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Global equatorial variability of 850 and 200 hPa zonal winds from rawinsondes between 1963 and 1989

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Abstract. The longitude-height-time variability of 3-month averaged zonal wind anomalies at 850 and 200 hPa over the equatorial area (5°N - 5°S) is analyzed using a three-dimensional dataset constructed from rawinsonde data (1963-1989). The first mode, closely related to the Southern Oscillation Index, suggests a strong vertical coupling associated with a horizontal out-of-phase pattern between the central/western Pacific and the remainder of the equatorial belt. The vertical coupling appears to be phase-locked to the annual cycle with strongest intensities found over South America and near the maritime continent early in the calendar year and over the Pacific basin and Africa during the second half of the year. This mode of variability can be viewed as a standing pattern superimposed with an eastward-migrating component, coherent with the annual cycle. This westerly moving mode originates near the maritime continent during the northern autumn, and tends to precede El Niño/Southern Oscillation events in the central and eastern Pacific Ocean. Variance is mainly concentrated in the 3-8 year low-frequency time scale throughout the tropics, and in the 2-3 year quasi-biennial band from 110° - 120°E to 180° .

Introduction

Numerous authors have documented important features of the tropical atmospheric circulation structure and variability. Bjerknes (1969), Newell et al. (1974), Julian and Chervin (1978) and Krishnamurti (1985), for example, have shown evidence of the existence of a Walker cell over the Pacific Ocean and of the East-West divergent circulations. Lorenc (1984) and Johnson et al. (1985), among others, have studied the effects of the rotational and divergent components of the horizontal wind in the context of the global dynamics. Sardeshmukh and Hoskins (1987) found that the divergent portion of the circulation is weaker than the rotational one, even along the equator. Computation of these components is very sensitive to the quality of the wind data supplied by the rawinsonde network and the various schemes utilized to analyze the data. This last point is more evident when long periods and large regions have to be considered to portray correctly the large scale variability of the tropical atmospheric dynamics. Because of this, upper tropospheric zonal winds at 150 or 200 hPa have often been used as a proxy of the East-West circulation (Arkin 1982 ; Gutzler and Harrison 1987 ; Ropelewski et al. 1992, among others). This paper complements these last studies. It investigates, not the divergent circulations, but the vertical coherence (VC) which results from the longitude-

time-height structure of the wind circulation across large areas in the tropics. In particular, VC analysis focuses on the statistical coupling between zonal monthly anomaly winds in the low (850 hPa) and the high (200 hPa) levels of the troposphere (Lambergéon et al. 1981 ; Fontaine and Janicot 1992). The monthly mean observational field used in this study were extracted from the three-dimensional dataset compiled by the Geophysical Fluid Dynamic Laboratory. An objective analysis scheme (Conditional Relaxation Analysis Method) was used to obtain values on a global grid (2.5° latitude and 5° longitude spacing) from the irregularly spaced rawinsonde network (Oort, 1983). Only the subset May 1963 - December 1989 along the equatorial plane is used here because of the differences in the analysis schemes and quality control procedures utilized during this period and earlier years (see Oort 1983 and Oort and Liu 1993 for a full description). Some areas, as eastern Pacific Ocean or western Indian Ocean, should be interpreted cautiously since rawinsondes are rare or absent (see fig. 1 of Oort and Liu, 1993). The time series of standardized monthly means were smoothed by a 3-month running average to enhance the signal to noise ratio and to filter the variance associated with the 40-50 day oscillation. Tests of significance take into account the temporal autocorrelation in the series.

Longitude-height combined Principal Component Analysis

The upper and lower troposphere wind anomalies tend to be out-of-phase near the Equator, which reveals the 'baroclinic' structure of the atmosphere (Lau, 1985 ; Gutzler and Harrison, 1987 ; Rasmusson, 1991). A combined principal component analysis (CPCA) is used to objectively determine the dominant spatio-temporal modes of the vertical structure of the zonal wind anomalies in the equatorial plane (5°N - 5°S) from May-July 1963 to October-December 1989. This allows for focusing on the recurrent structure of combined variability of the equatorial zonal wind anomalies at 850 (U850) and 200 (U200) hPa by taking into account both the structure of the correlation matrix of each variable and the structure of the cross-correlation matrix between both variables. Longitudinal weights, time series and spectrum of the leading combined mode are shown in figure 1. The leading combined mode (PC1), which explains 31.3% of the total variance, represents a standing pattern with a clear inverse relationship between U850 and U200 and a horizontal node near 120°W and 120°E (fig. 1a). The vertical coupling is especially strong over South America, near the maritime continent and over the central Pacific Ocean. The associated time series (fig. 1b) clearly shows the alterations between La Niña/Southern Oscillation events (LNSO hereafter) with negative values in 1967, 1970-71, 1973, 1975, 1984-85, 1988 and El Niño/Southern Oscillation events (ENSO hereafter) with positive values in 1965, 1969, 1972, 1976-77, 1982-83, 1986-87. PC1 is stron-

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Figure 1. The leading recurrent mode of combined variability of equatorial 3-month running averaged zonal wind anomalies at 850 hPa (U850) and 200 hPa (U200): Loading pattern of U850 (U200) in the solid (dashed) line (a), time series (b) and spectrum (c). Filled circles (c) indicate significant peaks at the 0.1 level according to a Monte-Carlo simulation of 1000 pseudorandom time series with lag-one correlation and total variance scaled to be comparable to the leading combined mode. The frequencies higher than 1 cycle / 12 months are not displayed.

gly correlated ($r=+0.77$, significant at $p=0.01$) with the Tahiti-Darwin Southern Oscillation Index (SOI) and the spectrum of this mode (fig. 1c) exhibits a significant dominant peak at 50-60 months and a second peak at 20-30 months. These features are detailed by using CPCA on the U850 and U200 3-month running averages (January-March, February-April, ..., December-February). Displayed are the time-longitude cross-sections of the linear correlation between U850 and U200 (fig. 2a) as well as the loading patterns of PC1 at 850 hPa (fig. 2b) and 200 hPa (fig. 2c). Two points are worth emphasizing. First, the vertical coupling between U850 and U200 is strongly phase-locked to the annual cycle with an eastward displacement of the strongest negative correlations from South America (February-May) to Africa (July-September) and from the eastern Indian Ocean (February-April) to western and central Pacific (June-December). The weakest vertical coupling (positive or near zero correlations) over eastern Pacific Ocean and western Indian Ocean corresponds to the less well-documented areas. Second, the longitudinal structure of the leading combined mode is seasonally stable at 200 hPa, but slightly varying at 850 hPa (fig. 2b-c).

Standing mode and eastward propagating phase

The statistical relationship between SOI and the leading combined mode involving U850 and U200 must be defined

clearly since previous studies (Barnett, 1983, 1984; Yasunari, 1985; Gutzler and Harrison, 1987) have indicated that the associated zonal variability does not portray a standing mode. Stratified low SOI and ENSO (1965, 1969, 1972, 1976-77, 1982-83, 1986-87) periods and high SOI and LNSO (1964, 1970-71, 1973, 1975, 1988) periods are thus examined in further details by using 36 month composites of difference between U850 and U200 starting in January(-1), one year before the height of the ENSO or LNSO event and ending in December(+1) one year after (fig.3). When one phase of any warm or cold event spanned two years (i.e. 1970-71 or 1982-83), only the first year of the event was used as the year(0). These ENSO and LNSO composites display reversed VC patterns during their respective mature phase (May-June(0) - May-June(+1)). This highlights out the out-of-phase variations between the central and eastern Pacific Ocean, and the remainder of the equatorial belt, as described by Lau (1985). This standing signal seems to be preceded by a progressive

Figure 2. Equatorial time-longitude cross sections of (a) the correlations between U850 and U200, (b) the loading pattern at 850 hPa and (c) 200 hPa of the leading combined mode. The labels in the ordinate refer to central months of each 3-month running period. The solid (dashed) line indicates positive (negative) value with an interval of 0.25. Light (dark) shading indicates negative (positive) values exceeding the 90% level of significance, when the temporal redundancy is taken into account. The leading combined mode explains, respectively 33.7% (JFM), 35.1% (FMA), 36.3% (MAM), 36.4% (AMJ), 33.7% (MJJ), 32.5% (JJA), 33.3% (JAS), 35.5% (ASO), 42.5% (SON), 40.6% (OND), 37.1% (NDJ), 33.6% (DJF) of the total variance.

Figure 3. Distribution of standardized departures from the 1963-1989 mean of U850-U200 (contour interval : 0.50) along the equator, plotted as functions of longitude and time period in the life cycle of a typical ENSO (a) and LNSO (b) episodes. Light (dark) shading indicates negative (positive) anomalies exceeding the 90% level of significance, according to the Student's t-test.

eastward-migrating phase, originating near the maritime continent. This phase, not significant at the 0.1 level, is however also reported by Barnett et al. (1991, their fig. 8) : it clearly occurs before the mature phase of the ENSO composite (the

36 month stratified period) from September(-1) to April(0). The eastward migrating phase is less clear during the LNSO composite (figure 3a). The existence of a biennial alternance of significant anomalies before and during an ENSO event (figure 3b) is consistent with the previous results of Meehl (1987) : a "strong" annual cycle (year(-1)) tends to occur before a "weak" annual cycle (year(0)). The propagating phase can be detailed through time-longitude cross-sections of the differences U850-U200. The data are bandpass smoothed, using a recursive filter (Butterworth method), according to the two dominant frequency-bands previously used by Barnett (1991) and Ropelewski et al. (1992) : the 18-32 band denoted QB for quasi biennial, and the 36-84 month, denoted LF for low frequency. The filtered cross-sections (fig. 4) exhibit distinct eastward-migrating phases in both the QB band (fig. 4a) and in the LF band (fig. 4b). The propagating QB signal is particularly evident along the eastern parts of the Indian Ocean and western parts of the Pacific Ocean (100°E - 180°W), while the LF signal is larger but still not significant in the 140°W - 50°E domain. A time modulation is also evident : the QB (LF) variability is stronger within the years 1971-76 and 1982-86 (1969-1976 and 1982-1988) during which the major warm events occurred (Ropelewski et al., 1992).

Figure 4. Equatorial time-longitude cross-sections of filtered U850-U200 : (a) quasi-biennially (18-32 months) and (b) low-pass filtered (36-84 months). Values are displayed into five shadings : lower than -0.75 standardized deviations (white), between -0.75 and -0.25 (clear grey), between -0.25 and 0.25 (grey), between 0.25 and 0.75 (dark grey) and higher than 0.75 (black). The zero line is highlighted.

Discussion and conclusion

A simple but robust statistical analysis taking into account the negative correlations between the zonal wind velocity anomalies at 850 and 200 hPa was used to stress the variability of the VC in the equatorial plane. An examination of the leading combined mode of the equatorial zonal wind anomalies at 850 and 200 hPa and time-longitude cross sections of the difference between both levels confirm numerous features of the tropical dynamics. They attest first to a clear VC modulation through the mean seasonal cycle. Negative correlations increase in absolute sense, mainly in the western and central Pacific Ocean and in the Atlantic Ocean, when the East-West thermal gradient between the western warm pool and the eastern cold tongue is well established (during the northern summer). Second, the first VC mode of variability (31.3% of

the total variance) is large and appears to be closely linked to the SOI time-series. It mainly portrays an out-of-phase relationship between the central Pacific Ocean and the remainder of the equatorial belt, except the maritime continent. The mature phase of ENSO events (from May-June to April-May) corresponds to a standing phase of this widespread tropospheric signal. A warm event is associated with a decreasing intensity of the mean zonal monthly winds at 850 and 200 hPa in the equatorial plane accompanied by low level westerly and/or high level easterly anomalies in the Pacific basin. The opposite pattern is observed in the Indian Ocean and Africa monsoonal areas where low level easterly anomalies are associated with high level westerly anomalies reducing both the westerly component of the monsoon and the Tropical Easterly Jet during the northern summer. Another important point concerns the reversing of this VC pattern during LNSO events, a fact in accordance with the concept of "weak" / "strong" annual cycle associated with warm / cold events (Meehl, 1987). ENSO events tend to be preceded then followed by eastward-migrating periods that migrate from the maritime continent towards the central Pacific Ocean before dissipating in the eastern parts of the Pacific basin. This agrees with the results of Barnett (1983), Yasunari (1985), Gutzler and Harrison (1987), Rasmusson (1991) and provides some evidence that SOI (the atmospheric component of ENSO) is not directly forced by warm anomalies into eastern and central Pacific Ocean. Two mechanisms could be suggested : (1) each area may be independently affected during the mature phase of ENSO and LNSO events ; (2) a progressive eastward-migrating mode, most apparent in the Indian-Pacific domain and strongly linked to the annual cycle, could trigger each ENSO or LNSO event. The mean speed of the eastward phase could be compatible with the coupled air-sea forcing suggested by Meehl (1993). The distinction between a clear biennial signal (20-30 months), which is stronger in the eastern Indian Ocean and the central Pacific Ocean, and a low-frequency signal (36-84 months) which is observed throughout the equatorial region is also confirmed (Yasunari, 1985 ; Gutzler and Harrison, 1987), but in this case, it is terms of a zonal vertical coupling in the equatorial plane.

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