On The Dominance of 28-Month Harmonic in the Equatorial-Stratospheric-Wind Quasi Biennial Oscillation

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Abstract: The Quasi Biennial Oscillation, the downward propagating easterly and westerly wind regimes in the equatorial stratosphere, has been investigated according to robust statistics that utilizes the amplitude/vector probable error ratio to provide the confidence level of the investigated harmonic. The amplitude-to-noise ratio is found to be the highest in correspondence of the 28- month harmonic for each examined height; the relative amplitude and phase values are found, respectively, to decrease and increase with the height and 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.

Keywords: QBO, vector probable error.

INTRODUCTION

The equatorial-stratospheric wind (ESW) oscillates between easterly and westerly directions, with a period of nearly two years: this periodic oscillation is called Quasi Biennial Oscillation (QBO) [1-5]. Regarding its physical explanation, Lindzen and Holton [6], Lindzen [7] argued that QBO is typical of planets with rotating stratified atmospheres and equatorial convection deriving essentially from the stratospheric absorption of vertically upward transferring westerly Kelvin waves, which supply a westerly force, and easterly Rossby-gravity waves provide an easterly force. The QBO is related to the occurrence of different natural stratospheric and tropospheric phenomena like geopotential height anomalies at high latitudes [8], the Indian summer monsoon rainfall [9-10], the stratwarming occurrences [11] and the decay of aerosol loading following volcanic eruptions [12]. General Circulation Models (GCMs) are unable to generate realistic QBO [13] despite attempts 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 [14]. In order to identify a dominant cycle, we have revisited the monthly ESW series according to statistical methods that are routinely used in geomagnetism [15] but scarcely used in climatology.

DATA COLLECTION AND ANALYSIS

We have analyzed the monthly values of equatorial-stratospheric winds as measured by the Freie Universitat of Berlin since 1953 for different heights combining the observations of the three radiosonde stations: 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). This data set is supposed to be representative of the equatorial belt since the longitudinal differences in the phase of the QBO are small [16]. Some uncertainties arose at higher levels during the early years because of the scarcity of observations [17] and for this reason 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) as available from the web site: http: //www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat.

Fig. (**1**) shows the time plot of the monthly values of ESW relative only to 15 hPa level. Autocorrelation and spectral analyses have been applied to the available ESW monthly values relative to different heights and the results have been obtained according to 48 degrees of freedom deriving from a compromise between data resolution and statistical stability, i.e. between the available 672 monthly ESW values and the investigated period around 24 months [18]. At first sight, it appears that the autocorrelation coefficient exhibits a decreasing and oscillating behavior centered on 28 months (Fig. **2a**) while the normalized power spectrum (Fig. **2b**), obtained as Fourier transform of autocorrelation coefficient, shows that not less than the 75% of monthly variance is concentrated on 28 months. To obtain a more detailed information on the relative dominant harmonic, two separate and specific statistical methods are employed here: the vector probable error and the phase averaging analyses. 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: In the first approach, the Fourier coefficients 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

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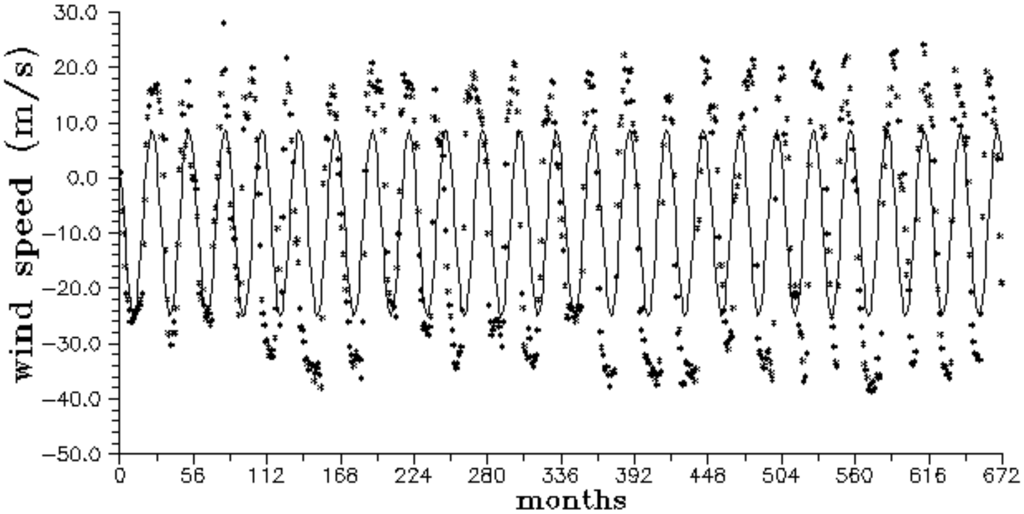

Fig. (1). Time plot of monthly values of 15hPa observed equatorial-stratospheric wind (* points) (interval 1953-2008) and monthly values computed according to its 28-month harmonic (continuous line).

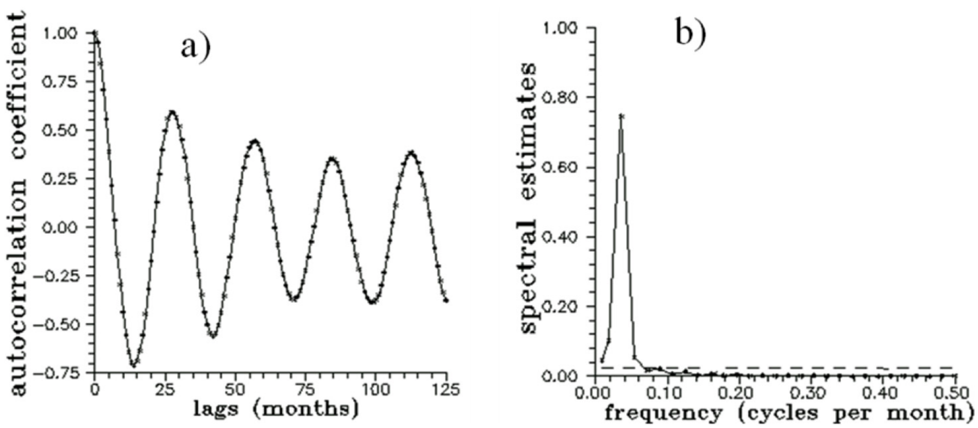

Fig. (2). a) Autocorrelation coefficients of 15 hPa monthly ESW series for various time lags; **b**) Normalized spectral estimates of 15 hPa monthly EWS series. The dashed line indicates the 95% confidence level of the equivalent white-noise process based on 47 degrees of freedom.

calculated for the investigated harmonic: (i) the center of gravity A of all points, corresponding to the harmonic coefficients as computed from all series; (ii) the standard errors σ_x, σ_y from A of the available Fourier coefficients relative to each subinterval. The vector probable error (vpe) is given by: vpe = 0.83256 $(\sigma_x^2 + \sigma_y^2)^{0.5}$. The confidence level of the investigated harmonic is computed according to the equation: $1\text{-}\exp[-(0.833\ A/vpe)^2]$. The harmonic is found to be confident at 95% (99%) level when A ≥ 2.08 vpe (A ≥ 2.58 vpe) [15, 18, 19].

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. To evaluate the accuracy of R, we have computed the random variable W= 0.5 ln[(1+R)/(1-R)] that is characterized by an approximately normal distribution with a mean equal to 0.5 ln[(1+R)/(1-R)] and variance equal to $(N\text{-}3)^{-1}$ [18], [20]. 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. The harmonic is found to be confident at 95% (99%) level when the relationship W = 0.5 $(N\text{-}3)^{0.5}$ ln[(1+R)/(1-R)] provides values ≥ 1.96 (≥ 2.58). It appears that such statistical methods, even if scarcely used in climatology, offers more freedom in the data selection enabling the non-cyclic changes to be removed and the confidence level of each harmonic to be obtained.

RESULTS

The application of vector probable error and phase averaging analyses to the available monthly values of ESW data has provided the highest values of vpe and R, confident at a level greater than 99%, only when we subdivide the ESW 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**. Fig. (**3**) reports the plot of the average 28-month cycle of ESW for each investigated altitude. Fig. (**1**) reports the time plot of the monthly observed values of ESW together with the monthly values computed according to its 28-month harmonic. The 28-month harmonic accounts for about the 60% 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. The amplitude and phase of the 28-month harmonic are found, respectively, to decrease

Table 1. Values of Amplitude (*A*), Phase (*φ*), Vector Probable Error (*vpe*) and Confidence Level of the 28 Month Harmonic Computed from the Monthly Values of Equatorial-Stratospheric Winds (ESW), Available from 1953 to 2008 for Six Different Heights *H*. *μ* and σ Represent the Mean and the Standard Deviation of the Investigated Winds. *R* is the Correlation Coefficient Among the 28 Monthly Observed QBO Values and Computed According to the First Fourier Harmonic. The Percentage of Variance is Relative to the Examined Monthly ESW Series Explained by the 28-Month Cycle. The Lag Represents the Number of Months Occurring to Pass Two Successive Heights

Atmospheric Pressure	*H (km)*	*μ ± σ (m/s)*	*A (m/s)*	*φ (°)*	*vpe*	*A/vpe*	*R*	*Confidence Level*	*Percentage of Variance*	*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

and to increase with the height. At the bottom of the stratosphere the amplitude is the lowest and equal to 4.7 m/s and gradually increasing with height up to 16.8 m/s at the top of the stratosphere. The 28-month cycle propagates downward and Table **1** shows that it takes 11.7 months to descend from 15 hPa to 70 hPa equal to 0.92 month/km. Table **1** shows that 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 50 hPa, while the westerly regime from 50 hPa to 70 hPa. (Fig. **3**) further shows that the amplitude of easterly regime, relatively to 15, 20 and 30 hPa levels, is stronger than the westerly regime.

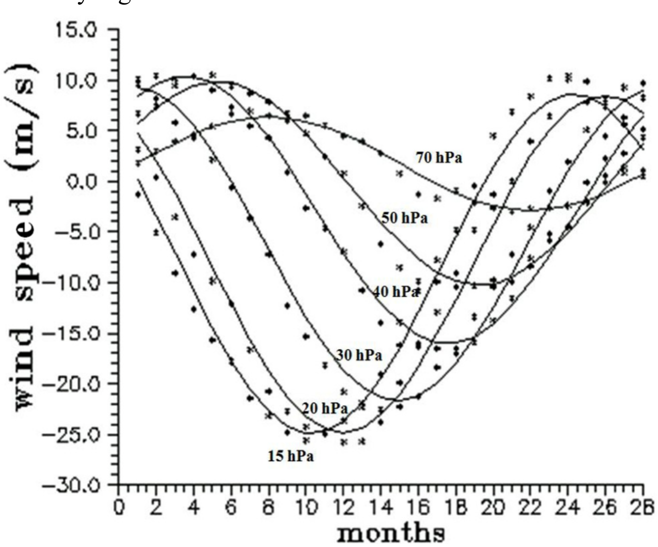

Fig. (3). Average 28-month harmonic of equatorial stratospheric wind for different height. The continuous curve represents the first Fourier harmonic. The values relative to 70 hPa, 50hPa, 40 hPa, 30 hPa, 20 hPa, 15 hPa are reported on the plot from the top of the graph downwards, respectively.

DISCUSSION

The application of two different statistical analyses to the monthly equatorial-stratospheric winds has evidenced the dominance of 28-month period, confident at a level greater than 99% (Figs. **2**, **3**), that accounts for about 60% 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. Similar statistical analyses [21] applied to monthly series of Multivariate Enso Index (MEI) have allowed the identification of a quasi biennial harmonic at a level of confidence higher than 99%. Since the highest values of MEI represent El Niño events, the obtained results would suggest the strict relationship between El Niño and the equatorial stratospheric winds. On the other hand, the observed rapid descent of westerly QBO is found to be accompanied with the El Niño, while all slower descents were out of El Niño event [22]. The phase of the wind takes about a year to descend from 15 to 70 hPa, according to Ebdon and Veryard [23]. It appears that wind regimes propagate down as time progresses: they move downwards at 0.87 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. They start at 15 hPa 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. The downward propagation occurs without the loss of amplitude between 29 and 22 km, but there is rapid attenuation below 22 km in agreement with Holton and Tan [24]. 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 past. To perform such a test, a comparison is made, for each month "t", among the observed ESW monthly values, and the synthetic monthly values that are derived from the equation:

$$ESW\ (t) = A \sin\left[(360/28)/t + \varphi\right]$$

The analysis of 15 hPa wind data was made using the values of A = 16.8 and φ=151° (Table **1**). Fig. (**1**) shows that all the minima and maxima of ESW are found to occur in correspondence of minima and maxima values of the 28-month cycle. Assuming a forecast for the period after 2008, the 28-month cycle suggests an estimate for the next westerly equatorial wind occurrence at 15 hPa level on December 2010.

CONCLUSION

The QBO is a well known mode of interannual variability in the zonal winds in the equatorial stratosphere. The driving force of 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. The application of robust statistical analyses, which is scarcely used by climatologists, has evidenced that the zonally symmetric easterly and westerly wind regimes regularly alternate 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 about the 60% 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. Assuming that the present QBO cycle will have a dominant period of 28 months, we can forecast that the maximum westerly phase of QBO will occur on December 2010.

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