be able to tap the West Pacific warm pool and enhance any incipient new warm events. These and other considerations discussed below dictate that direct correlation analyses between the QBO and ENSO will show only weak and inconsistent associations. However, this weak statistical association should not be interpreted as a lack of a physical relationship between these two phenomena.

Another exceptional situation indicated in Table 1 occurs during the second half of 1976 (following the protracted 1973–1975 period of cold SSTs) wherein a weak warm event appears during the later stages of the westerly QBO. This case illustrates the somewhat variable timing of QBO influence on coupled tropical Pacific air-ocean interactions. In this case, the warm pool and seasonal cycle were very favorable and it was possible for the coupled system to enter a weak El Niño mode before the full influence of the easterly shear regime arrived. However, most exceptions to a one-to-one correspondence between QBO west-to-east zonal wind shifts and the onset

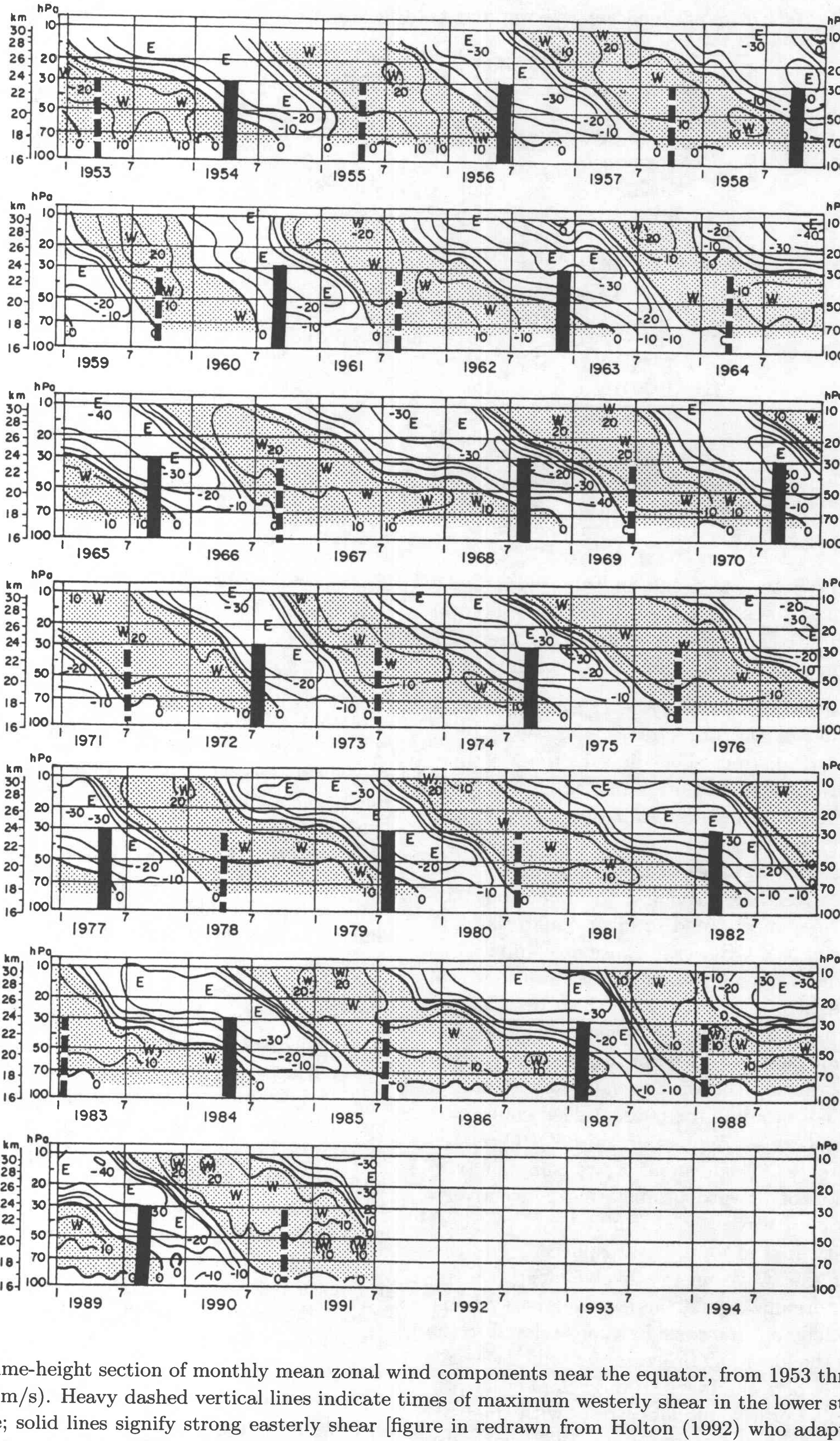

Fig. 3. Time-height section of monthly mean zonal wind components near the equator, from 1953 through 1992 (m/s). Heavy dashed vertical lines indicate times of maximum westerly shear in the lower stratosphere; solid lines signify strong easterly shear [figure in redrawn from Holton (1992) who adapted it from Naujokat (1986)].

Table 1. Tabulation of the 18 QBO east phase events which have been documented since 1951 in relation to the occurrence of significant SST warming (El Niños) in the equatorial East Pacific Ocean.

No.	Year	El Niño		Notes and Considerations
1.	1951–1952	Yes		Protracted warming
2.	1954		No	
3.	1956–1957	Yes		
4.	1958–1959		No	
5.	1960		No	Weaker warming
6.	1963	Yes		
7.	1965	Yes		
8.	1968–1969	Yes		
9.	1970–1971		No	
10.	1972	Yes		
11.	1974–1975		No	Diminished cold event
12.	1976–1977	Yes		
13.	1979–1980		No	
14.	1981–1982	Yes		
15.	1984		No	
16.	1986–1987	Yes		
17.	1989–1990		No	Weak abortive warming early in 1990
18.	1991–1992	Yes		

of distinct ENSO warm events in Table 1 (and vice versa for east-to-west QBO and ENSO cold events) can be attributed to the time required for the West Pacific warm pool to recharge between warm events.

3.2 Physical processes linking QBO wind anomalies and deep tropical convection

At least two distinct shear-linked processes may contribute to QBO modulation of ENSO. First, hydrostatic effects in the lower stratosphere and upper troposphere, due to the contrasting thermal regimes attending the two phases of the QBO, may act to modulate convective activity in a zone along the equator. These effects tend to favor equatorial convection during the QBO east phase as compared to the west phase. Secondly, conditions resulting from weak (versus strong) vertical wind shear between the lower stratosphere and upper troposphere (*i.e.*, between 50 and 200 mb) in tropical areas away from the equator during the west (versus east) phase of the QBO may promote (or reduce) deep convection feedback processes. A possible third QBO-related physical process, the degree of transmission versus reflection of upward propagating convectively-induced gravity waves, is also influenced by shear and stability in the lower stratosphere. The dissipation of this wave energy likely affects the regional scale organization of large convective systems. We shall briefly outline considerations related to the first two of the foregoing processes for which we have made a series of preliminary studies. Some very preliminary collaborative modeling tests with the CSU "RAMS" model (see Cotton, *et al.*, 1982) have also produced promising results on gravity wave-linked processes related to the QBO (not shown, see Knaff, 1992).

Hydrostatic processes:

A conceptual illustration of the time variation of upper tropospheric height anomalies in relation to the time variation of stratospheric winds and temperature was shown in Fig. 2. Note in this figure that upward and downward bulges of upper tropospheric (200 mb) heights accompany the QBO easterly shear (cold anomaly) and westerly shear (warm anomaly) modes, respectively. In Fig. 4, comparative vertical-time sections for observed stratospheric temperature (top panel) and zonal wind anomalies (bottom panel) along with height anomalies for the 100 and 200 mb pressure surfaces are shown for data taken at Singapore. Note that positive (negative) upper tropospheric height anomalies tend to be closely associated with easterly (westerly) shear and hence, with cold (warm) conditions in the lower stratosphere. QBO-stratified height data for the entire (surface to 50 mb) Singapore profile are shown in Fig. 5 wherein mean east phase height anomalies have been subtracted from the mean west phase anomaly values for each level. The difference data plotted in Fig. 5 indicate a mean west-minus-east height difference of approximately 15 meters at 100 mb. This height difference is somewhat smaller than what might be inferred from the data in Fig. 4, in this case because of the greater smoothing in Fig. 5 and because of possible feedback effects due to ENSO (see Gage and Reid, 1987; Reid *et al.*, 1989) in Fig. 4.

The associations between the QBO and tropospheric pressure-height anomalies in Figs. 4 and 5 illustrate the components of one physical process whereby the QBO can perturb regional scale tropical convective activity. As illustrated in Fig. 6, the

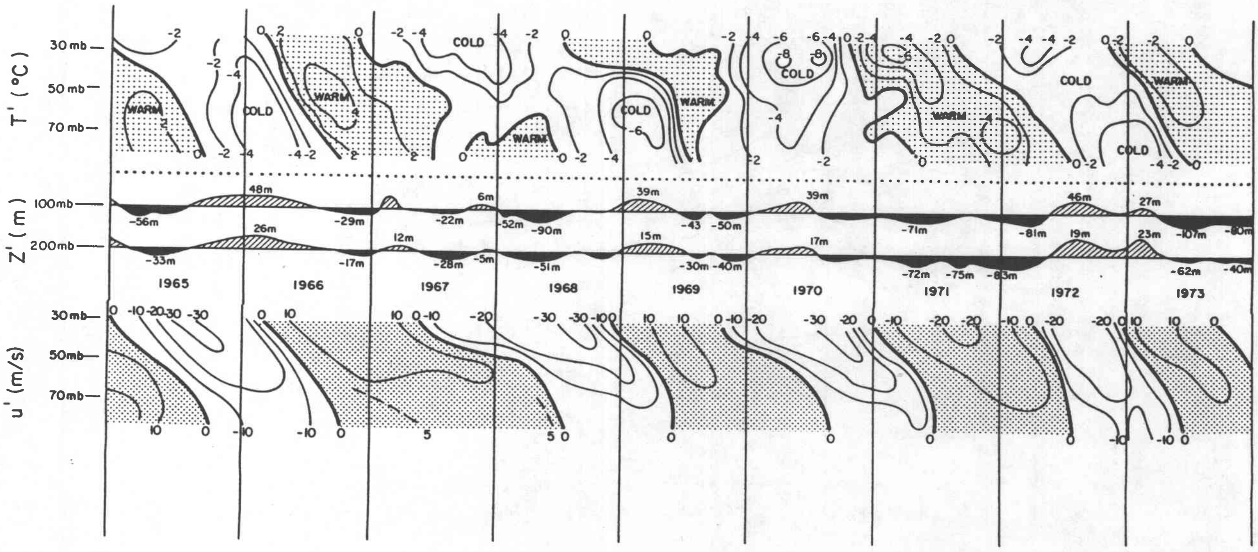

Fig. 4. Time variations of monthly mean stratospheric zonal wind (m/s), temperature anomalies (°C) and upper tropospheric height anomalies (m) at Singapore (1.4°N) for 1965 through 1973. East phase QBO winds (negative values in top panel) typically coincide with cold anomalies (middle panel) at the three stratospheric levels (30, 50 and 70 mb) and with positive height anomalies at 200 mb (bottom panel). Conversely, westerly QBO winds (shaded) correspond to warm stratospheric temperature anomalies and negative 200 mb height anomalies. The middle part of the diagram shows the 100 mb and 200 mb height anomalies which are associated with these different east versus west QBO phase changes.

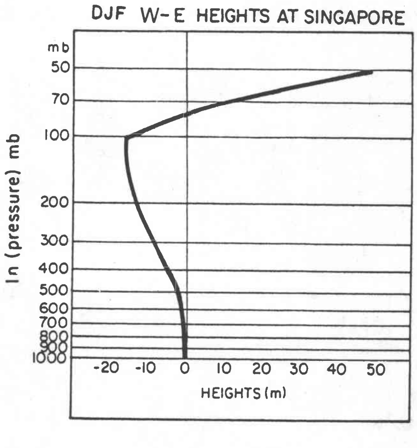

Fig. 5. Vertical profile of mean QBO stratified (*i.e.*, west phase minus east phase) height anomalies, from the surface to 50 mb during December to February at Singapore (1.4°N, 104°E). Data reflect mean anomalies for 1965–1985. The difference values shows that the upper tropospheric heights are higher during the easterly QBO phase.

process involves hydrodynamic effects tied to the strong QBO-induced stratospheric thermal anomalies near the equator. The diagrams in Fig. 6 illustrate the contrasting thermal-thickness regimes associated with easterly and westerly QBO wind shear. Both observational data and theoretical (*i.e.*, thermal wind) considerations dictate that easterly vertical shear associated with the east phase of the QBO must also be associated with a comparatively cool and, therefore, thin stratosphere. Dunkerton and Delisi (1985) have documented a much larger amplitude QBO temperature oscillation occurring near the equator in comparison to those in off-equator areas. Moreover, Dunkerton and Delesi also show a tendency for a 180° phase difference between QBO temperature anomalies near the equator versus areas 10 to 20° off-the-equator. Consequently, strong east phase on-equator cooling occurs in association with weak warming in latitudes beyond 10°, or at off-the-equator locations. For these reasons, east phase (versus west phase) stratospheric layer thickness differences (*i.e.*, pressure heights) are notably greater near the equator than in the off-equator areas, as well as being out of phase. Consequently, an anomalous upward (downward) "bulge" is often imposed on the upper tropospheric surfaces near the equator during the cold (warm) anomaly of the QBO east (west) phase in Fig. 6.

Evidence of the QBO-linked bulges in Fig. 6 has been reported by Reid and Gage (1985) and was illustrated in sounding data for Singapore in Fig. 5. As indicated in Fig. 6, a positive east phase upper tropospheric height gradient (due to this bulge) likely extends from the equator to approximately 7° latitude (see Hamilton, 1984; Dunkerton and Delesi, 1985). One effect of this east phase height gradient is to inhibit easterly flow in the upper troposphere

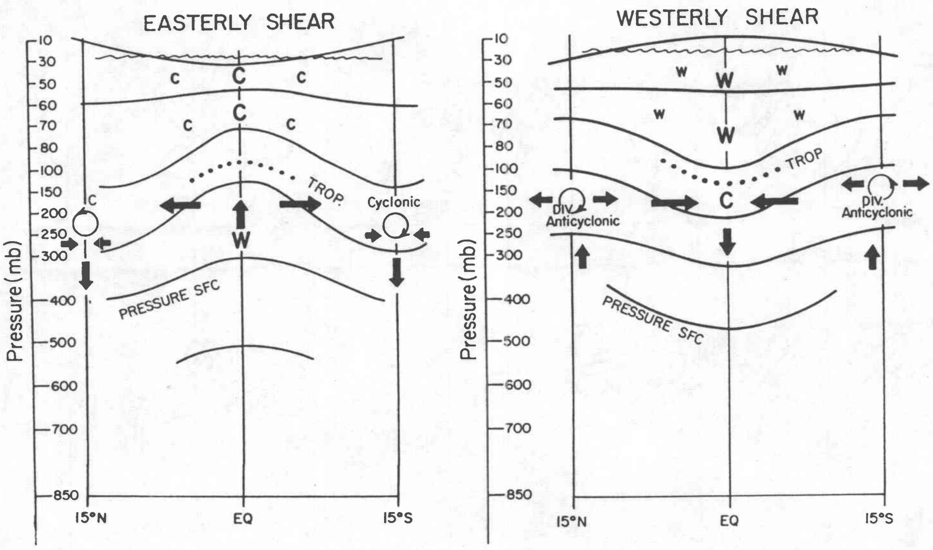

Fig. 6. Conceptual illustration of atmospheric cross sections of pressure surface height anomalies extending from 15°N to 15°S and from the surface to 10 mb for QBO easterly shear phase (left panel) and westerly shear phase (right panel) conditions. The downward (west phase) and upward (east phase) anomaly bulges in the upper troposphere pressure surface heights are emphasized. Comparative upper tropospheric cyclonic versus anticyclonic circulation tendencies associated with the off-equator convergence zones are also indicated. Stratospheric conditions reflect west phase Warm (W) and increased thickness effects versus east phase Cool (C) and diminished thickness.

on the equatorial side of the monsoon convergence zones. Consequently, as shown in the idealized 200 mb plan view in Fig. 7 (top left), westerly upper tropospheric flow anomalies during the QBO east phase will favor and likely strengthen upper level divergence along the equator and thus inhibit the overall off-equator upper level divergent monsoon circulations and convective activity. The combined plan view and meridional-vertical cross section extending from approximately 12°N to 12°S latitude in Fig. 7 offer an idealized illustration of these wind, pressure-height and convective differences for both QBO modes.

Reiterating, an inferred tendency for enhanced net QBO west phase subsidence to occur near the equator in association with enhanced off-equator convection (*e.g.*, Figs. 6 and 7) should act to partly suppress west phase convection along the equator during both Boreal and Austral monsoon seasons. Conversely, the data and illustrations in Figs. 4 through 7 suggest that during periods with deep QBO easterlies, convectively enhanced positive height anomaly gradients between the equator and 7° latitude will systematically oppose and thereby likely weaken easterly upper tropospheric outflow from the monsoon convergence zones. The resulting weaker monsoon circulations during the QBO east phase should thus be less of an inhibiting factor on all forms of deep equatorial warm pool convection (notably, the interseasonal oscillation or ISO) which would tend to extend farther eastward into adjacent

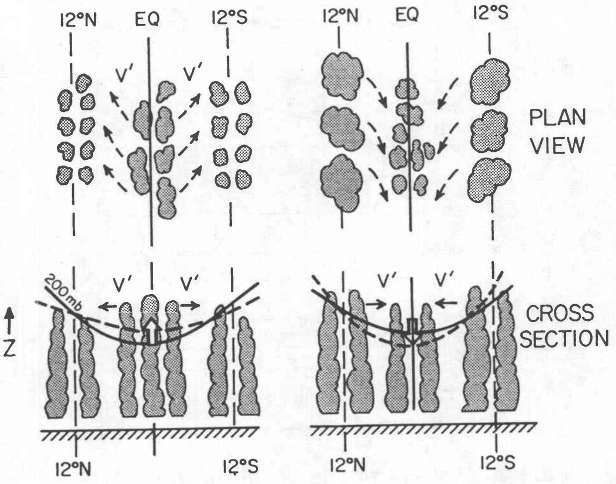

Fig. 7. Idealized plan view (top panel) and cross section (bottom) of 200 mb circulation and heights respectively between 12°N and 12°S for the east phase (left side) and west phase (right side) of the QBO. V′ signifies anomalous divergent 200 mb meridional winds indicating equatorial divergence (east phase) versus convergence (west phase) in response to the contrasting 200 mb pressure height conditions illustrated in Fig. 6. The solid contour in the bottom panel represents the mean 200 mb height whereas the dashed contour represents the heights associated with each phase of the QBO.

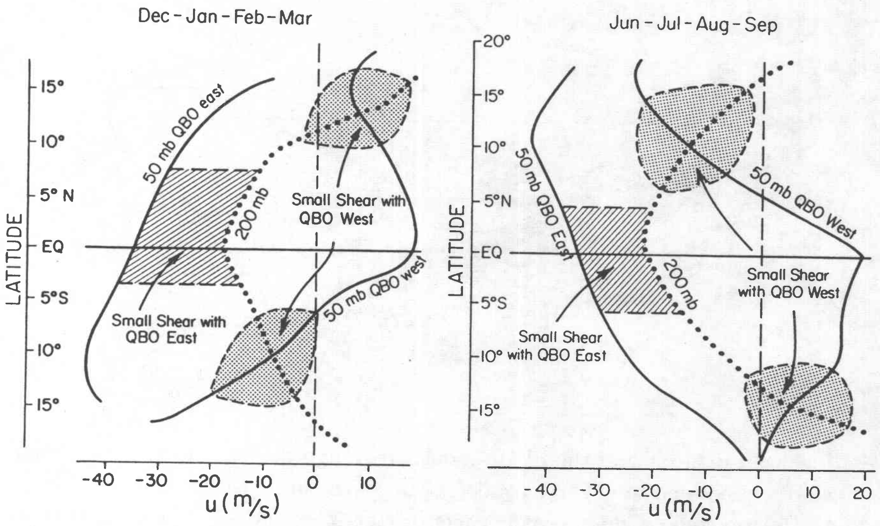

Fig. 8. Absolute value of mean zonal wind speeds at 50 mb (solid line) for December through March (left); and June through September (right) for typical east and west phase QBO periods. Zonal winds at 200 mb are shown as dashed lines. The shaded areas enclose conditions of minimum 50 to 200 mb zonal wind shear. Note that near-the-equator minimum 50 to 200 mb shear occurs with QBO east winds while, by contrast, at 15°N or 15°S minimum 50 to 200 mb zonal wind shear occurs with QBO westerly phase conditions.

areas of the Pacific along the equator. In this way, subtle hydrodynamic effects due entirely to the QBO may be systematically tied to the ENSO-linked convection modulation effects described previously. We propose that it is this specific association which most likely links the easterly QBO with the onset of El Niño events.

Processes due to troposphere-stratosphere vertical wind shear:

Convective anomalies due to the QBO also occur in off-equator areas as the result of strong QBO-linked variations of the vertical wind shear between the upper troposphere and lower stratosphere. There are several processes which are detailed below whereby deep tropical convection may induce warming effects in the lower stratosphere. However, for such warming effects to feedback and enhance deep broadscale convective activity, they must remain superposed over the areas of strong upper tropospheric warming created by the associated convective systems. The extent of this vertical coupling will vary with the strength of the wind shear between the upper troposphere and lower stratosphere and therefore, as a function of the QBO.

Zonal wind speeds at 50 mb for QBO east and west phases are shown in Fig. 8 for the tropics from 15°S to 15°N latitude for both the northern and southern summer periods. Mean 200 mb zonal wind speeds are also shown for both periods. Areas of relatively weak zonal wind shear between 50 and 200 mb are outlined and shaded. Weak shear occurs near the equator during the east phase and in areas

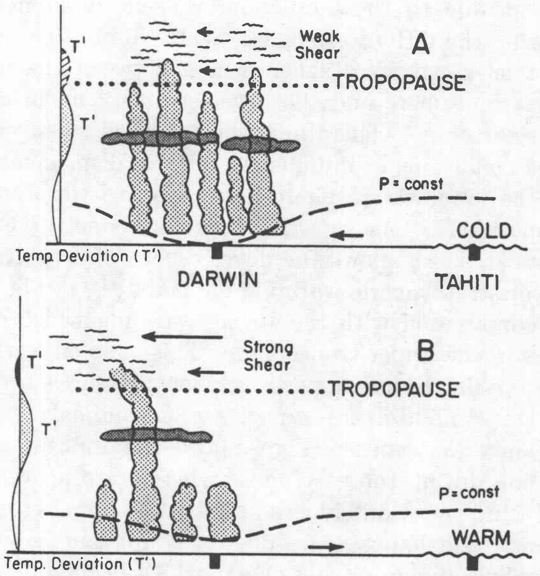

Fig. 9. Conceptual illustration of relative displacement of the tops of deep off-equator convective storms penetrating the lower stratosphere during the east (lower panel) and west (top panel) phases of the QBO. The difference in lower stratospheric temperature anomalies for the two modes is indicated at the as T′ (left) and the anomalous pressure values at Darwin and Tahiti are also indicated. A conceptual qualitative representation rather than precise difference values is intended.

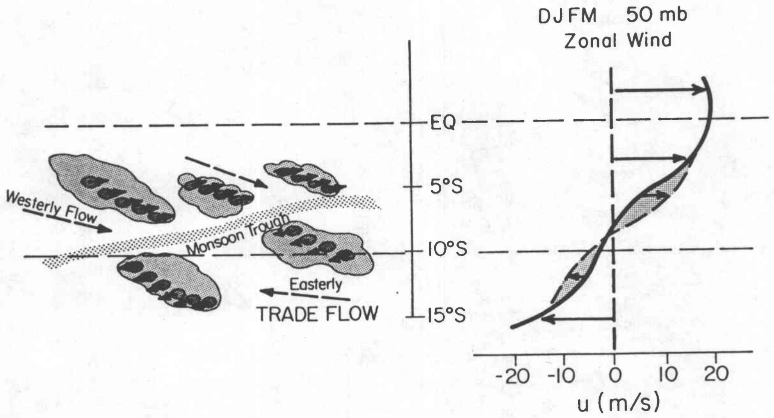

Fig. 10. (Left) Idealized plan view of the SPCZ monsoon trough during the Austral summer showing the converging wind regimes and broad areas of deep line convection. (Right) Schematic of mean December through March 50 mb zonal wind speeds between the equator and 15°S (solid curve) and the positive vorticity perturbation due to deep upward transport of low level momentum into the lower stratosphere (shaded area).

farther off the equator during the QBO west phase. Note that the speed values shown in Fig. 8 are the actual wind speeds, not anomalies.

Figure 9 offers a conceptual rendering of the main effects due to these off-equator shear differences. During the QBO west phase, vastly diminished net vertical zonal wind shear occurs between the upper troposphere and the lower stratosphere in off-equator areas. This diminished vertical shear creates conditions of diminished relative displacement of the lower stratosphere in relation to the upper troposphere. As shown in the top panel of Fig. 9, weak shear allows the development of a positive lower stratospheric warming anomaly (T' in Fig. 9) in conjunction with the strong warming which occurs in the upper troposphere. This coupled warming is reflected as comparatively low pressure surface at Darwin and hence, a positive SOI anomaly.

The lower panel in Fig. 9 shows the opposite situation during the east phase wherein strong vertical wind speed differences between the upper troposphere and lower stratosphere disrupt the vertical coupling of the heating effects which occur in each of the two layers. The influence of the strong east phase shear is represented in this figure as a weak negative lower stratospheric temperature anomaly associated with a weak positive surface pressure anomaly at Darwin.

To reiterate, a modest enhancement of net vertical column warming which occurs in the lower stratosphere over deep convection can enhance the overall strength of the associated convective systems. Though relatively small, this enhancement can feedback to further enhance the strength of convective circulations on cluster and larger, regional circulation scales. As the phases of the QBO strongly alter the vertical coupling between the upper troposphere and lower stratosphere, these feedback effects will vary with the QBO, being stronger in the west and weaker in the east phase QBO. Although these differences will manifest themselves as surface pressure variations of at most a few millibars, such differences are likely sufficient to disrupt the quasi-unstable equilibrium between the atmosphere and a fully "charged" warm pool.

Two processes whereby the convectively driven lower stratospheric warming effects indicated in Fig. 9 might actually develop are illustrated in Figs. 10 and 11. The left panel of Fig. 10 shows the broad-scale circulations of the lower troposphere which are associated with the South Pacific Convergence Zone (SPCZ) monsoon trough during the Austral summer. The physical processes attending deep vertical convective lines may cause a net transfer of westerly zonal momentum to the lower stratosphere in the region north of the monsoon trough. Similarly, deep convective processes in the trade wind areas south of the trough, may cause an increase in lower stratospheric easterlies. Consequently, the aggregate effect of deep convective line cells penetrating the tropopause will likely lead to stratospheric westerly wind increases north of the trough and an increase of easterly momentum south of the trough. These trends will combine to cause a weak enhancement of relative vorticity in the lower stratosphere as illustrated on the right side of Fig. 10. The net increase of relative vorticity in the lower stratosphere will manifest itself as a modest heating anomaly and as a weak decrease of surface pressure during the QBO west phase as was indicated in Fig. 9. Strong shear during the QBO east phase will (due to strong easterly stratospheric wind ventilation) preclude such surface pressure decreases.

An alternative process described by Knaff (1992),

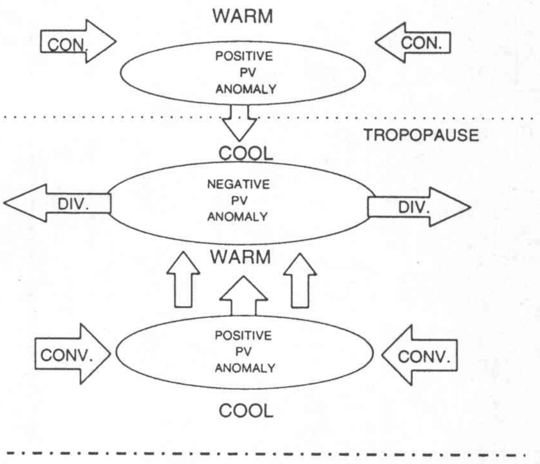

Fig. 11. Hypothetical structure of potential vorticity (PV) anomalies associated with the thermal structure and circulation in areas of deep persistent tropical convection. Broad arrows indicate the primary vertical and horizontal convergence features and areas of anomalous warming and cooling are also labeled (modified and adapted from Raymond and Jiang, 1990).

which may lead to the same stratospheric vorticity enhancement effect during the QBO west phase is shown in Fig. 11. The lower portion of this figure illustrates the configuration of potential vorticity (PV) anomalies which are known to be associated with strong tropical convective systems (see Raymond and Jiang, 1990). In Fig. 11, we have modified the well known PV dipole structure of the lower tropospheric convergence (positive PV) and upper tropospheric divergence (negative PV) to include an additional positive PV anomaly in the lower stratosphere. As indicated in Fig. 11, a positive lower stratospheric PV anomaly should develop in response to the strong divergent flows in the upper troposphere above intense monsoon convection. This stratospheric vorticity must also manifest itself as an enhanced warming effect. When low shear west phase QBO conditions allow this warming anomaly to remain superposed over the areas of strong mid-tropospheric heating of intense convective systems, a modest additional decrease of low level pressure within the monsoon trough should develop (*i.e.*, Fig. 9).

Notice also that these off-equator QBO convection modulation effects tend to compliment the on-equator mechanisms described above. That is, off-equator convection should be enhanced by effects of the QBO west phase which (as was proposed in the prior section) also tend to diminish on-equator convection. Conversely, the east phase QBO has the opposite enhancement versus suppression effects. Consequently, any tendency for on-equator convection to actively suppress off-equator convection, or vice-versa, will further strengthen the overall effects of the QBO-linked mechanism. At the same time, the monsoons are closely phase locked with the annual cycle. Hence, while interacting with the mode (but not necessarily the amplitude) of the quasi-periodic QBO (and ENSO feedback effects as well) highly variable spatial and phase relationships will occur in the troposphere. These highly transient effects complicate the task of finding any full time comprehensive ties between the phase and amplitude of the QBO versus the monsoon circulations.

Gravity wave dissipation processes:

Tripoli and Kanak (1991) have demonstrated important effects of stability and wind shear in the lower stratosphere and upper troposphere for the organization of deep convection in tropical cloud clusters. Their study showed that as much as 90 % of the available potential energy generated during the early stage development of these cells is manifest as upward propagating inertia-gravity waves. The fate of this wave energy, and hence of nearby circulations and the subsequent development of the convective systems, was shown to be closely tied to lower stratospheric wind shear and stability conditions. Consequently, it is reasonable to infer that the integrated effects of contrasting conditions in the lower stratosphere linked to each phase of the QBO and acting on seasonal time scales, might have cumulative effects which influence the unstable-equilibrium of coupled equatorial Pacific warm pool ocean-atmosphere interactions. However, as we are uncertain as to precisely how the dissipation of vertically propagating inertia-gravity wave flux will influence broadscale deep convection in this context, we will defer development of this concept to another time.

3.3 Summary of mechanisms

An illustration summarizing all of the foregoing QBO-linked effects is shown in Fig. 12. As shown in the top panel of this figure, easterly QBO wind shear is associated with enhanced deep convection on the equator which may also act through a local Hadley cell anomaly to inhibit nearby off-equator monsoon-convergence convection. The influence of the local Hadley circulation anomaly is represented in Fig. 12 as the direction of the 200 mb meridional wind anomaly which would be associated with either the east phase on-equator enhancement of convection (top) or the west phase off-equator convective enhancement (bottom). Monsoon convection is also inhibited by the strong east phase vertical shear-ventilation feedback effects which were just described. The reverse set of associations and effects during the QBO westerly shear phase is illustrated in the bottom panel of Fig. 12. Each set of QBO-linked convective effects in Fig. 12 is shown in

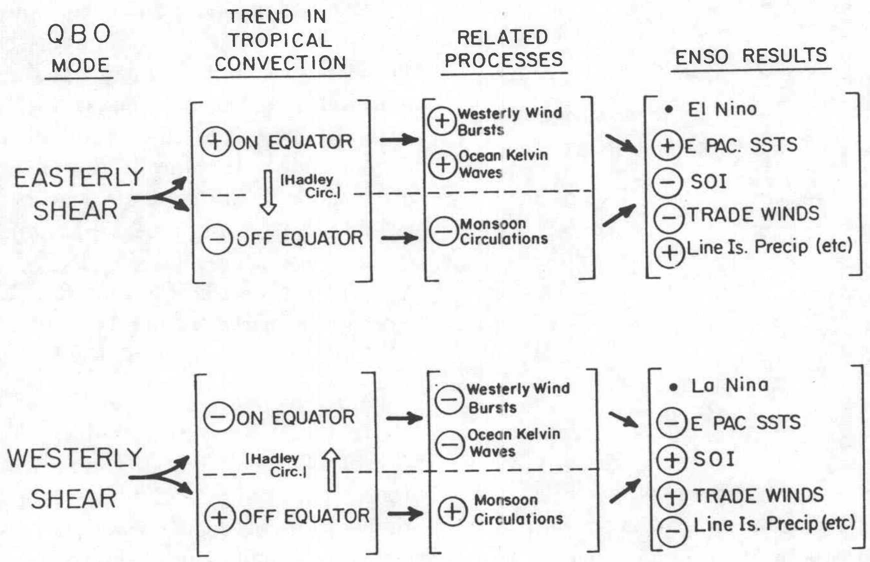

Fig. 12. Schematic showing the sequence of events linking the east and west phases of the QBO to the El Niño (top) and La Niña (bottom) respectively. Each QBO mode favors a specific trend in the distribution of convection and therby, acts to enhance (+) or diminish (−) conditions related to processes which promote either one or the other ENSO mode. The local Hadley circulations are represented as 200 mb meridional flow anomalies directed away from the equator during QBO easterly shear and toward the equator during QBO westerly shear.

association with one or more physical processes, the convective trend for which is depicted by either a plus or minus sign. Hence, these schematics summarize the foregoing sequence of effects whereby the east and west QBO phases promote El Niño and La Niña conditions, respectively.

4. Evidence for the hypothesis

Observational evidence of an association between the QBO, tropical convection and ENSO has already been presented in Table 1 and in Figs. 2, 3, 4, 5 and 8. Additional empirical data are presented in this section which lend further support to the hypothesis of a QBO modulation of ENSO variability. This evidence includes observations related to the incidence of tropical cyclones, the Intraseasonal (30–60 day) Oscillation (ISO), summer monsoon variability in West Africa, India and Australia, regional surface pressure, rainfall and Outgoing Long-wave Radiation (OLR) cloud data.

Tropical cyclone data

Strong convection penetrating the tropopause (*e.g.*, Fig. 9), similar to that which occurs in the warm pool region, also occurs near the center of developing tropical cyclones. Hence, our hypothesis requires that the incidence of tropical cyclones might also be influenced by the phase of the QBO (see Gray, 1984; 1988 and Shapiro, 1989). This premise appears to be verified in the data in Table 2 wherein it is shown that the incidence of intense Pacific and Atlantic Basin tropical cyclones is highly biased, by a factor of greater than two-to-one, to the west phase of the QBO. Because tropical storms occur in what we have termed "off-the-equator" latitudes, it follows that the development of intense tropical cyclones might be favored by conditions in the lower stratosphere which are not strongly sheared or ventilated, as occurs during westerly QBO conditions. These direct effects of the QBO on the incidence of strong tropical cyclones support the contention that similar influences, acting for periods of many months over the broad areas of deep tropical convection throughout the West Pacific, could induce anomalous surface pressure trends over regional scale areas.

Regional anomalies in surface data

The foregoing hypothetical arguments require that regional pressure and circulation anomalies respond in a somewhat systematic way to QBO-linked variations of intense convective activity in the equatorial and tropical Pacific. However, as interannual variability in this region is often overwhelmed by feedback processes driven by strong ENSO events, there is some difficulty in consistently seeing robust and coherent meridional trends during each QBO east and west phase mode. Nevertheless, monthly mean values for several representative regional climate variables are shown in Table 3, stratified for 12 month QBO transition periods. In these transition-based analyses, seasonality considerations were imposed such that only years wherein transitions occurred from either distinctly westerly or distinctly easterly QBO conditions throughout the

Table 2. Summary of the number of intense typhoons occurring in the Atlantic, NW Pacific and Australia regions, stratified by the phase of the 50 mb QBO at Truk (7.5°N, 152°E). Northwest Pacific data start in 1958 while the Australia region (roughly 90°E to 180°E) data start in 1952. Data for the Atlantic basin include 1949 through 1988.

Typhoons with maximum winds exceeding:	QBO West Phase	QBO East Phase	QBO Intermediate Period	Ratio of West to East Phase
Northwest Pacific, 0°–20°N				
82 ms^{-1}	15	3	4	5.0
72 ms^{-1}	45	20	8	2.3
Australia Region, 0°–20°S				
51 ms^{-1}	17	9	0	1.9
44 ms^{-1}	40	23	2	1.7
33 ms^{-1}	87	50	8	1.7
Atlantic Region (40 Years of Data)				
50 ms^{-1}	59	29	12	2.0

Table 3. Sampling of mean trends in monthly values of ENSO indices for years during which the QBO winds reverse directions throughout the lower stratosphere. That is, transition years with distinct westerly anomalies in January changing to easterly anomalies by the end of the year (December) and vice versa. Mean values for east-to-west transition years are subtracted from west-to-east transition years. Data include surface pressure (mb ×10) at Darwin and Tahiti, surface zonal wind anomalies (m/s) at Tarawa, mean SST anomaly for the Nino 3 zone of the equatorial Pacific (°C) and anomalous line Island Precipitation (%, of normalized longterm mean, see Wright, 1985).

Month	1	2	3	4	5	6	7	8	9	10	11	12
Darwin Pres.	−14.3	−6.3	−2.1	4.7	−1.7	−0.4	−2.7	2.0	−0.6	3.2	4.7	2.1
Tahiti Pres.	4.5	4.9	6.0	2.4	4.3	1.3	−2.7	−1.7	−4.3	2.8	−3.6	−4.5
Tarawa Wind	−1.0	−1.0	−1.2	−0.3	−0.3	0.2	0.7	1.1	1.5	1.3	−0.4	1.1
E. Pc. SST.	−0.5	−0.3	−0.2	−0.1	−0.1	0.1	0.2	0.3	0.4	0.3	0.3	0.4
Line Is. Pcp.	−28.4	−15.3	−26.5	−13.3	−5.4	−8.4	17.9	13.9	24.3	40.7	34.0	22.7

lower stratosphere during January to the opposite phase during the following December were included in the analysis. Because our hypothetical mechanism dictates that the onset of easterly QBO winds is a key factor in initiating ENSO warm events and related feedback processes, years of strong, preexisting warm events during January were not included for the analysis in this table. The QBO-linked trends indicated in the data in Table 3 are consistent with the expected sequence of effects attending the onset of warm events; notably, west-to-east transitions promoting SST warming in the Central and East Pacific, positive pressure anomalies at Darwin, and so forth, which are accentuated by subtracting these trends from values for the east-to-west transition periods (which tend to promote La Niña).

An illustration of the spatial distribution of anomalous sea level pressure (SLP) differences throughout the tropical West Pacific region associated with the West minus east phase of the QBO is shown in Fig. 13. This figure shows the mean west phase minus mean east phase SLP anomaly conditions for Jan–Mar for all regional stations with at least 50 % of all possible data reports for the period. Note that the anomaly pattern in Fig. 13 is consistent with the proposed mechanism and with the OLR cloud data which are shown below in Fig. 14. A complimentary spatial distribution of rainfall anomalies (not shown, see Table 4 and Knaff, 1992) is also generally observed. Representative January to March precipitation data summarized in Table 4 show trends which are consistent with west phase enhancement for off-equator stations versus diminished west phase precipitation for stations near the equator (*i.e.*, low pressure, enhanced convection) and vice versa for the east phase.

The 30–60 day oscillation

Kuma (1990) using Singapore (1.4°N latitude) rawinsonde data, observed a QBO-linked variation in the intensity of the 30–60 day oscillation (ISO). This effect was noted to be especially pronounced during the Austral summer (December to March) period. A stronger ISO was observed to occur in association with mean stratospheric zonal wind conditions resembling the east phase anomaly of the QBO at 70 mb whereas weaker oscillations were associated with comparatively strong westerly wind anomalies. As was suggested above in Fig. 6, on-equator east-

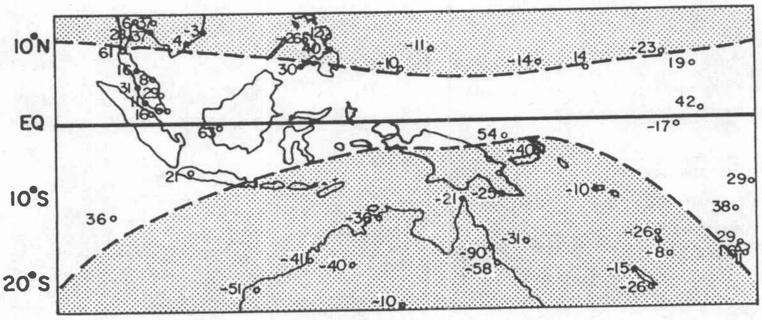

Fig. 13. Analysis of QBO linked sea level pressure (SLP) anomalies in 10^{-2} mb. Areas of negative anomalies are shaded. Values are shown for moderately reliable (less than 50 % missing data) station locations in the tropical West Pacific and Eastern Indian Oceans. These figures show the mean QBO west phase minus east phase anomaly conditions for January through March. Values reflect average three-month differences for ten west-to-east phase QBO transition years minus mean values for twelve east-to-west QBO transition years (also compare with data in the lower portion of Table 4).

erly stratospheric wind anomalies at 70 mb are associated with a favorable equatorial hydrostatic environment in the upper troposphere during the easterly QBO phase. Hence, QBO easterlies should tend to promote a stronger 30–60 day oscillation with enhanced eastward propagation of deep convective activity along the equator. This increase in equatorial convective activity may also partly compensate for reduced regional convection occurring in adjacent off-equator areas during the QBO east phase.

Using composited OLR data, Kuma showed that the distribution of deep equatorial convection associated with periods of weak 30–60 day oscillations (hence, with westerly QBO wind anomalies) tended to be confined to the western most portions of the warm pool. In contrast, Kuma found deep convection during periods of strong 30–60 day oscillations (hence, during the QBO east phase) which exhibited an eastward expanded component, often extending beyond the dateline. As shown in Fig. 14, we have also made a stratification of regional West Pacific OLR data [and for Highly Reflective Cloud (HRC) data as well], but expressly for months with reasonably strong easterly positive and westerly zonal wind anomalies at 50 mb [(*i.e.*, for anomalies less than −5 m/s (east phase) or greater than +5 m/s (west phase)]. Together, these east and west-phase stratifications account for approximately 75 % of all data during this 15 year period. As noted in the caption for Fig. 14, we have subtracted east phase convection (strong on the equator) from west phase convection (strong off the equator), yielding the comparatively weak equatorial convective anomaly with strong convection in the SPCZ and over much of Australia during the Southern Summer.

Monsoon circulations

Further evidence of systematic QBO modulation of regional tropical convection can be obtained from inspection of simple data for the African, Indian and Australian monsoons. As shown in Table 5, a QBO stratified analysis of an all-India monsoon precipitation index (from Parthasarathy, 1991) reveals a mean difference of +0.93 standardized deviations for the QBO west phase minus east phase seasons. These results are also consistent with earlier Indian Monsoon-QBO associations reported by Mukherjee *et al.* (1985) and by Bhalme *et al.* (1987). In addition, Meehl (1987) proposed the concept of comparatively strong and weak "monsoon years" in Asia, Australia and the West Pacific; each monsoon year beginning with onset of the Indian Monsoon and characterized by its strength, expressed as an all-India rainfall anomaly (see also Yasunari, 1992). Meehl observed that the character of the subsequent monsoons occurring throughout the West Pacific region (*i.e.*, Australia and the SPCZ) during the remainder of each monsoon year seemed to follow the trend of the Indian monsoon. A biennial mode of oceanic heat storage and loss was proposed to explain these trends. However, it is notable that for the 22 years selected by Meehl (11 strong and 11 weak monsoons) for the post 1951 period, 19 of these 22 are consistent with our postulated west phase QBO-strong monsoon versus east phase-weak monsoon association.

It is also shown in Table 5 that the major monsoons of West Africa have a distinct QBO signal. In this case, the comparatively equatorial (*i.e.*, 5 to 8°N latitude) August to November Gulf of Guinea monsoon shows an on-equator anomaly mode, being 0.39 standard deviations below normal for QBO west phase minus east phase differences; hence, it is relatively wet during the east phase. Conversely, the off-equator June to September Western Sahel monsoon (10–17°N) is 0.47 standard deviations higher during the west versus the east phase (see Landsea and Gray, 1992). Moreover, the strength of the Australian summer monsoon, which is represented

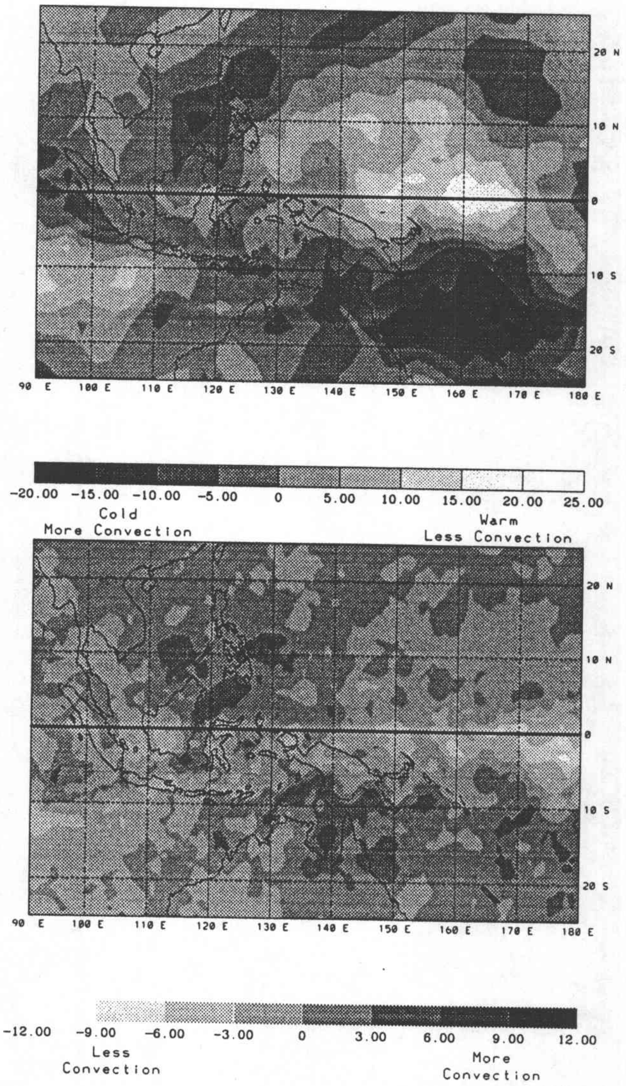

Fig. 14. Differences between composited December to February OLR (top) and HRC (bottom) anomaly data for QBO west phase minus QBO east phase. The OLR data, expressed as Watts/m^2, are for years 1974–1989. The HRC data (1971–1988) represent the normalized incidence of deep convective clouds. Note the distinct on versus off-equator differences in each panel (from Knaff, 1992).

in Table 5 by the seasonal duration of 850 mb westerlies at Darwin (see Holland, 1986), is comparatively stronger during the QBO west phase. This difference is related to stronger easterlies at 150 mb as well as stronger low level (*i.e.*, 850 mb) monsoon westerlies during the QBO west phase. Conversely, less persistent 850 mb westerlies (and weaker 150 mb easterlies (see Knaff, 1992) occur at Darwin with the QBO east phase. These associations were illustrated conceptually in Fig. 7.

Table 4. West phase minus east phase precipitation (percentage) differences for selected stations in the West and Central Pacific; Top) equatorial (±6°), Bottom) off-equator (8–18° latitude) (from Knaff, 1992).

JFM EQUATORIAL PRECIPITATION

Station	Lat	Lon	West–East Difference
Singapore	1.4	−103.9	−2 %
Kuala Lumpur	3.1	−101.6	−22 %
Malacca	2.3	−102.3	−10 %
Kuching	1.5	−110.3	−15 %
Madang	−5.2	−145.8	−15 %
Rabaul	−4.2	−152.2	−18 %
Ocean Is	−0.9	−169.5	−32 %
Tarawa	1.4	−172.9	−13 %
			Ave. = −16 %

JFM OFF-EQUATOR PRECIPITATION

Station	Lat	Lon	West–East Difference
Aparri	18.4	−121.6	21 %
Cebu	10.3	−123.9	35 %
Milingimbi	−12.1	−134.9	10 %
Darwin	−12.4	−130.9	11 %
Guam	13.6	−144.8	10 %
Truk	7.5	−151.9	65 %
Kwajalein	8.7	−167.7	42 %
			Ave. = =27 %

Collectively, the results in Table 5 and in Figs. 6, 7, 13 and 14 suggest that the strength of the two primary Eastern Hemisphere summer monsoons plus the West African monsoons are all related to the phase of the QBO cycle in the lower stratosphere. In this context, as strength of the Australian summer monsoon is related to anomalous surface pressure at Darwin, we have thereby shown a link to the SOI and the strength of the Pacific trade winds. Weak Australian monsoons are typically associated with higher than normal Darwin surface pressure, a weaker SOI, weaker trade winds and consequently a higher probability for the development of warm ENSO events.

Additional considerations

There is an Austral summer-to-winter (December to July) bias for the modal changes (versus persistence) of ENSO indices. El Niños typically begin between January and July, intensify during northern fall, and attain their maximum anomaly values during the following (northern) winter (Rasmusson and Carpender, 1982). This seasonal bias is observed for trends in virtually all ENSO indices including the SOI, equatorial SST anomalies, Line Island precipitation and West Pacific low level zonal wind anomalies (see Wright, 1985; Wright *et al.*, 1988; Trenberth and Shea, 1987). Note also that a similar seasonal-

Table 5. Mean and median values for monsoon related data, stratified for westerly stratospheric shear conditions, easterly stratospheric shear condition, and their differences for the Gulf of Guinea rainfall index (near equator convection), detrended Western Sahel rainfall index (Landsea, 1991), all India rainfall (Parthasarathy, 1991), and for the duration of westerly winds at Darwin, Australia (Holland, 1986). Note that all of these indices suggest that **off**-equator monsoons are stronger during westerly shear conditions and near equator convection (*i.e.*, the Gulf of Guinea) is stronger during QBO easterly shear years.

	Guld of Guinea (5°N to 8°N) precipitation (σ)		Western Sahel (10°N to 17°N) precipitation (σ)		All India (9°N to 27°N) precipitation (σ)		Darwin, Australia (12°S) duration of low level westerlies (days)	
	mean	median	mean	median	mean	median	mean	median
ABO west phase	−0.25	−0.31	+0.19	+0.11	+0.47	+0.66	82	80
QBO east phase	+0.14	+0.41	−0.28	−0.17	−0.46	−1.0	62	64
West-East difference	−0.39	−0.76	+0.47	+0.28	+0.93	+1.02	20	16

ity factor is also observed for reversals of the stratospheric QBO wherein there is a tendency for lower stratospheric zonal wind anomalies to turn easterly between April and July (see Dunkerton and Delisi, 1985; Dunkerton, 1990; Maruyama, 1991; Yasunari, 1989).

In view of these tendencies, a concept of temporally varying, seasonally biased windows for favorable interactions between the QBO and ENSO can be proposed in terms of the annual cycles of SLP at Darwin and Tahiti (*i.e.*, the SOI). The amplitude of the pressure difference between these two stations, and thus the SOI as illustrated in Fig. 15, is greatest in January and least in July; a weaker and less well organized Walker Circulation occurring between June and November. Conceptually (*i.e.*, Fig. 12), the onset of the east phase QBO during the Austral winter to spring period may induce anomalous weakening of off-equator convection in North Australia and the SPCZ. The resulting negative anomaly of the SOI at this time of year will be imposed on the portion of the annual cycle wherein the mean amplitude of the SOI declines from its January maximum to its June minimum.

In addition, net vertical wind shear through the troposphere in the equatorial Pacific east of the Dateline transforms from a December maximum to a July minimum, as shown in Fig. 16. The July minimum of vertical shear in the troposphere shown for the central Pacific in Fig. 16 is especially favorable for feedback to deep convection as lower surface pressure. In addition, the east phase QBO shear between the upper troposphere and lower stratosphere (*cf*, Fig. 8 and Fig. 16) is least during the Northern summer, thereby allowing for better vertical coupling of lower stratospheric-upper tropospheric warming effects in equatorial convection in the Central Pacific. Hence, if during the January to June season, (1) the onset of easterly QBO vertical shear occurs in the lower stratosphere closely in phase with the annual decline of the SOI and (2), the heat content of the West Pacific warm pool is at a relatively high level, then these combined effects are highly favorable for the initiation and eastward propagation of deep convection near the equator. Collectively, these seasonally biased tendencies should then be followed by further weakening of the trade and Walker circulations, additional eastward expansion of deep equatorial convection, intensification of low level westerly wind bursts, warming of SSTs in the eastern portions of the equatorial Pacific and the full development of an ENSO warm event.

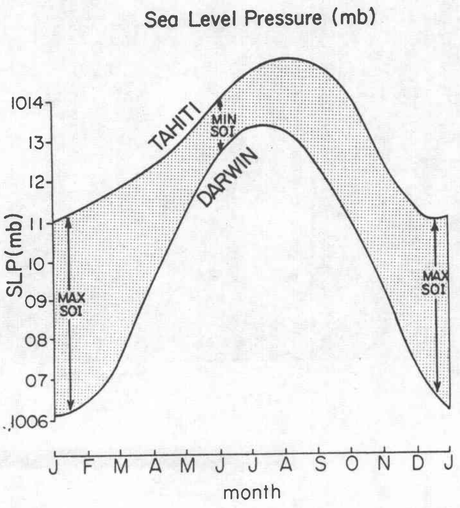

Fig. 15. Mean annual cycle of monthly sea level pressure at Darwin and Tahiti. The January maximum and July minimum values of the SOI (Tahiti-Darwin SLP) are indicated by the vertical bars.

In this way, the year-to-year variations of the phase relationship between the QBO and the seasonal cycle may also partly explain why relatively strong El Niños typically occur on a variable 4 to 7

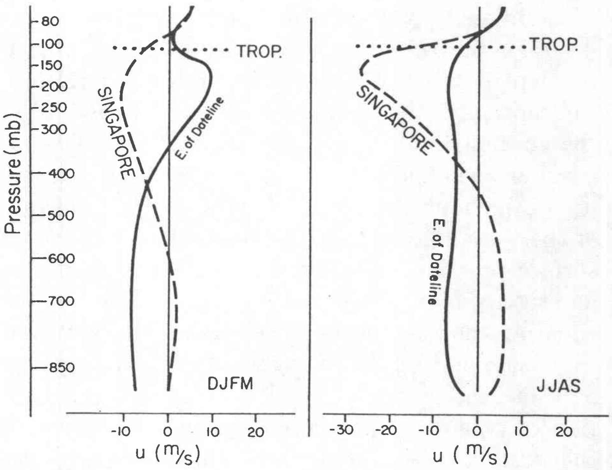

Fig. 16. Comparative vertical profiles of seasonal mean tropospheric zonal winds at Singapore (103°E, 1.4°N dashed line) and on the equator in the central Pacific near and east of the Dateline (180°, 0° solid line) for December through March (left) and for June through September (right) in m/s. The profiles near the Dateline are based primarily on data from Sadler, *et al.* (1987).

year time scale. This timing concept, as illustrated in Fig. 17, accommodates the incidence of QBO easterly shear events at 2–3 year intervals in relation to a 4 to 7 year cycle of thermal recharge of the West Pacific warm pool. As shown in Fig. 17, when the thermal recharge process has advanced past a threshold condition, it is likely to discharge in support of an incipient ENSO warm event following the onset of both seasonally favorable conditions and of easterly QBO shear. The unlikely trend of an ever increasing warm pool heat storage in lieu of El Niño events is indicated by the upward sloped line in the top panel of Fig. 17. These physical ideas appear to be supported by the frequency of ENSO warm events as shown in Table 1.

5. Summary and conclusions

Indisputable proof of a clear association between the stratospheric QBO and the ENSO cycle would help to explain the variable onset, intensity, and duration of most ENSO warm and cold events. However, as we have shown , the nature of direct QBO-ENSO associations is not obvious and details of QBO-ENSO associations of the type being proposed tend to be masked by powerful and persistent ENSO feedback effects which are dependent upon the characteristics of additional time varying conditions, especially the annual cycle. The discussion in Section 3.1 noted that, by this hypothesis, the east phase of the QBO typically will not initiate an El Niño event if the Pacific warm pool is in a discharged condition. Similarly, the onset of the west phase of the QBO often tends to occur just at the height of well developed El Niños. In the latter situation, the monsoon suppressing effects of the El Niño in the tropical West Pacific (*e.g.*, Australia and the SPCZ) will mask the monsoon enhancing effects of the west phase QBO. Moreover, the "triggering" aspect of the proposed QBO-ENSO relationship will result in associations with the troposphere which are not necessarily linear and which have diffuse lead/lag associations. In addition, the on-equator QBO-linked hydrostatic effects are tied to the net wind shear through a fairly deep layer of the lower stratosphere whereas the off-equator QBO effects are likely dominated primarily by the zonal displacement of the upper troposphere in relation to the lower levels of the stratosphere.

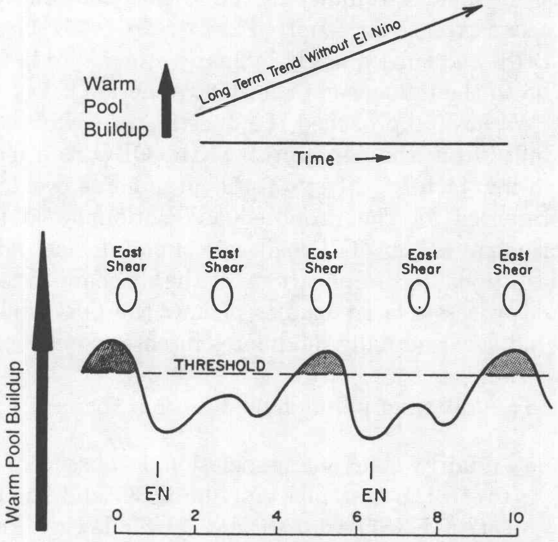

Fig. 17. (Top) Response of warm pool heating in lieu of El Niño events. (Bottom) Idealized response of the West Pacific warm pool to the effects of periodic easterly QBO shear events (represented as small ovals) in the lower stratosphere. Heat storage in the warm pool is shown to slowly accumulate until a critical threshold is passed after which heat is discharged in El Niño events, indicated as (EN), which are triggered by the destabilizing effects of the east phase QBO on regional low latitude convective activity. Time in years is shown on the abscissa.

Spectral methods and correlation tests may not be as well suited to revealing such QBO-troposphere associations as are the simple compositing efforts which have been used here for identifying and assessing details of the physical relationships between the QBO and the ENSO. Hence, it is likely that much of the biennial variability in the troposphere and the oceans extensively reported by Berlage (1957), Brier (1978) and subsequently by many others, are in fact due to the influence of the stratospheric QBO.

We have approached the question of ENSO variability from the perspective of the QBO as a modulating factor. Most of the arguments we have presented for the proposed association lie in two principal areas: (1) Broadscale climatological manifestations and implications of the mechanism; and (2) process-related studies of how the QBO-linked wind shear actually modulates intense tropical convection.

The following points have been put forward:

- A fairly coherent association is observed between the east phase of the QBO and the onset of ENSO warm events; by allowing for a multi-year characteristic recharge interval for the warm pool heat content and for phasing with the annual cycle, the inferred association becomes very consistent.
- Hydrostatic (thermal wind) effects of QBO-linked zonal wind shear are likely to enhance deep convective activity along the equator during the QBO east phase while inhibiting this equatorial convection during the west phase.
- These hydrostatic effects, in conjunction with contrasting shear-ventilation effects in the lower stratosphere in areas approximately 8 to 20° off the equator have the opposite QBO-deep convection enhancement relationship; hence, the west phase QBO enhances and east phase inhibits deep off-equator convection.
- The configuration of these QBO-linked convective effects, including the sign of the anomalies and their distribution and timing, is closely consistent with the observed east QBO-El Niño, west QBO-La Niña relationship.
- The inferred mean meridional difference effects due to such associations are observed in regional precipitation, surface pressure and cloud data, as well as in the incidence of tropical cyclones.
- Considerations of highly transient phase associations between the QBO, the annual cycle and strong ENSO-driven feedback effects complicate the spectrum of the tropospheric response to QBO-induced anomalies. These responses tend to be closely phase locked to the annual cycle, occasionally reversing phase and, thereby, lacking of a strong cospectral link with the QBO.

In approaching the question of ENSO variability from the perspective that the QBO may be a modulating factor and, by introducing the concept of meridionally varying on-off equator differences in deep convective activity, we have obtained plausible explanations of many ENSO-related questions. Conceptually, the effects of the east phase QBO should contribute to an abbreviated Austral summer monsoon and with diminished convective activity throughout the North Australia-SPCZ portion of the West Pacific area. An anomalous increase of surface pressure will then develop throughout this monsoon region. At the same time, closer to the equator, the east phase QBO favors the eastward expansion of deep ISO convection along the equator and into the East Pacific. This eastward propagation of equatorial convection, in conjunction with the weak monsoon, contributes to a weaker Walker circulation which accompanies the concurrent development of lower surface pressure in the southeast Pacific and hence, a negative SOI anomaly. As the ITCZ moves toward the equator during the March–June transition season, the eastward expanded QBO east phase equatorial Pacific convective anomalies may act to further weaken the SOI and the trade winds, thereby promoting further eastward expansion of warm SSTs along the equator. The weak upper troposphere-lower stratosphere zonal wind shear in the East Pacific during this season is also favorable for this expansion. Consequently, the proposed mechanism accommodates the well known collapse of the trade winds and weakening of the SOI and Walker circulations, as well as most other key physical changes attending the onset of the typical ENSO warm events. Through a reverse set of associations, the west phase QBO favors the onset or enhancement of cold La Niña ENSO conditions. It is hoped that the plausibility of this proposed QBO-convection driven effect will be given consideration as an important component of ENSO variability.

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成層圏 QBO の ENSO 変動への影響

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赤道成層圏における東西風の準二年周期振動 (QBO) がエルニーニョ—南方振動 (ENSO) 現象のタイミングを積極的に調整するという—仮説メカニズムを記述した。このメカニズムには、QBO の位相にリンクして変わる風のシア過程と呼応して熱帯太平洋 warm pool 地域に広く見られる深い対流活動の南北再分布が含まれている。すなわち赤道から約±7°以内での深い対流活動に適した条件は QBO の東西シアの位相に呼応して起こる。同時に、QBO の東風位相の間、深い対流は赤道からさらに離れた（緯度 8–18°）モンスーン収束帯で阻害される。QBO の西風シアの位相の間は反対の傾向が起こり、深い対流は抑制され、モンスーン対流が強まる。対流活動の QBO にリンクした傾向に呼応して起こる太平洋地域の気圧と循環の

偏差は、QBOの東風位相の間、暖かいENSO現象（すなわちエルニーニョ）に導く条件と一致する。逆に、冷たいENSO現象（すなわちラニーニャ）の発達に適した条件はQBOの西風位相に伴って起こる傾向がある。この仮説メカニズムはなお若干の試験的な面を残しているけれども、広範な経験則はENSO変動の積極的で基本的な成分としてQBOに対する興味深い議論を呈示している。