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HYPOTHESIZED MECHANISM FOR STRATOSPHERIC QBO INFLUENCE ON ENSO VARIABILITY

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Abstract. A hypothetical mechanism is described whereby the QBO of zonal winds in the lower tropical stratosphere alters the distribution of intense deep convective activity throughout the tropical West Pacific. In conjunction with the annual cycle and the buildup of heat in the West Pacific warm pool, these QBO-linked variations of deep convection cause variations in the Central Pacific trade winds and Walker circulation which in turn govern the occurrence of ENSO events in the tropical Pacific. Although some details of the hypothetical mechanism are tentative, empirical results present a compelling argument for the stratospheric QBO to at least partly regulate ENSO variability.

Introduction

The rather well known El Niño–Southern Oscillation (ENSO) phenomenon consists primarily of a long-term 3-7 year heat storage and release cycle occurring in the Pacific Ocean-atmosphere system. The existence of the ENSO is due in part to the tendency for regional deep convective activity to be concentrated over the very warm surface waters of the tropical West Pacific. A partial breakdown of the easterly trade wind circulations maintaining this concentrated "warm pool" convection accompanies the onset of an El Niño. In addition to being the center of the upward branch of the regional east-west Pacific Walker cell, this Indonesia–North Australia (INA)–West Pacific warm pool is also the region most favored for tropospheric (to) stratospheric mass transfer.

Less well-known are the strong interannual oscillations of the east-west (zonal) winds of the tropical stratosphere. By virtue of the unusual, approximately 28-month period of these high altitude (18–30 km or 80–10 mb) winds [see Naujokat, 1986], the phenomenon is termed the Quasi-Biennial Oscillation or QBO. This note describes a possible mechanism whereby the QBO may provide a sort of switching mechanism which actively influences the occurrence of ENSO events. Rather than actually "forcing" the warm El Niño and cold La Niña modes, it is proposed that the QBO establishes conditions conducive to seasonal and latitudinal anomalies in the distribution of intense deep convection over the INA and equatorial West Pacific region. When properly phased with the annual cycle, these rather modest QBO linked effects could initiate additional feedback processes affecting regional convection which inturn affect the regional distribution of pressure, the Pacific trade wind circulation and ultimately, ENSO.

Gray [1984] previously identified an association between the phase of the QBO and the seasonal incidence of Atlantic tropical cyclones. In general, the observed incidence of strong hurricanes is greatly increased during the QBO west-phase. This association was subsequently extended to other tropical cyclone basins [Gray, 1988]. Shapiro [1989] has also presented results confirming these associations. Recently, Lau and Shea [1988], Barnett [1989, 1990], and Rasmusson et al. [1990] have identified strong three-to-six year and 24-month (biennial) oscillations in ENSO linked tropical Pacific atmospheric and Sea Surface Temperature (SST) anomaly data. Upon closer inspection, the 24-month biennial oscillations in these studies appear to share a common low frequency (decadal scale) amplitude and phase modulation, tending to occasionally reverse phase. However, because of their fairly precise 24-month periodicity, the authors concluded that these SST and tropospheric biennial signals are not likely related to the 28-month QBO. Nevertheless, Yasunari [1989], Kuma [1990], Gray and Sheaffer [1991], Gray et al. (manuscript submitted to the *J. Meteor. Soc. Japan*, 1991), Knaff et al. [1991] and Angell [1991] have shown evidence of and argue for direct linkages between the QBO and ENSO linked tropospheric and oceanic variability in equatorial regions.

The main features of our proposed ENSO-QBO association are illustrated in Figure 1. Time series of layer averaged equatorial QBO zonal wind anomalies and of Pacific SST anomalies for the last 40 years are shown. Note that SST warming periods in Figure 1 tend to occur in association with transitions from the QBO west-phase to the east-phase. Thirteen of these 17 west-to-east transition cases are associated with a notable warming of the SSTs. The remaining four periods wherein the QBO turned easterly with no distinct warming include: 1954–1955, following the multi-year 1951-1953 warm event: 1958-1959, following the strong 1957-1958 El Niño; 1970 1971, just after the 1969 warming; and 1983-1984, following the very strong 1982-1983 El Niño. These observations imply an ocean-atmosphere feedback process wherein warm events, once underway, tend to persist irrespective of the QBO until the energy reserve of the west Pacific "warm pool" is depleted. Eventually, the ocean and atmosphere return to a "normal" or La Niña state as cool SST anomalies develop in the East Pacific and oceanic heat energy recharge begins again in the West Pacific warm pool. As discussed below, a period of time on the order of at least several years is needed for the warm pool thermal reservoir to fully "recharge" and again become quasi-unstable to trade wind variability. This timing requirement may explain why the four QBO west-to-east transitions identified previously did not trigger sizable warmings.

Hypothetical Mechanism Linking the Lower Stratospheric QBO and ENSO

The sequence of events which occur in the proposed QBO–ENSO interaction is summarized in the diagram shown in Figure 2. As noted in the introduction, the QBO seems to affect the distribution of intense warm pool convection. Following the diagram in Figure 2, variations in the distribution of convection in turn perturb the regional east-west distribution of surface pressure, thence the trade winds, oceanic surface and internal wave activity and eventually, SSTs in the eastern Pacific. To fully explain these connections, we must first identify a physical process whereby the QBO may influence regional convective activity. Subsequently, we must then show that variations in the distribution of this process in space and time are consistent with the observed distribution of intense convection and with trends in regional atmospheric circulation features linked to ENSO.

The most probable convection linked process through which the QBO might either inhibit or promote regional anomalies of convective activity involves contrasting east-phase versus west-phase vertical wind shear conditions between the upper troposphere and lower stratosphere (between approximately 200 mb and 50 mb). Figure 3 provides a conceptual illustration of these contrasting vertical wind shear conditions and their effects during the Austral summer period (December–March). The primary warming influence of deep convective activity on atmospheric temperature deviations, as indicated on the left in Figure 3,

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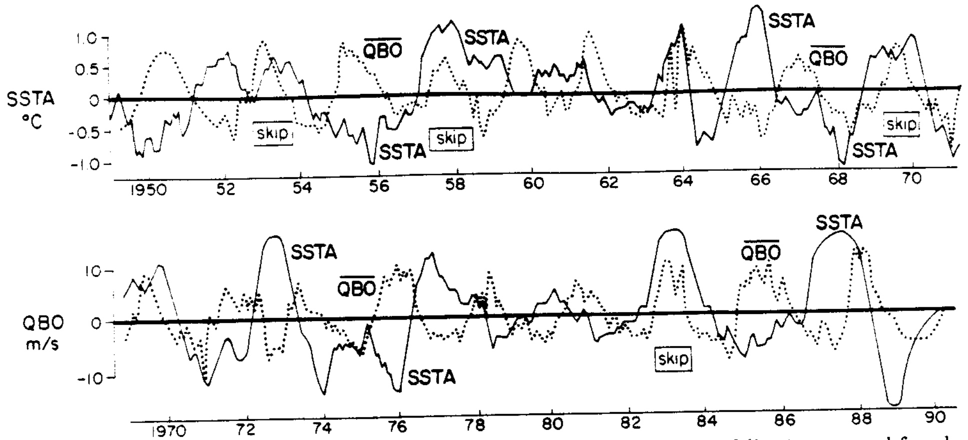

Fig. 1. Comparative time series of mean stratospheric zonal wind anomalies (dotted line) averaged for the layer extending from 70 to 10 mb (16—30 km), versus SST anomalies (solid line) in an area of the Eastern Pacific extending from the equator to 10°S latitude and from the Dateline to 90°W longitude. ENSO warming typically occurs with the QBO east phase. Implications of the "skip" periods are described in the text.

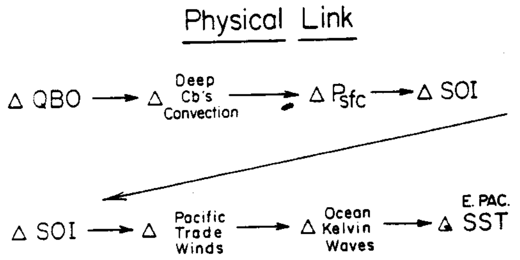

Fig. 2. Conceptual diagram of the sequence of event-associations which link the stratospheric QBO to ENSO variability by altering the distribution of intense convective activity in the tropical Pacific. The distribution of convection varies with the QBO east-phase in such a way as to cause negative values of the SOI, thereby leading to weaker trade winds, ocean Kelvin waves and an ENSO warm event. The reverse occurs with the QBO west-phase.

occurs in the upper troposphere. This upper tropospheric warming leads to relatively low surface pressure values in tropical regions experiencing deep convection.

Convection penetrating into the lower stratosphere is frequently observed in the warm pool area. This penetrating convection may cause an additional small but significant warming of the lower stratosphere as rapidly rising air parcels overshoot their level of neutral buoyancy, entrain warmer stratospheric air and force a compensating subsidence and warming effect. This additional (i.e., stratospheric) warming creates a modest additional surface pressure decrease in regions of intense deep convection, provided that the areas of stratospheric warming remain superposed over the areas of upper tropospheric warming. This latter condition is possible if the difference in horizontal wind direction and speed between the lower stratosphere and the upper troposphere is not too great (i.e., weak vertical shear). The weak vertical wind shear condition illustrated in the top panel of Figure 3 would thus be favorable for anomalously lower surface pressure and for enhanced further convection. The opposite effects with no convection enhancing feedback attend the strong wind shear condition illustrated in the bottom panel.

Other conditions being equal, the maintenance of positive temperature deviations of 0.5°, 1.0°, and 1.5° in the 50–100 mb layer of the lower stratosphere would cause the equivalent of 10, 20, and 30 m thickness difference, respectively. A 20 meter thickness difference is equivalent to a 2 mb surface pressure change which approximates the regional pressure anomalies associated with most ENSO events. Consequently, this simple analysis demonstrates the potential importance of maintaining convectively induced warming of the lower stratosphere superposed over areas of upper tropospheric warming, as is facilitated by minimum vertical shear between the two levels. Data showing this shear effect are presented below and in detail in the previously cited forthcoming article by Gray et al. (1991).

Occurrence of the effects illustrated in Figure 3 follows the highly variable spatial and seasonal distribution of upper tropospheric–lower stratospheric vertical wind shear. This is shown for the Austral summer season in shear in Figure 4. The distribution of this shear also varies in a manner which is consistent with important features of

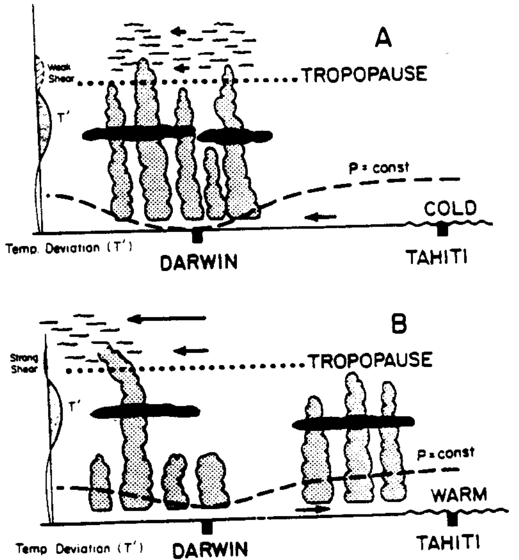

Fig. 3. Conceptual representation of the effects of comparatively weak vertical wind shear in the lower stratosphere of off-equator areas (hence "Darwin") for the Austral summer during the west-phase of the QBO. (Bottom) As in top but for the strong ventilation and related effects during the east-phase of the QBO. Comparative heights of a lower tropospheric constant pressure surface are also shown. QBO related differences in the vertical profile of convective heating are shown at the left where shading above the tropopause represents warming effects of deep convective activity.

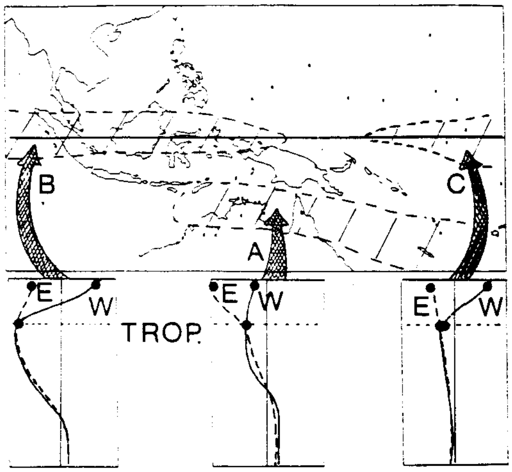

Fig. 4. Comparative QBO east-phase (E) and west-phase (W) representations of the basic differences in zonal wind profiles during the November-March portion of the annual cycle. Profiles are shown for areas near the equator in the far West Pacific (B) and near the Dateline (C), as well as off-the-equator in the SPCZ and in the Australian monsoon circulation (A). The "dots" on the profiles emphasize key differences in the vertical shear values between the upper troposphere and lower stratosphere.

ENSO variability. Insert Box A in Figure 4 illustrates the vertical wind shear in what we term "off–equator" areas which, in this case, lie between approximately 8-18°S. These off-equator areas in the Southern Hemisphere include Northern Australia and much of the South Pacific Convergence Zone (SPCZ). Vastly diminished off-equator vertical wind shear is observed across the tropopause in the Area A (North Australia) region during the west-phase of the QBO. It follows from the processes illustrated in Figure 3, that the diminished west-phase off-equator shear situation will promote a modest regional negative pressure anomaly with enhanced low level convergence and additional deep regional convective activity. In contrast, QBO west-phase stratospheric winds in near-equator areas (i.e., ±7° latitude) shown in Boxes B and C of Figure 4 create a strong west-phase vertical shear situation which is nearly opposite that of the off–equator (Box A) region. Hence, a condition of strong shear with little deep convective enhancing feedback occurs all along the equator but with low shear and enhanced convection in the off-equator areas.

The QBO east-phase (in Figure 4) creates a diminished cross-tropopause vertical wind shear effect in the near-equator areas and thus promotes conditions favorable to the eastward expansion of deep equatorial convective activity along the equator. Enhanced east-phase equatorial convection expanding into the Central and East Pacific due to this favorable condition must lead to a systematic weakening of the local Walker circulation. Note in Figure 4, Box C, that a minimal vertical shear situation develops across the tropopause near the Dateline during the east–phase. This easterly QBO situation is especially favorable for enhanced eastward propagation of convective activity in association with the 30–60 day oscillation. This convection is presumably accompanied by enhanced low level westerly wind burst activity. Concurrently, deep east-phase tropical convective activity in the off-equator monsoon regions (Box A) tends to be suppressed as a result of the strong (easterly) vertical zonal wind shear above the tropopause. The resulting diminished monsoon convection in the off–equator areas of the West Pacific leads to higher surface pressure in these areas, to lower pressures in the East Pacific and thus, negative pressure anomalies in the Tahiti minus Darwin Southern Oscillation pressure Index (SOI). These negative SOI anomalies then cause a further weakening of the Walker and equatorial trade wind circulations, leading to El Niño events.

Note that the SOI reaches it annual maximum during the Austral summer (Dec-March) and then decreases rapidly to a July-August minimum. Hence, for an El Niño to begin, it may be important that the onset of El Niño promoting QBO east-phase effects approximately coincide with this annual weakening of the SOI. The time variation of the phase association of the QBO and the annual cycle may thus be an additional factor in the timing of El Niño events.

Observational Evidence of a QBO–ENSO Link

Associations between the QBO and Pacific SSTs are shown in Figure 1, in Table 1, and in Yasunari [1989], Angell [1991] and in Gray et al. (1991). The association between the QBO and tropical cyclones was described in the Introduction. In this section, we briefly summarize additional evidence of a QBO modulation of the equatorial 30–60 day oscillation, in tropical Pacific SSTs and in regional monsoon related circulations including the distribution of precipitation and surface pressure. These observations support the contention that the lower stratospheric QBO zonal wind anomalies, coupled with the annual cycle, acts as a timing mechanism for ENSO variations through the modification and redistribution of West Pacific–Indonesian regional deep convection. A more complete discussion of these data is given in Gray et al. (1991).

We find evidence that the QBO affects the strength of all major monsoon circulations. Specifically, during the North African summer monsoon season (June–September), mean detrended precipitation for the Western Sahel is 0.36 standard deviations (σ) greater during (weak-shear) west-phase QBO periods as compared to (strong-shear) east-phase periods. Similar relationships are found when examining precipitation data for the Indian Monsoon. When regional Indian rainfall data are stratified into wet ($\sigma \geq$

Table 1: ENSO indices for years during which the QBO winds reverse directions; that is, for transition years with westerly anomalies in January changing to easterly anomalies by the end of the year and vice versa. Mean values for east-to-west transition years are subtracted from those for west-to-east transition years. Data include surface pressure (mb x 10) at Darwin and Tahiti, surface zonal wind anomalies (m/s) at Tarawa, mean SST anomaly for the equatorial Pacific (°C) (90-180°W, 0-10°S), 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
West–to–East Transitions												
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

+1) and dry ($\sigma \leq -1$) monsoons (see Shukla, 1987), a 3 to 1 ratio in the incidence of wet versus dry monsoons occurs during westerly QBO periods. The opposite relationship applies to the dry monsoons wherein the incidence of dry monsoon years is three times more frequent during QBO east-phase periods.

QBO linked trends are also observed in the INA regional summer monsoon (December–March). Using Darwin rawindsondes, we find stronger lower level (850 mb) westerlies (inflow) and stronger upper level (150 mb) easterlies (outflow) during the QBO west phase. Distinctive near-equator versus off-equator differences in the upper troposphere to lower stratosphere wind shear shown in Figure 4 are reflected in the distribution of surface pressure and precipitation anomalies (not shown). In general, the off-equator monsoon regions of Australia and the South Pacific Convergence Zone (SPCZ) show greater amounts of precipitation and lower surface pressure during low-shear west-phase QBO periods (see Gray et al., 1991.). Not only is the Australian regional monsoon pressure lower and precipitation greater in west QBO periods, but data for the Northwest Pacific monsoon region also indicate similar results for the Boreal summer. In contrast, near-equator stations show suppressed precipitation and higher pressure during the west-phase versus east-phase QBO periods.

A sampling of monthly QBO linked trends in pressure, precipitation, SST and trade wind anomalies for several representative locations is given in Table 1. In general, the differences shown in this table are not large in relation to the very strong interannual variability due to ENSO linked feedback processes; the statistical significance of these differences being at the 90% confidence level, at best. There is, however, a remarkable consistency in the spatial distribution of these differences which argues for the mechanism (see Gray et al., 1991).

Results relating the QBO to the strength of the 30–60 day or Intraseasonal Oscillation (ISO) of equatorial low level zonal winds, surface pressure, and convection (see Madden and Julian, 1972) have also been examined. The 30–60 day oscillation propagates eastward through the INA region and is observed to be strongest during the December–March period in the Indonesian region. Findings by Kuma [1990] suggest that this primarily on-equator oscillation is appreciably stronger during the east-phase of the QBO. Analyses of satellite derived Out-going Long-wave Radiation (OLR) data by Kuma [1990] and by Gray et al. (1991) show greatly expanded deep equatorial ISO convection in the Central Pacific during the QBO east phase. This apparent QBO modulation of the ISO would help explain the weaker ISO and higher surface pressures along the equatorial zone during the west-phase QBO. Furthermore, variation of the ISO has been proposed as a likely factor in onset of warm ENSO events, as discussed by Lau and Chan [1988].

Summary

If deep convection linked tropospheric feedback effects are tied to the lower stratospheric QBO, then the conditions they promote will occur over large areas and will persist for periods of time which are adequate to force changes in the tropical regional circulation (i.e., months to years). We find that the most likely process by which the QBO may modify and redistribute regional deep convection is through the contrasting effects of the east-phase versus west-phase vertical wind shear between the lower stratosphere and upper troposphere. This assertion is in agreement with the observed spatial and temporal variability of this shear. In regions where this vertical shear is strong, we also observe positive surface pressure anomalies and decreased deep convection (OLR) and precipitation. Conversely, in regions where this shear is weak, the opposite anomaly situations are observed. The resulting alteration of Pacific regional surface pressure (i.e., the SOI) due to the contrasting QBO effects influences the equatorial trade winds in a way entirely consistent with that required to produce the observed variations of the ENSO.

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