QBO of the Equatorial-Stratospheric Winds Revisited: New methods to verify the dominance of 28-month cycle

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Abstract
The equatorial-stratospheric wind that shows a Quasi Biennial Oscillation (22-32 months) has been revisited using a dual statistical detail regarding the search of the dominance harmonics. Data were used from the Freie Universitat of Berlin since 1953 for different heights combining the observations of the three radiosonde stations. The dominant period of 28 months has been reaffirmed but with a discernible amplitude and a phase, respectively, inversely varying with height. Such a cycle suggests an estimate for the coming easterly equatorial wind occurrence at 15 hPa level at the end of 2009. The 28-month harmonic is found to take about a year to descend from 15 to 70 hPa with a progressive lag of about 1 month/km. At the top of the stratosphere, easterlies dominate, while at the bottom, westerlies are more likely to be found. Correlation with sunspot numbers and seasonal rainfall is discussed.

Keywords: QBO; Stratospheric winds; equatorial; 28-months.

1. INTRODUCTION

The equatorial-stratospheric wind (ESW) oscillates between easterly and westerly directions and with a period around 24 months called Quasi Biennal Oscillation(QBO) on a regional basis e.g. Canton Island and Christmas Island (Baldwin et al., 2001; Graystone, 1959; Ebdon, 1960; Reed et al., 1961;Veryard and Edbon, 1961; Angel and Korshover, 1964). Regarding its physical explanation, Lindzen and Holton (1968), Lindzen (1987), Andrews et al. (1987) came slowly to the conclusion that QBO is typical of planets with rotating stratified atmospheres and equatorial convection deriving essentially from the stratospheric absorption of vertically upwards transferring westerly Kelvin waves, which contribute a westerly force, and easterly Rossby-gravity waves, which contribute an easterly force. The QBO is related to the occurrence of different natural stratospheric and tropospheric phenomena like the geopotential height at high latitudes (Holton and Tan, 1980), the Indian summer monsoon rainfall (Bhalme et al., 1987; Mukherjee at al., 1985) and the decay of aerosol loading following volcanic eruptions (Thomas et al., 2008). Most GCMs are unable to generate spontaneous and realistic QBO (Horinouchi and Yoden,1998) even if attempts are made to include QBO forcing in GCMs either by assimilating the observed equatorial–stratospheric wind to the model winds or by considering a sufficient spatial resolution, a realistic simulation of tropical convection and the effects of gravity waves (Giorgetta et al., 2006). The relationship between QBOs of stratospheric winds, ENSO variability and other atmospheric parameters has been examined by Kane (2006). There, the 50-mbar

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tropical zonal wind has a predominent quasi-biennial oscillation (QBO) mode with an average period of *circa* 28 months, variation in the range 21-33 months and amplitudes varying within ± 20 per cent. However, for the Southern Oscillation, Tahiti minus Darwin (T-D), sea-surface temperature (SST) and equatorial rainfall indices, QBO is not the strongest mode. Periods of 3.6 and approximatelly 6 years are stronger. The QBO modes for these and other parameters (e.g. surface winds and winds in upper and lower troposphere and stratospheric winter temperature at the North Pole) are very irregular, with amplitudes, phases, and sometimes even period having large changes with time. It seems that these have little relationship with the 50-mbar zonal wind QBO and may have altogether different origins.

To provide a different forecasting contribution of monthly ESW for different pressures we here apply a novel non-conventional data analysis procedure, consisting of robust statistical techniques. This way we have computed amplitudes, phases, alternative spectrum analysis and lags of ESWs at a 99% confidence level.

2. DATA COLLECTION AND ANALYSIS

The monthly values of equatorial-stratospheric winds are analysed, as measured by the Freie Universitat of Berlin since 1953 for different heights combining the observations of the three radiosonde stations, attached retrieval noise (error) levels 1-5 m/sec (Rochon et al., 2006; Backus and Gilbert, 1970): Canton Island (lat: 2° 46' S; long:171° 43' W; interval: January 1953- August 1967), Gan (lat: 0° 41' S; long: 73° 9' E; interval: September 1967 – December 1975) and Singapore (lat: 1° 22' N; long: 103° 55' E; interval: January 1976 – December 2008). Observations are usually available twice daily at 00 and 12. Only earlier years have less frequent observations, sometimes less than 10 per month. This data set is supposed to be representative of the equatorial belt since all studies have shown that longitudinal differences in the phase of the QBO are small (Naujokat , 1986; Labitzke et al. 2002). Detailed information on all aspects of the QBO, the merged data, its dynamics and its global effects, can be found in a most recent review paper of Baldwin et al (2001), including a comprehensive bibliography. A study of the coupling between the tropical QBO and the global stratospheric circulation has been performed by Marquardt (1998); while, time-height section of monthly mean zonal winds (m/s) at these three equatorial stations and for the 7 height levels are clearly presented as isopleths at 10 m/s intervals; where easterlies and westerlies are defined (e.g. Kinnersley & Pawson, 1996).

Some uncertainties arose at higher levels during the early years from the scarcity of observations, and for this we have limited the analysis of monthly ESW to 70 hPa (18.8 km), 50 hPa (20.6 km), 40hPa (22 km), 30hPa (23.9 km), 20hPa (26.5 km) and 15hPa (29 km), available from the web site: http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat . In fact because the QBO shows a high degree of zonal symmetry this has allowed the merging the equatorial zonal wind profiles of the individual stations into one dataset covering a longer time period (Naujokat, 1986). Another rationale of the stratified by height harmonic analysis is because the QBO modulates the solar signal in the stratosphere, and in turn is modulated by the sun, therefore, it was necessary to stratify the data of the long series for which the equatorial QBO in the lower stratosphere included its westerly or easterly phase.

At any rate, though the computed accuracy is high, the measurements inhere variations that need to be considered. The ability of three reanalysis systems (from NCEP/NCAR, NASA and ECMWF) to reproduce the observed QBO at Singapore as derived from rawinsonde observations (Naujokat 1986) has been discussed (Pawson and Fiorino, 1996). The *reanalyses project* employs fixed and state-of-the-art global models and data assimilation systems to "reanalyze" all available observational data (operational as well as from archives and field campaigns) so as to produce a dynamically consistent, global description of the atmosphere over long time periods. While the skill of climate simulation models has advanced over the last decade, mainly through improvements in modeling, further progress will depend on the availability and the quality of comprehensive validation data sets covering long time periods.

However, even if reanalysis is considered (or defined) as the best source of data for climate model verification, prudence warrants a comparison against quasi-independent observations and other traditional data sets. Further, the tropical stratosphere may include fewer input data than other regions,

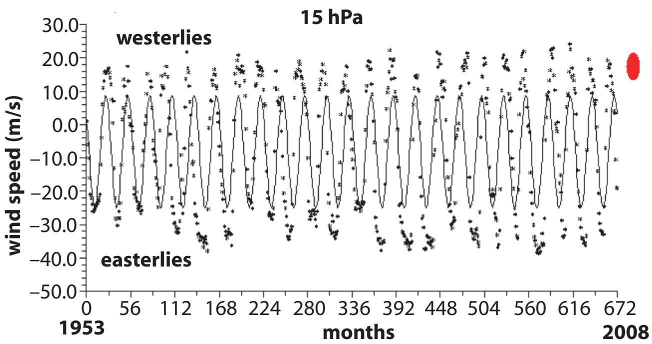

Figure 1 Time plot of monthly values of 15hPa observed equatorial-stratospheric wind (* points) (interval 1953-2008) and monthly values computed according to its 28-month harmonic (continuous line). Red ellipse the expected value (with error) at the end of 2009.

but a successful representation of this region must be regarded as a benefit of any model, and an insufficient simulation should not receive undue criticism. Thus, any statistical use of data must be treated cautiously and additional elaborative methods are most welcome.

The QBO in zonal wind (see Baldwin et al. 2001 for a recent review) is directly observed in operational wind measurements by radiosondes at equatorial meteorological observatories.

Figure 1 shows the time plot of the monthly values of ESW relative to 15 hPa level. We have previously applied spectral analysis to monthly data sets relative to different heights according to 48 degrees of freedom. All the normalized power spectra, obtained as Fourier transform of autocorrelation coefficient, show that the 75% of monthly variance concentrated around the 24 month period. To obtain a more detailed information on the relative dominant harmonic, two new separate and specific statistical methods are here employed: the *vector probable (vpe)* and the *phase averaging analysis*. Both methods subdivide the entire observation interval into non-overlapping subintervals (with a length equal to the period of the harmonic to be investigated) after the filtering of non-cyclic variation performed according to the least square analysis.

A: The first approach consists in the calculation of the Fourier coefficients for each of the subintervals and of the scattering of the individual harmonics from the center of gravity *A* of all points, corresponding to the harmonic coefficients as computed from all series. It is based on Bartels (1932) and developed by Cecere et al. (1981). In brief, the time series is subdivided into *N* smaller subintervals, which are equal in length and do not overlap. Tne Fourier coefficients x_n and y_n (for the term to be tested) are calculated for each subinterval. These can be plotted suitably as periodogram vectors in the complex plane, whereby their end points form a point cloud. Then the following statistics are calculated for each harmonic "*n*" : (i) the center of gravity (x_o, y_o) of all points, corresponding to the harmonic coefficients as computed from all series, ii) the standard deviation σ_x and σ_y for the harmonic "*n*" of each subinterval from (x_o, y_o). If the distribution is normal, the probable error assumes the equation of an ellipse $Q(x,y) = f(r, x, y, \sigma_x, \sigma_y)$, r = correlation coefficient. For $r = 0$ and $\sigma_x = \sigma_y$ the ellipse degenerates into a circle whose radius is the vector probable error. Other subroutines compute correct amplitude and phase and spectral estimates per subinterval. The reliability is computed according to the *vector probable error (vpe)* equal to the root-mean square radius of the point cloud. The confidence level of the harmonic is computed according to the equation:

$1\text{-}\exp[-(0.833\ A/vpe)^2]$, i.e. the scattering from A. The harmonic is found to be confident at 95% (99%) level when A ≥ 2.08 vpe (A ≥ 2.58 vpe) (Cecere et al., 1981).

B: The second approach concerns the calculation of the correlation coefficient R amongst the N monthly values, constituting the mean investigated cycle, and those computed according to the first Fourier harmonic. All spectra have been computed as Fourier transforms of autocorrelation function and smoothed by a Hanning function to reduce signal windowing effects. To evaluate the accuracy of

R, we have computed the random variable W = 0.5 ln[(1+R)/(1–R)] that has an approximately normal distribution with a mean equal to (N–3) + 0.5 ln[(1+R)/(1-R)] and a variance equal to $(N-3)^{-1}$ (Bendat and Piersol, 1971; Mazzarella and Palumbo, 1994). The level of confidence of R is obtained by testing W (normalized to a mean equal to zero and to a variance equal to one) versus the null hypothesis of zero population relationship according to the standard one-sided z test. (z is the standardized normal variable, and R^2 indicates the percentage of Z variance accounted for by regression on the two data variables). The harmonic is found to be confident at 95% (99%) level when the relationship $W = \sqrt{(N-3)}/2 \ln(1+R)/(1-R)$ provides values $z_{a/2} \geq 1.96$, (≥ 2.58).

3. RESULTS

After many trials, we have found that values of vpe and R are the highest and confident at a level greater than 99% only when we subdivide the wind series into subintervals of 28 months. The values of amplitude, phase, vpe, R and confidence level of such harmonic, for the different investigated altitudes, are reported on Table 1. Here the six atmospheric levels are shown corresponding to 18.8 to 29 km height with respective mean values of wind velocity -8.2 (easterly regime) to 1.9 m/s (westerly regime) and amplitudes from 5 m/s to 17 m/s for 70 hPa to 15 hPa respectively. It is apparent the large amplitudes (A m/s) and wave phase for low levels. The 15 hPa data of the first line of Table 1 provide expected values for 2009 (Fig.1). In Fig.1 the data series for the monthly 15 hPa values is plotted together with the computed 28-month harmonic to appreciate the degree of their matching based on the computed analytical data at a confidence level of >99%, as discussed below..

Figure 2 reports the plot of the average 28 month cycle of ESW for each investigated altitude. The 28-month harmonic accounts for around 40% of the monthly wind variability from 15 to 70 hPa levels, while the same harmonic accounts for about 30% from 40 to 70 hPa level with the onset of westerlies. Both contributions are significant with respect of the known 24 months QBO. The amplitude and phase of the 28-month harmonic are found to vary inversely with the height. At the bottom of the stratosphere the amplitude is the lowest and equal to 4.7 m/s and gradually increasing the height up to 16.8 m/s at the top of the stratosphere. The 28-month cycle propagates downward and Table I shows that the time lag takes 11.7 months to descend from 15 hPa to 70 hPa equal to 0.90 km/month. Table 1 shows that

Table 1 Values of amplitude (A), phase (φ), vector probable error (vpe) and confidence level of the 28 month cycle obtained from the monthly values of equatorial-stratospheric winds, available from 1953 to 2008 for six different heights; R represents the correlation coefficient among the 28 monthly observed QBO values and computed according to the first Fourier harmonic. The 15 hPa data are predicted for 2009.

Atmospheric pressure	H (km)	mean value (m/s)	sigma (m/s)	A (m/s)	φ(°)	vpe	A/vpe	R	confidence level	%	lag (months))
15 hPa	29.0	–8.2	19.8	16.8	151	3.1	5.5	0.99	greater than 99%	37	
20 hPa	26.5	–8.2	19.5	16.7	129	3.0	5.6	0.99	greater than 99%	38	1.7
30 hPa	23.9	–6.2	17.9	15.4	92	2.8	5.5	0.99	greater than 99%	39	2.9
40 hPa	22.0	–2.8	15.9	13.2	57	2.5	5.2	0.99	greater than 99%	37	2.7
50 hPa	20.6	–0.2	13.0	10.0	35	2.2	4.6	0.99	greater than 99%	33	1.7
70 hPa	18.8	1.9	6.3	4.7	0	1.0	4.6	0.99	greater than 99%	28	2.7

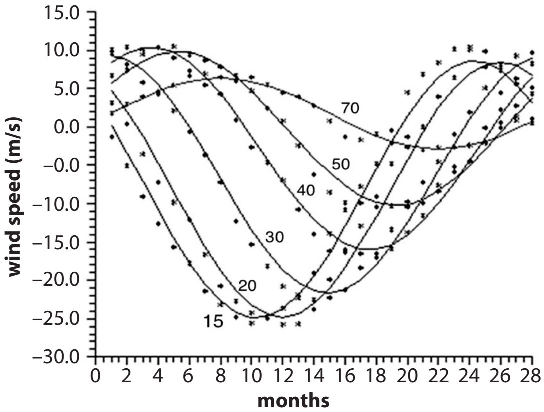

Figure 2 Average 28-month cycle of the equatorial stratospheric wind for different height. The continuous curve represents the first Fourier harmonic. The values relative to 70hPa, 50hPa, 40 hPa, 30 hPa, 20 hPa, 15 hPa are reported on the plot from the top of the graph downwards, respectively.

the mean values are systematically increasing with negative value up to 50 hPa and positive value from 50 hPa to 70 hPa, to indicate that the easterly regime characterizes the stratosphere from 15hPa to 40 hPa while the westerly regime from 40 hPa to 70 hPa. Figure 2 shows, moreover, that the amplitude of easterly regime (negative) of the 28 month harmonic, relatively to 15, 20 and 30 hPa levels, is stronger than the westerly regime

4. DISCUSSION

The application of two different statistical analyses to the monthly equatorial-stratospheric wind has evidenced the dominance of 28-month period, confident at a level greater than 99% (Figures 1, 2), that accounts for about the 40% of the overall monthly variability.

The values of A/vpe ratio (Table 1) show that the 28-month harmonic is much more statistically significant inside the bin enclosed between 15 and 40 hPa levels in respect to that enclosed between 40 and 70 hPa. Moreover, the phase of the wind takes about a year to descend from 15 to 70 hPa, in fair agreement with Ebdon and Veryard (1961). The analysis of equatorial-stratospheric wind show that: the wind regimes propagate down as time progresses: they move downwards at less than 1.00 km/month and decrease in magnitude as the height decreases; the longer lag, equal to 1.5 km/month occurs in the passage from 15 to 20 hPa and decreases under the 1 km/month value for the successive levels to 0.87 km/month for the whole interval. They start at 15hPa and descend to 70hPa with the maximum amplitude of 16.8m/s found at 15 hPa level; easterlies are generally stronger than westerlies; westerly winds last longer than easterly winds at higher levels while the converse is true at lower levels; the westerlies move down faster than the easterlies. If the 28-month harmonic is to be usefully utilized as a predictor of equatorial-stratospheric wind, it is anticipated to verify its forecasting power in the future. To perform such a test, a comparison is made, for each month "t", among the observed ESW monthly values, and the synthetic monthly values derived from the equation: $ESW(t) = A \sin[(360/28)/t + \varphi)]$. The analysis of 15 hPa wind data was made using the values of $A = 16.8$ and $\varphi = 151°$ (Table 1). Such a cycle suggests an estimate for the coming easterly equatorial wind occurrence at 15 hPa level at the end of 2009.

The importance of the reinforced prominent QBO with the 28-month oscillation and the predictability of 15 hPa wind amplitude and phase, brings in again the effects of QBO of ESW in the complex interaction of dynamics in stratosphere and the solar - climatic proxy indices relationship (Labitzke et al., 2008; Mazzarella, 2008; Liritzis and Petropoulos 1987; Liritzis & Galloway 1995; Liritzis et al., 1995). Amongst the atmospheric phenomena involved in such a relationship are those occurring in the stratosphere which affects weather at the ground. Thus, the sunspot cycle effect on the lower stratosphere and the dominant 28 months cycle, at least for the upper heights of 15 hPa at 29 km, exhibit minima of easterly winds that almost coincide with solar activity maxima at 1958/9, 1970/1, 1980/1, 10901/2, 2001/2 (Labitzke et al., 2008) (see Fig.1). This might provide a further insight for a mechanism of the well known solar-climate-ocean links on a stratified scale, e.g. stratosphere connection to solar cycle and ocean (Meehl et al., 2009).

In the case of the QBO, and the dominance of 28 months this has to be accounted for in modelling (e.g. Climate Chemistry Modelling), since QBO is an internal mode of atmospheric variability and not a "forcing" one.

The 28 months dominance of the QBO effects on circulation and chemistry should not be neglected, especially as the QBO is generated by internal processes of the atmosphere, but is not simulated in most current climate chemistry models (CCMs). Indeed, small time scales forcings external to an atmosphere-only model, with the exception of the QBO, are generated by El Nino/La Nina, QBO, solar sunspot cycle, volcanic eruptions, trends in emissions etc. Therefore, assimilation of the zonal wind in the QBO domain can add the 28 months cycle to the system, thus providing for example its effects on transport and chemistry. For this reason it would be of interest to include the 28 months cycle in climate chemistry experiments e.g. for SCOUT-O3 and CCMVal by means of assimilation, so that the QBO follows a prescribed external harmonic of 28 months dominant oscillation. Moreover, the 28 months cycle could be related to the 60 months or around twice the 28 months and 26 months oscillation of El Niño/Southern Oscillation of the Multivariate ENSO Index (MEI). MEI is considered as the most representative since it links six different meteorological parameters measured over the tropical Pacific: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and cloudiness of the sky (Mazzarella et al, 2009). In fact, the application of statistical analyses to the available monthly MEI has evidenced two harmonics of 26 and 60-month periods, confident at a level greater than 99%, whose Fourier synthesis accounts for more than 25% of the overall monthly MEI variability. This 26-month cycle would suggests a possible relationship between the series of MEI and the present tropical stratospheric winds that follow the Quasi Biennial Oscillation with average period found here equal to 28-months, that is different from the 26 months period, at the 99% level.

On the other hand, tracks of the SW monsoon storms and depressions (e.g. the Indian monsoon, Pacific sea surface temperatures and precipitation link) in association with the stratospheric wind are coupled with the fluctuations in SW monsoon rainfall and it was noted that easterly / westerly wind at 10 hPa, in some manner, suppresses / enhances monsoon storms and depressions activity affecting their tracks (Sikder et al., 1993). Therefore the studies that reconfirm ESW links with other climate parameters aid solar-cycle predictions to estimate how that circulation, and the regional climate patterns related to it, might vary over the next decade or two.

Overall, the obtained results lead to a) similar conclusions earlier arrived with conventional analysis tools for the QBO, b) the reinforce the 28-months harmonic for six heights, well documented with different techniques used, and c) prediction of the 15 hPa at the end of 2009 of amplitude 16.8±3.1 and mean value -8 m/s easterly.

5. CONCLUSION

The quasi-biennial oscillation (QBO) in the zonal winds in the equatorial stratosphere is a well known mode of interannual variability. The driving force for the QBO is the vertical transfer of momentum from the troposphere to stratosphere by a broad spectrum of vertically propagating waves including Kelvin and Rossby-gravity waves. It is here evidenced, that the zonally symmetric easterly and westerly wind regimes alternate regularly with a dominant period of 28 months. The alternating wind regimes propagate downward at an approximate rate of 1 km/month to the tropopause. The amplitude of the easterly phase is stronger than the westerly phase. The easterly zonal winds can reach as high as 25m/s, whereas the westerly zonal winds reach 10 m/s. The 28 -month harmonic accounts for the about the 35-40% of the monthly wind variability from 15 to 70 hPa levels, while the same harmonic accounts for the 30% from 40 to 70 hPa level and this provides a reasonable forecasting power of zonal equatorial stratospheric winds. A predicted coming easterly equatorial wind occurrence at 15 hPa level is made for the end of 2009 having an amplitude of 16.8±3.1 m/s. The occurrence of this oscillation is linked to ENSO MIE index, rainfall and solar cycle forcing, which reinforce the sun-climate relationships and may help predict regional climatic patterns.

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