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Is there a quasi-biennial oscillation in tropical deep convection?

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Abstract. We investigate the possibility that the stratospheric Quasi-Biennial Oscillation (QBO) modulates deep convection in the tropics. Interannual variations of outgoing longwave radiation (OLR) in the tropics during 1975-87 are compared with stratospheric zonal winds at Singapore (a measure of the QBO), and with the Tahiti - Darwin sea level pressure difference (the Southern Oscillation Index, or SOI). A monthly time series of anomalous OLR was constructed for regions of consistently low OLR, thus targeting areas of chronic deep convection. This "chronic cold" index and the SOI correlate at -0.6 for zero lag. The "chronic cold" index correlates with 30 hPa Singapore winds at +0.3 and with 50 hPa - 70 hPa wind differences at +0.4, both near zero lag. These results are not inconsistent with the hypothesis that deep convection may be enhanced in chronically cold areas when QBO westward shear exists in the lower stratosphere, and diminished during eastward shear.

1. Introduction

Intriguing quasi-biennial variability has been found in a variety of tropospheric weather phenomena related to tropical convection, including rainfall [e.g., *Gray et al.*, 1992a; *Hastenrath*, 1991; *Kane*, 1995], the yearly number of Atlantic hurricanes [*Gray et al.*, 1992b], tropical 700 hPa and 200 hPa zonal winds [*Yasunari*, 1989; *Knaff*, 1993], sea-level pressure near Indonesia [*Gray et al.*, 1992a], and outgoing longwave radiation (OLR) near Indonesia during the boreal fall and winter [*Knaff*, 1993]. Long term fluctuations of the ocean or land surface have been invoked to explain tropospheric quasi-biennial variability [*Trenberth*, 1980; *Nichols*, 1978; *Meehl*, 1987]. The fascinating possibility also exists that the stratospheric quasi-biennial oscillation (QBO) can influence deep convection by modulating the cloud top environment [*Gray et al.*, 1992a, b].

The QBO consists of alternating bands of easterlies and westerlies descending with time in the equatorial stratosphere, with a period ranging from ~20-32 months (Fig. 1). *Lindzen and Holton's* [1968] original theoretical explanation still stands: tropical convection excites a wide array of vertically propagating waves, which impart eastward or westward momentum to the flow. Wave-driven subsidence and warming accompany the eastward shear layer, while ascent and cooling occur in the westward shear layer [*e.g., Plumb and Bell*, 1982]. *Reid and Gage* [1985] showed that the QBO modulates the tropical tropopause altitude by several hundred meters, lowering it when eastward shear exists in the lower stratosphere. Here we exploit a twelve-year record of outgoing longwave radiation (OLR) to test the proposition that the QBO modulates deep tropical convection. We also explore the relationship between OLR and the El Niño - Southern Oscillation (ENSO).

2. Data and Analysis

Monthly mean values of OLR, averaged in 5°x 5° boxes, were obtained from the NASA Langley Research Center. These values were constructed from radiances measured by the Earth Radiation Budget (ERB) wide-field-of-view (WFOV) instrument. This instrument type flew on the Nimbus 6 and Nimbus 7 polar-orbiting satellites, for which equatorial crossings always occurred near local noon and midnight. Nimbus 6 covered the period July 1975 - June 1978, while Nimbus 7 covered the period November 1978 - October 1987 (except for May 1986), together providing a nearly continuous 12 year record. With respect to instrument type and time of overpass, no other record of such length offers comparable consistency.

Record-mean values of OLR for each month were constructed for each 5°x 5° box, yielding a mean annual cycle. Monthly OLR anomalies were calculated by subtracting the record-mean monthly values from the corresponding individual monthly values. These anomalies were then averaged over the region 15°S - 15°N to create a single time series called "tropical anomaly". We found and removed an offset between average Nimbus 6 and average Nimbus 7 "tropical anomaly" values (Nimbus 7 values were 1.79 W-m^{-2} higher).

OLR is affected by the height, areal density, and frequency of clouds occurring in each box. An OLR flux of 240 W-m^{-2}, which corresponds to a box-average blackbody temperature of 255 K and a rain rate of about 210 mm-mo^{-1} [*Wang*, 1994], indicates deep convection or thick cirrus in a box. A second time series, called "transient cold", was generated by averaging anomalies over the tropics, but including only those boxes which had a raw monthly value less than 240 W-m^{-2}. A third anomaly time series, called "cold area", was created by counting the number of boxes with OLR below

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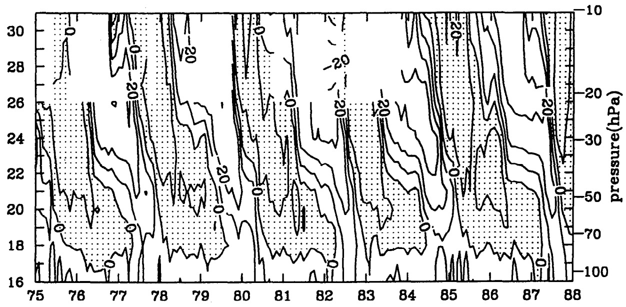

Figure 1. Time altitude section of monthly mean values of zonal wind at Singapore during January 1975 - January 1988. Months with no values are left blank. Eastward flow is stippled. The contour interval is 10 m-s^{-1}.

240 W-m^{-2} for an individual month and subtracting the record-mean count for that month. A fourth time series, called "chronic cold", contains OLR anomalies averaged only for boxes which have a record-mean monthly value below 240 W-m^{-2}.

The "chronic cold" index measures anomalous convection for regions dominated over the long term by deep convection, while the "transient cold" index measures anomalous convection wherever deep convection happens to occur. Figure 2 illustrates the difference between areas contributing to the two time series. The boxes in Fig. 2a are used to calculate all January "chronic cold" values. Comparison of Figs. 2b and 2c illustrates that the boxes used to calculate January "transient cold" values can vary substantially from year to year. Also note that, as partially illustrated by Fig. 2a, throughout the year most of the "chronic" deep convection occurs near Amazonia, the Congo Basin and especially the Indonesian region. This must be kept in mind in interpreting the relationship between the "chronic cold" index and the Southern Oscillation Index (SOI).

The SOI is calculated by the NCEP Climate Prediction Center as ten times the monthly mean Tahiti minus Darwin sea level pressure difference divided by a 30-year standard deviation of this difference (see Chelliah, 1990). Stratospheric zonal winds over Singapore (1°N, 104°E) are used as a measure of the QBO. Rawinsonde profiles for the period January 1957 - December 1990 were obtained from the National Center for Atmospheric Research and averaged for each month. Available levels with a sufficient quantity of data included 100, 70, 50, and 30 hPa. Deep tropical clouds can penetrate into the 70-50 hPa layer, especially near Indonesia. The climatological tropopause is near 80 hPa (~17 km) over Singapore.

All correlation coefficients were calculated after applying 5 month running means to the data.

3. Results

The "tropical anomaly" time series (not shown) has maxima near 1975 and 1981, and minima near 1977 and 1984. This series does not exhibit any obvious relationship with ENSO or the QBO.

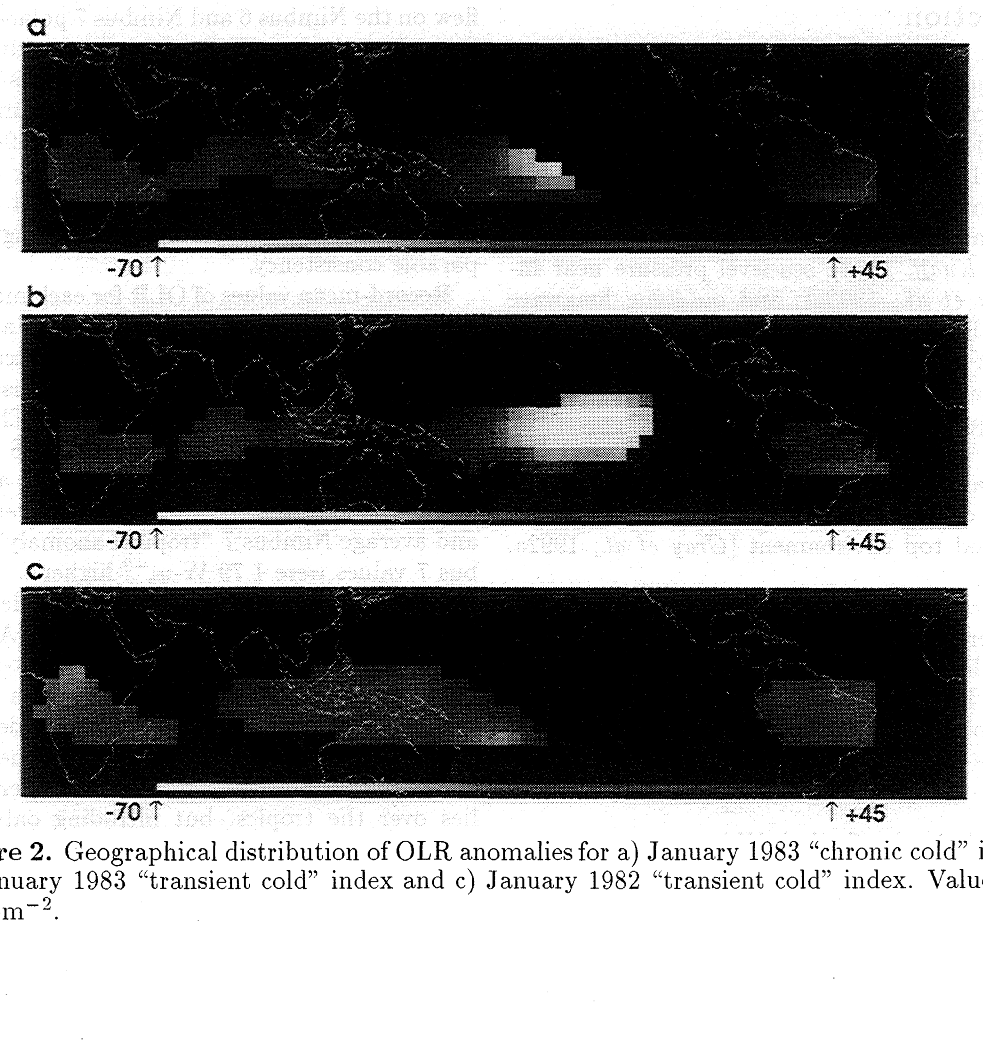

Figure 2. Geographical distribution of OLR anomalies for a) January 1983 "chronic cold" index, b) January 1983 "transient cold" index and c) January 1982 "transient cold" index. Values are in W-m^{-2}.

The "chronic cold", "transient cold", and SOI time series are shown in Fig. 3. The "chronic cold" and SOI time series tend to phase in opposition, especially in the latter half of the record. The correlation coefficient at zero lag is -0.6, implying that when Tahiti sea level pressure is high, chronically cold boxes contain more intense convection. Figure 2 confirms that a pronounced shift of convection occurred during 1982-83 from the Indonesian region toward the central Pacific Ocean [*cf. Fig. 5b, Yulaeva and Wallace*, 1994]. Thus, the conspicuous warm spike in the "chronic cold" index most likely resulted simply from convection shifting out of the sector defined as "chronic cold" during the 1982-83 El Niño. The "transient cold" and SOI indices tend to phase together, with a correlation coefficient of +0.4 at zero lag. Both are strongly negative during the 1982-83 El Niño, supporting the notion that convection had shifted out of the Indonesian sector into a region that does not usually experience strong convection.

Fig. 4 shows that the "chronic cold" and "cold area" series tend to phase in opposition, indicating a larger area of deep convection when typically convective regions have enhanced deep convection. During 1982, however, "chronic" convection weakened as the areal extent of cold clouds increased, further illustrating the shift of convection from the Indonesian region.

One may see from Fig. 1 that if a quantity is correlated with 30 hPa winds, it would be correlated with 70 hPa winds several months later. Correlation coefficients were calculated for the "chronic cold" index and Singapore winds at several levels and for a range of lags. At 30 hPa, the two time series correlate at +0.30 with zero lag. At 50 hPa, the maximum correlation of +0.36 occurs near 5 months lag (OLR phases with zonal winds from 5 months later). At 70 hPa the maximum correlation diminishes to +0.32 and is at 7-8 months lag. From Fig. 1 it can be seen that when 30 hPa winds are eastward, eastward shear tends to exist in the lowest stratosphere. The 50 minus 70 hPa wind difference time series correlates with the "chronic cold" time series at 0.41 near 1-2 months lag. In contrast, the "transient cold" index and Singapore winds have correlation coefficients of 0.1 or less for all wind levels.

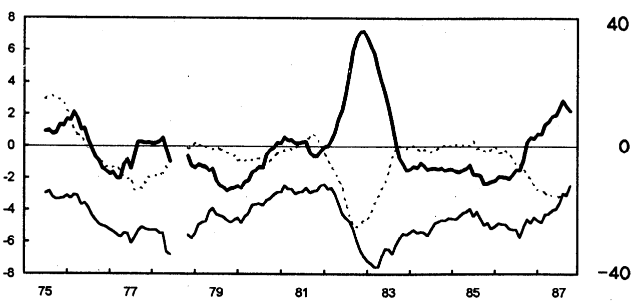

Figure 3. Time variation of the "chronic cold" (bold solid), "transient cold" (light solid), and SOI (dashed) indices during July 1975 - October 1987. Values have been smoothed with a 12 month running mean filter for plotting only. The OLR scale is on the left in W-m^{-2}; the SOI scale is on the right.

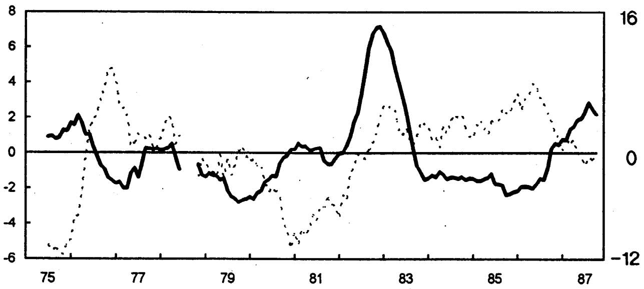

Figure 4. Time variation of the "chronic cold" (solid) and "cold area" (dashed) indices during July 1975 - October 1987. Values have been smoothed with a 12 month running mean filter. The "chronic cold" scale is on the left in W-m^{-2}; the "cold area" scale is on the right in number of 5°x 5° boxes.

From a statistical point of view, ~17% of the variance of "chronic" convection might be explained by lower stratospheric wind shear associated with the QBO. We employ the Student's t-test to assess the statistical significance of the 0.41 correlation found for 50 - 70 hPa winds and the "chronic cold" time series, assuming the null hypothesis of zero correlation. The QBO has a significant autocorrelation. Knowledge of the QBO in a given month is a useful predictor for several months, yet it is very hard to predict the month of onset or duration of the next wind regime. Taking the number of independent samples as the 11 eastward and westward QBO regimes during the record, we get 9 degrees of freedom. Then $t = 1.35$, suggesting that the null hypothesis can be rejected at the 90% confidence level.

Figure 5 shows the "chronic cold" time series plotted with the monthly mean 50 hPa minus 70 hPa zonal wind at Singapore. Most of the positive correlation between these two curves comes from the period 1975 - 1983. High OLR (weaker convection) tends to occur when wind shear is eastward; low OLR (stronger convection) tends to occur when wind shear is westward. This relationship degrades toward the end and even appears to reverse sign.

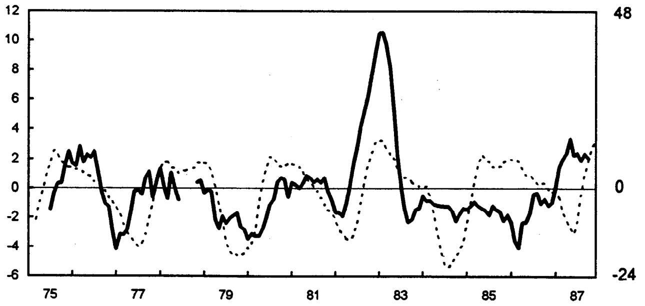

Figure 5. Time variation of the "chronic cold" index (solid) and the 50 hPa minus 70 hPa zonal wind difference at Singapore (dashed) during July 1975 - October 1987. All values have been smoothed with a 5 month running mean filter. The "chronic cold" scale is on the left in W-m^{-2}; the wind difference scale is on the right in m-s^{-1}.

The "chronic cold" index behaves very similarly when a threshold of 250 or 220 W-m^{-2} is used to determine chronically convective regions.

4. Discussion

The "chronic cold" index suggests quasi-biennial variability, especially in the first half of the record. However, the existence of any physical link to the QBO is uncertain. In Fig. 5 the two indices tend to be out of phase during 1984 - 1987, and the data record only spans 11 QBO wind regimes. The .41 correlation is modest, with about a 1 in 10 likelihood of occurring by chance. There are, however, several possible physical bases for a direct causal relationship. Since the QBO is driven by convectively excited waves, it is possible that there is a subtle influence of deep convection variability on the rate of descent of QBO shear zones. This *upward* influence hypothesis would be exceedingly difficult to test using observations alone, since the spectrum and variability of vertically propagating waves have not been adequately characterized.

Two *downward* influence hypotheses have been proposed, one involving static stability and tropopause height changes, the other involving wind shear [*Gray et al.*, 1992a; *Knaff*, 1993]. Descending QBO eastward shear would warm and lower the tropopause, and enhance static stability near cloud tops. Descending westward shear would raise and cool the tropopause, and reduce static stability [*Plumb and Bell*, 1982]. It is plausible that a QBO warm anomaly near 70 hPa would inhibit deep convection, while a cold anomaly would allow deep convection to reach higher altitudes. The wind shear itself may affect convection. Strong upper-tropospheric to lower-stratospheric wind shear of either sign could alter the internal coherence of convective complexes and limit their growth. Since upper tropospheric winds vary substantially on an annual cycle and with geographical location, a QBO shear anomaly could either enhance or diminish local wind shear.

If any of these mechanisms are operating in "chronic cold" regions, why does the "transient cold" index show little QBO variability? The "transient cold" index, heavily influenced by the migration of deep convection, correlates well with the SOI. The migration of deep convection, in turn, is modulated by ENSO (see Fig. 2 and *Yulaeva and Wallace*, [1994]). Therefore, ENSO-induced variations may dominate a quasi-biennial oscillation of the "transient cold" index. In addition, the "transient cold" time series may tend to capture somewhat shallower convective clouds than are commonly found in the "chronic cold" areas. These clouds may be less subject to the influence of lower stratospheric winds. We plan to investigate the OLR-ENSO connection more thoroughly and carry out a more comprehensive OLR-QBO study using a longer OLR record.

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