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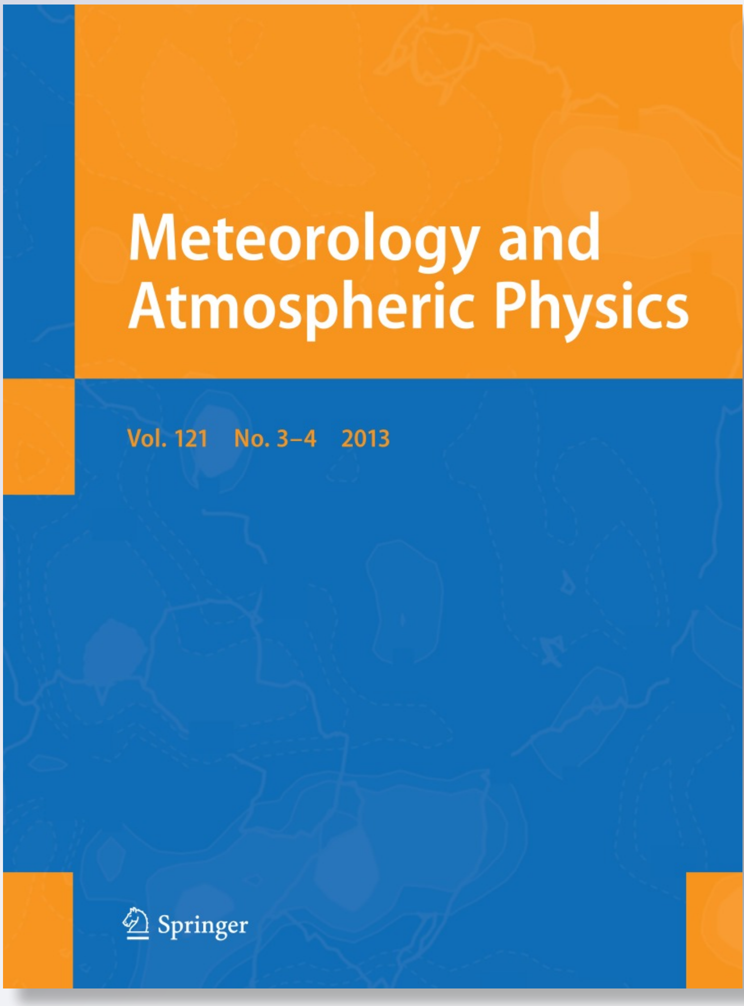

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ORIGINAL PAPER

Quasi-periodic imprints in the equatorial troposphere and stratosphere in three decades of reanalysis data

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Abstract Wavelet analysis is applied to zonal mean zonal wind and temperature fields to represent characteristics of temporal periodic features different from the annual and semi-annual recurrence in the troposphere and stratosphere. A daily database of reanalyses is used for the period 1979–2008, which comprises the era of satellite-based data, as some discontinuities have been observed around 1978 in previous studies. Levels for this study have been chosen at 400 and 10 hPa, respectively in the middle troposphere and middle stratosphere. As representative for diverse latitudinal regions we have respectively selected 0°, ±20°, ±40°, ±60°, ±80°. Significant features were only found at the equator. The period of the quasi-biennial oscillation (QBO) is found to exhibit a decreasing trend in time over the 30 years studied. Potential harmonics of the QBO are found in the tropical stratosphere but also troposphere. However, they do not exhibit the same tendency. This fact supports in particular the idea that the QBO and the tropospheric biennial oscillation may be unrelated phenomena. Some of the observed features lie within the known range of variability of the El Niño Southern Oscillation. Faint effects of the 11-year solar cycle variability may have been observed in the troposphere and stratosphere, but no firm assertion may be made due to the low number of observed cycles for this kind of phenomenon in the used data-set time span. Short-term solar variabilities leave no relevant imprint.

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1 Introduction

The externally forced diurnal and annual or semiannual components and their harmonics produce obvious global signals in the atmosphere. Inter-annual large scale variability seems to be partly associated with the E1 Niño-Southern Oscillation, the quasi-biennial oscillation (QBO) and regional processes (which may however have hemispheric or global scale influence) such as the North Atlantic Oscillation (Peixoto and Oort 1992; Wallace and Hobbs 2006 and references therein). Decadal and interdecadal variability is less clearly understood and has been attributed either to internal variability in the thermohaline circulation of the oceans, coupled cryosphere-ocean-atmosphere cycles or external forcing due to the sun (e.g. Mann and Park 1994). We notice that the atmosphere is apt to host large scale periodic processes in time, which may however be modulated in frequency or amplitude by diverse internal or external factors (Barry and Chorley 2003; Wallace and Hobbs 2006 and references therein).

There are many recurrent phenomena that are not exactly periodic. There exist some attempts to reconstruct the varying QBO as early as 1900 with initial extremely sparse observational information (Brönnimann et al. 2007). Baldwin et al. (2001) give a good review of this phenomenon. Significant efforts have been devoted in trying to explain the observed variability of the QBO in time, for example through wave forcing (Geller et al. 1997), the influence of solar activity (Weng 2003) or in relation to the irregular in time El Niño-Southern Oscillation (ENSO), (e.g. by Taguchi 2010). Labitzke and van Loon (1988) found possible solar cycle and QBO links. However, there have been over the time also results that pose doubts on a possible significant QBO-solar cycle interaction or at least on its current description (see e.g. Fischer and Tung 2008).

Also, ENSO is apparently correlated with the QBO in some periods but not in others (Garfinkel and Hartmann 2010). Although it is generally accepted that the source for the QBO may ultimately lie in the tropical convection, the question still remains about what processes (with their corresponding variabilities) modulate the trigger. Another example of quasi-periodic behavior is the tropospheric biennial oscillation (TBO), which is a regional phenomenon with possible far reaching effects that exhibits an irregular evolution in time. In the context of various superposed phenomena with possible varying periods over time, an approach which shows some measure of the relevance of processes in terms of time and time scales and which is different from the more traditional time vs height diagrams may be of use. This leads us to the introduction of wavelets below.

Below we perform a study on global scales over 30 years of consistent atmospheric data to detect repetitive behavior that differs from the well-known nearly exact periodic semi-annual and annual cycles. We are here interested in detecting any phenomenon having global consequences (over all longitudes in a given latitude), regardless of smaller scale variations due to meridional and zonal effects.

2 Data and method

The motivation for the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis project (Kistler et al. 2001) was the apparent climate changes that resulted from modifications introduced in the operational global data assimilation system to improve forecasts. This behavior could affect to some extent the observation of true short term changes or inter-annual variabilities. The NCEP/NCAR reanalyses now cover the years from 1948 to the present. Reanalyses allow a calculation of long-term trends in diverse variables of the atmosphere. However changes in the observing systems within the reanalyses may obscure climate changes. In 1979 the satellite-observing system was established, which partially affected reanalysis results. For example, the QBO as depicted in the NCEP/NCAR reanalysis data, exhibits a discontinuous behavior around 1978 that manifests itself in several variables (Huesmann and Hitchman 2001, 2003; Kistler et al. 2001). The introduction of satellite data resulted in a significant change, suggesting that the results from 1979 to present day are the most reliable and coherent ones. Reanalysis can be used for daily to seasonal, inter-annual and inter-decadal timescales. The climatology before 1979 is more dominated by the model climatology in data-sparse areas, leading to the generation of some spurious trends.

Different outputs of the reanalyses are not uniformly reliable. The NCEP/NCAR fields have been graded according to the relative influence of the observed data and the assimilation model on the output field. Atmospheric temperature and zonal wind are significantly affected by the observations, and the numerical model does not have a strong influence. Therefore they are among the variables with the highest grade, which are considered to provide an estimate of the state of the atmosphere better than would be obtained with measurements alone (Kistler et al. 2001).

In this work we analyzed periodic patterns with zonal means (latitudinal circle average) of daily reanalysis data over 30 years (1979–2008) of air temperature and zonal wind at diverse latitudes (0°, ±20°, ±40°, ±60°, ±80°). We have chosen levels in the middle troposphere at 400 hPa and in the middle stratosphere at 10 hPa. In a similar way, Halenka (2002) used in a 50-year NCEP/NCAR reanalysis global circulation trend study the 500 and 50 hPa levels as representative for each of both atmospheric layers. We performed an analysis of recurrences, i.e. oscillations and periodicities present in the climatological time series.

Wavelets are like elementary building blocks in a decomposition similar to Fourier. The representation is an infinite series expansion of dilated, contracted and translated versions of a mother wavelet, each multiplied by a coefficient. The advantage of analyzing a signal with the wavelet tool is that it enables to study features locally matched to their scale, i.e., broad characteristics on a large scale and fine aspects on small scales. This property is especially useful for signals that are non-stationary, have transient components, exhibit behavior at different scales, or have spikes. Wavelets are specially suited to time-scale (or space-scale) analysis. Wether to use wavelets or Fourier depends on the purpose of the analysis. As many atmospheric signals are irregular, the importance of wavelets in this field of study lies in the bounded but flexible compromise of time and scale localization. The tool yields information not only about intensities of particular frequencies, but also about their location in time. For our study we used the continuous wavelet transform (CWT) technique (Torrence and Compo 1998). We point out that other multi-timescale analysis methods are also available (see e.g. Zhen-Shan and Xian 2007), each one with specific properties. We used as mother wavelet the Morlet and the Mexican hat functions, but as the results were qualitatively very similar we show below only the calculations for the former option. The Morlet wavelet (Fig. 1) is a plane wave modulated by a Gaussian: $\exp(ict)\exp(-t^2/2)$ with $c = 5$. Higher values of c yield rapid oscillations and lower values produce a wavelet whose mean significantly deviates from the necessary condition of being 0. In fact, an usual objection to this mother wavelet is that it does not exactly meet a zero mean. However, the corresponding errors turn

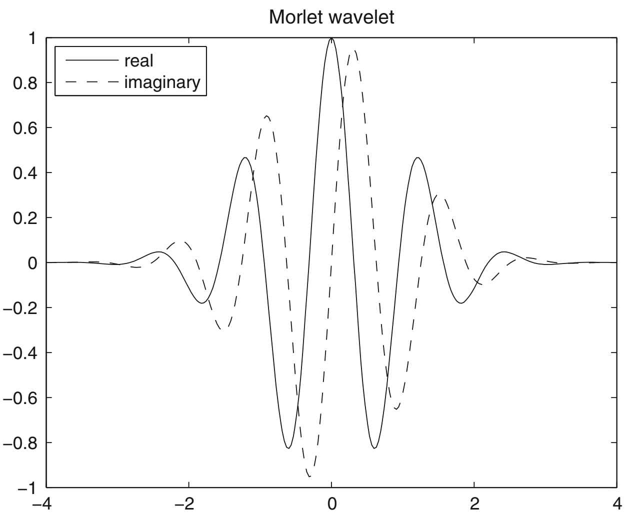

Fig. 1 The real and imaginary parts of the Morlet wavelet function with c=5

out to be negligible when choosing $c = 5$. Wavelet and structures we are looking for should have similar shape. The sinusoidal form of the Morlet wavelet makes this function an appropriate one to study wave-like phenomena. Another general advantage of the Morlet wavelet is that it is a complex function, so it may yield modulus and phase. In all wavelet diagrams below, the statistical significance at a 90 % confidence level of local maxima and minima used for calculations was corroborated following Torrence and Compo (1998) and Ge (2007), thereby assuming that the energy density has a Chi-square distribution with 2 degrees of freedom. As pointed out by Terradellas et al. (2001), some authors have used a red-noise background spectrum instead of the average energy density for each period (our method) as a reference to perform the statistical test, but the former option implies the application of additional hypotheses.

Significant features different from the annual and semi-annual cycles have been here only found at the equator. Therefore we only exhibit results for zonal wind and temperature at the troposphere and stratosphere in that region. Linear trends over 30 years were initially removed in each data-set. Many well-known extra-tropical oscillations in the troposphere remain unnoticed in our study because their main effects relate to pressure differences or surface ocean temperatures, which do not have an equivalent imprint on the variables analyzed here or the quasi-periodic features do not have strong consequences when averaged over a zonal circle (e.g. the Antarctic Oscillation and the North Pacific Oscillation). Dominant modes in the stratosphere besides the QBO in the equatorial region have not been so clearly identified up to now (Holton 1979) and are usually discussed in terms of troposphere-stratosphere exchanges (see e.g. Castanheira et al. 2009a, b).

3 Results

In Figs. 2 and 3a we respectively show the zonal mean equatorial temperature and zonal wind data between 1/1/1979 and 31/12/2008 used in this work at 400 and 10 hPa. Diverse behaviors and recurrent patterns may be observed for the different variables and altitudes. In Fig. 3b we show the zonal mean equatorial zonal wind at 30 and 70 hPa. In Figs. 2 and 3 we show the linear trends over the 30 years of the study that were initially removed. The tendencies are at least one order of magnitude stronger at 10 hPa as compared to any other pressure level results. There is a rich deployment of scales from a few months to several years, with a more significant presence of the smallest scales in the troposphere. Figures 2 and 3 will be further analyzed in the Discussion section.

3.1 Temperature in the troposphere

In Fig. 4 we show the coefficients of CWT applied to daily temperature over 30 years at 400 hPa. For the Morlet function the wavelet scales on the vertical axis have to be multiplied by 1.23 (see e.g. Terradellas et al. 2001) to convert them into time scales (years), which is the quantity

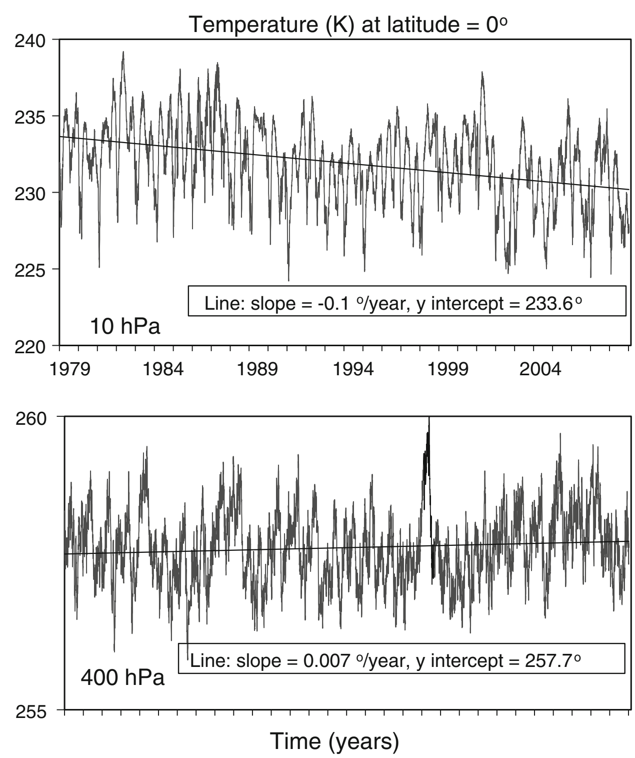

Fig. 2 The NCEP/NCAR reanalysis zonal mean equatorial temperature data at latitude 0 ^{o} between 1/1/1979 and 31/12/2008 used in this work at 400 and 10 hPa (notice the different vertical scales at both levels). Each linear trend over the 30 years is shown, including the slope and y intercept values

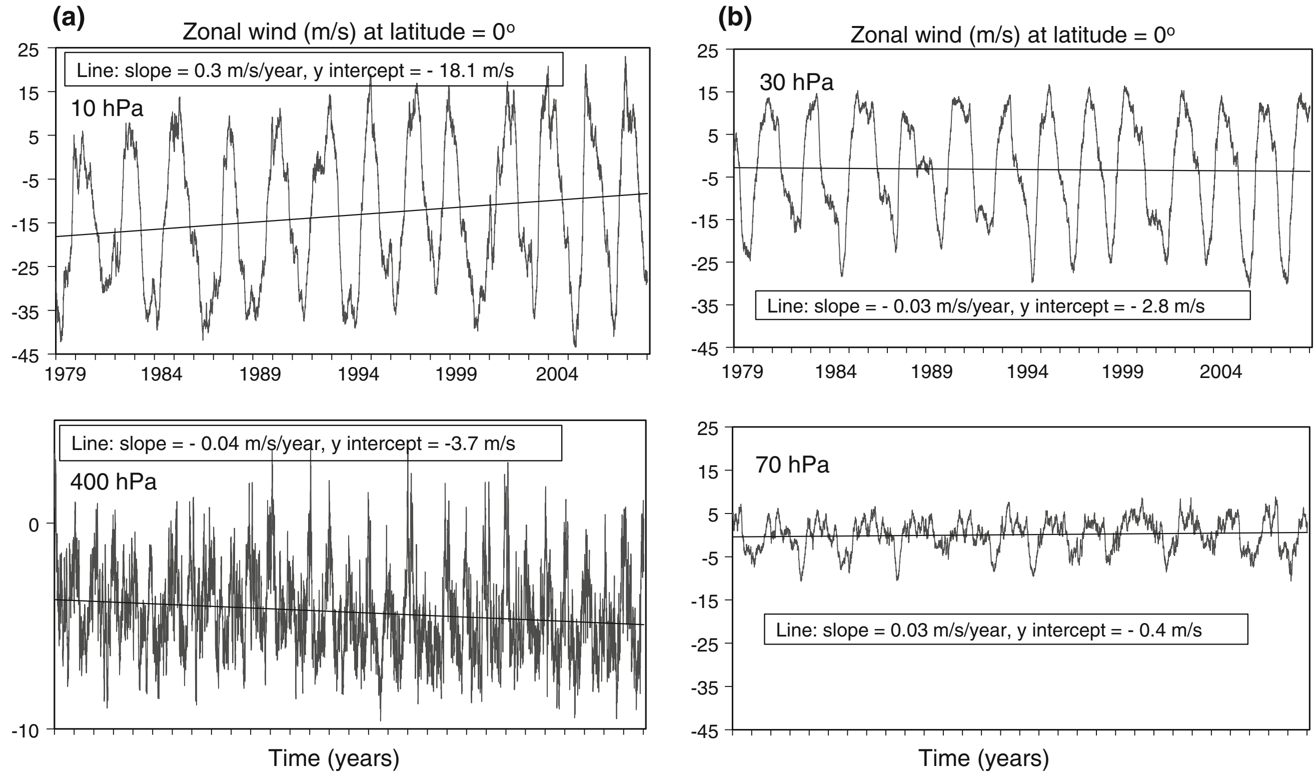

Fig. 3 The NCEP/NCAR reanalysis zonal mean equatorial zonal wind data at latitude 0 ^{o} between 1/1/1979 and 31/12/2008 used in this work at **a** 400 and 10 hPa (notice the different vertical scales at both levels), **b** 70 and 30 hPa. Each linear trend over the 30 years is shown, including the slope and *y* intercept values

shown in this and the following wavelet representations. The horizontal axis spans the 30 years of data. Fluctuations over time (horizontal axis) at given time scales (vertical axis) may be observed. Consecutive maxima and minima from left to right at the scales 0.5 and 1 year indicate the well-known tropical annual and semi-annual cycles, which are out of our scope. The same features will be seen in the following wavelet figures with more or less clarity. On the bottom to the right of the figure just one cycle of about 14 years may be inferred, but we do not further analyze this kind of cases here and in the following wavelet figures as no statistical inference can be made. Phenomena which do not possess sharp periods will exhibit dark and light patches at variable scales within a broad band. We focus our analysis here on three scale and time intervals that reveal a clear recurrence: zone 1tT includes scales around 2–2.5 years (only for about the last 8 years of data), zone 2tT encompasses scales around 3.5–4 years and zone 3tT roughly covers scales about 8 years.

In each of the three zones we searched the time of successive local maxima. The difference between two consecutive maxima is an indication of the period in the corresponding time span. In Table 1 we show the calculated periods for the three zones. No clear positive or negative trend in time may be observed in zone 2tT. Means

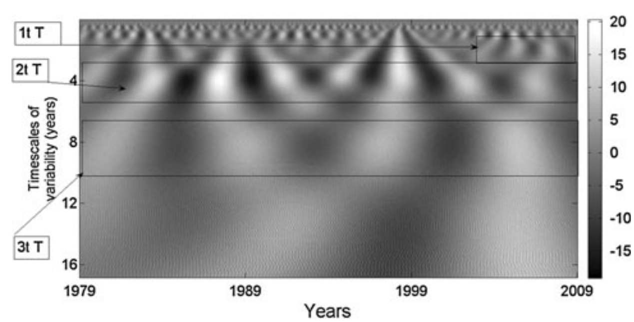

Fig. 4 The coefficients of CWT applied to daily zonal mean equatorial temperature over 30 years at 400 hPa and the areas (*boxes*) that reveal clear recurrence. The cone of influence is not shown as it only covers the zone close to the lower *left* and *right* corners and does not affect the identified zones

and uncertainties are also given, where the latter are estimated from the standard deviation or half the difference between maximum and minimum if there are respectively more or less than four values. The relation between periods associated with zones 2tT and 3tT is nearly harmonic and there are no significant differences. In zone 1tT we were able to find between years 2001 and 2008 only two periods, which are typical for the QBO. However, this kind of oscillation is usually considered to be present only in the

Table 1 Consecutive detected temperature periods at 400 hPa

Zone	Periods (months)	Mean (months)	Uncertainty (months)
1tT	29.0, 23.0	26.0	3.0
2tT	43.8, 48.4, 43.5, 44.8, 41.2, 49.3, 49.1	45.7	3.2
3tT	100.5, 99.8, 96.7	99.0	1.9

stratosphere. Relation with the other two periods is nearly harmonic and there are no significant differences. However, it must be taken into account that statistical power is here fair at the best.

3.2 Zonal wind in the troposphere

In Fig. 5 we show the CWT coefficients for daily zonal wind over 30 years at 400 hPa. Oscillations different from the annual and semi-annual cycles seem to be less clearly defined than with temperature. On the bottom cautiously two periods of about 11–12 years may be roughly inferred, possibly associated with the well-known solar cycle, but again we do not further analyze this kind of case. We identify now two intervals of interest, zone 1tV with scales about 2 years and time around years 1993–2000 and zone 2tV for scales between 3 and 4 years and time between years 1979 and 1997. In Table 2 we show the calculated periods, the means and uncertainties. No clear positive or negative trend in time may be observed in zone 2tV. In zone 1tV we just obtained 2 periods, which resemble the QBO. The relation with the period of zone 2tV is nearly harmonic, but differences are slightly significant. Both scales have counterparts in the temperature data with no significant differences. However, there is no noticeable equivalent period to zone 3tT over the 30 years.

3.3 Temperature in the stratosphere

In Fig. 6 we show the coefficients of CWT applied to daily temperature over 30 years at 10 hPa. On the bottom two periods of about 12 years may be again roughly inferred. We define zone 1sT around scales 2–2.5 years and zone 2sT between scales 4–5 years. In Fig. 7 we plot the calculated periods since year 1979 for zone 1sT. A negative trend in time may be observed with a correlation coefficient of −0.7, where the statistical significance of a hypothesis of no linear correlation is given by a probability lower than 0.01. Periods remain in the typical range for the QBO, but there is an average reduction of (12.1 ± 3.7) days per cycle. The relationship shown in the figure exhibits some notorious discrepancies from linear behavior, where the squared correlation coefficient is around 0.5. The trend is

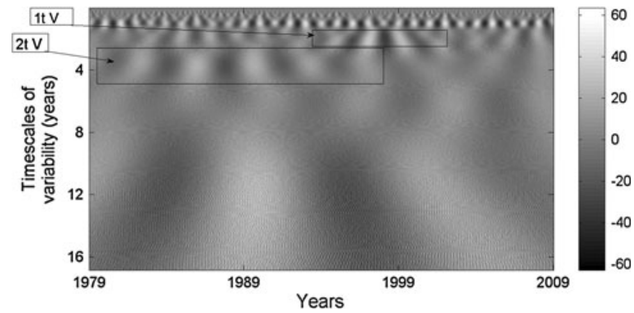

Fig. 5 The coefficients of CWT applied to daily zonal mean equatorial zonal wind over 30 years at 400 hPa and the areas (*boxes*) that reveal clear recurrence. The cone of influence is not shown as it only covers the zone close to the lower *left* and *right* corners and does not affect the identified zones

Table 2 Consecutive detected zonal wind periods at 400 hPa

Zone	Periods (months)	Mean (months)	Uncertainty (months)
1tV	23.1, 25.1	24.1	1.0
2tV	38.6, 44.5, 45.5, 44.4, 40.4	42.7	3.0

clear but if it is used to forecast future expected behavior it must be taken into account that the standard deviation of the dots with respect to the line is around 44 days, which means that intervals of almost 3 months (88 days) may superpose to the decreasing trend from one period to the next one. Although this work has been performed at 10 hPa, Fischer and Tung (2008) have shown that the period of the QBO is almost the same in the vertical in the stratosphere. The amplitude of the QBO is considered to be approximately Gaussian about the equator with a 12° half-width (Wallace 1973). We repeated the linear fits of QBO periods against time since year 1979 at other altitudes (30 and 70 hPa) and away from the Equator (latitudes −15°, −7.5°, 0°, 7.5° and 15°). Period reductions were also obtained at these positions and the results may be seen in Table 3. On the other hand, consecutive detected periods (years) for zone 2sT are 4.8, 4.7, 4.4, 4.5 and 5.2, which have a mean and an uncertainty of respectively 4.7 and 0.3. The mean period is typically the double of the QBO in zone 1sT, but no clear negative trend is detected.

3.4 Zonal wind in the stratosphere

In Fig. 8 we show the CWT coefficients for daily zonal wind over 30 years at 10 hPa. We define zone 1sV around scales 2–2.5 years and zone 2sV between scales 5–6 years for the time interval 1990–2004. In Fig. 9 we plot the calculated periods for zone 1sV. The negative trend in time also has a linear correlation coefficient of −0.7 and a statistical significance of no linear correlation given by a probability lower than 0.01. The tendency is similar to the temperature at the same height and latitude, as it is (12.0 ± 3.7) days (no significant difference between both slopes). The figure also shows discrepancies from simple linear behavior with a squared correlation coefficient around 0.5 and possible deviations of about 3 months from the linearly decreasing period. We also repeated the linear fits of QBO periods against time since year 1979 at other altitudes and away from the Equator for the zonal wind and the results may be seen in Table 3. For zone 2sV we just obtained two periods (years) of 5.9 and 5.4 between years 1991 and 2004. The mean and the uncertainty (in years) are respectively 5.7 and 0.3. Differences with zone 2sT are significant. The period 2sV is larger than the double of the QBO in zone 1sV, there are significant differences and no clear negative trend is detected.

3.5 Summary of observed cycles

We make in Fig. 10 an overview of the previous results, which shows average periods and uncertainties. We now analyze similarities and discrepancies. The zone 3tT has no counterpart in zonal wind and there is in addition no similar periodic behavior in the stratosphere. The cycles corresponding to zones 2tT and 2tV have no significant differences, but those corresponding to 2sT and 2sV do. In addition, the periods associated with tropospheric and stratospheric phenomena have significant differences. Zone 1tT and 1tV have no significant differences. Although they are close to the periods 1sT and 1sV (QBO), they cannot be compared because they do not mimic the decreasing trend. The two lines attributed to the QBO exhibit no significant differences between them. We also performed studies on the average phase shift between temperature and zonal wind in the two cases where periodicities were detected for an interval of time of at least 15 consecutive years: 2tT and 2tV on one side and 1sT and 1sV (the QBO) on the other side. For the former velocity was ahead of temperature by about 100°, whereas for the latter temperature was leading velocity by about 80°.

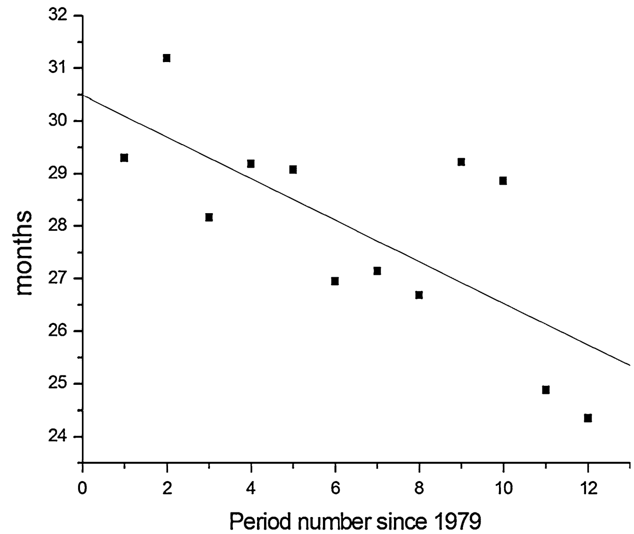

Fig. 7 The calculated consecutive periods for zone 1sT of Fig. 6

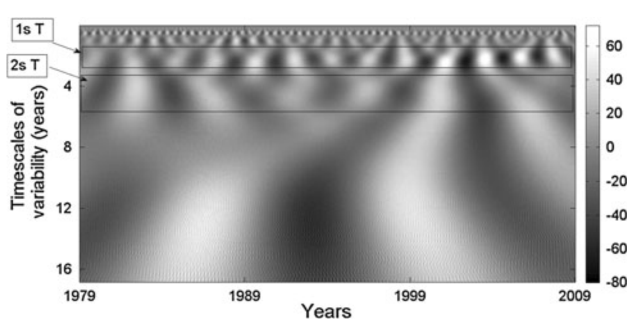

Fig. 6 The coefficients of CWT applied to daily zonal mean equatorial temperature over 30 years at 10 hPa and the areas (*boxes*) that reveal clear recurrence. The cone of influence is not shown as it only covers the zone close to the lower left and right corners and does not affect the identified zones

4 Discussion

Some large scale atmospheric oscillations are probably the product of feedback processes between different components, which may be interacting nonlinearly to produce quasi-periodic behavior, for example the atmosphere and the oceans respond to various physical stimuli on different timescales (e.g. Peixoto and Oort 1992; Wallace and Hobbs 2006 and references therein). The QBO is obvious as a nearly 26–30 months oscillation (e.g. Baldwin et al. 2001) of the equatorial zonal wind in the stratosphere and ENSO is a broad band phenomenon with typical 3–7 years recurrence (e.g. Philander 1990). The variabilities in these periods and from other phenomena that might be present in the atmosphere renders interpretation of harmonic analyzes somewhat challenging. The use of wavelets may be an advantage in this context. Here we examined cycles as seen in the NCEP/NCAR reanalyses.

In Figs. 2 and 3 many of the recurrent behaviors may be identified by visual inspection. The annual and semiannual cycles may be seen at least over some time intervals and two full cycles of about 12–15 years may be appreciated with the exception of the panels of zonal wind in the stratosphere, which clearly exhibit the QBO. This is just a qualitative subjective description which was more quantitatively confirmed with the wavelet tool in Figs. 4, 5, 6 and 8, which also led to the finding of additional features in the temperature and zonal wind in the troposphere and stratosphere.

Table 3 Coefficients from linear fit between QBO duration against period number since 1979 for temperature and zonal wind: slope (reflects variation in days per QBO period) ± uncertainty, squared correlation coefficient and the probability that results stem purely from chance, whereas "–" means that the QBO signal was not clear over 11 or 12 intervals during the 30 years studied or not detectable at all

Height (hPa)	−15	−7.5	Latitude (°) 0	7.5	15
Temperature					
10	–	–	−12.1 ± 3.7, 0.52, 0.01	–	–
30	–	−12.7 ± 4.7, 0.45, 0.02	−10.7 ± 3.5, 0.48, 0.01	−10.2 ± 4.6, 0.33, 0.05	–
70	–	–	–	–	–
Zonal wind					
10	−12.6 ± 3.9, 0.52, 0.01	−13.9 ± 3.9, 0.56, 0.01	−12.0 ± 3.7, 0.52, 0.01	−14.0 ± 4.2, 0.53, 0.01	−12.5 ± 4.5, 0.43, 0.02
30	−13.9 ± 3.9, 0.56, 0.01	−14.5 ± 4.5, 0.54, 0.01	−13.7 ± 4.0, 0.53, 0.01	−10.1 ± 4.5, 0.36, 0.05	−10.4 ± 4.6, 0.34, 0.05
70	−13.6 ± 6.4, 0.31, 0.06	−15.0 ± 6.4, 0.38, 0.04	−14.1 ± 4.9, 0.45, 0.02	−9.7 ± 5.3, 0.27, 0.10	−9.1 ± 3.9, 0.37, 0.05

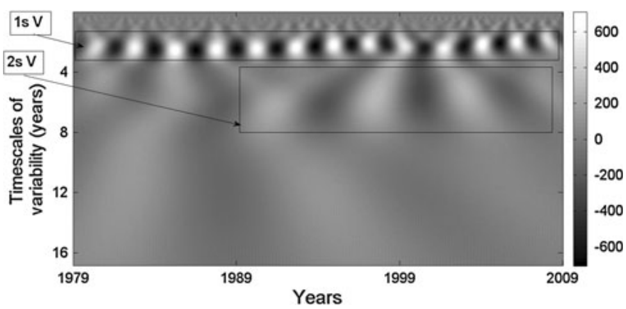

Fig. 8 The coefficients of CWT applied to daily zonal mean equatorial zonal wind over 30 years at 10 hPa and the areas (*boxes*) that reveal clear recurrence. The cone of influence is not shown as it only covers the zone close to the lower *left* and *right* corners and does not affect the identified zones

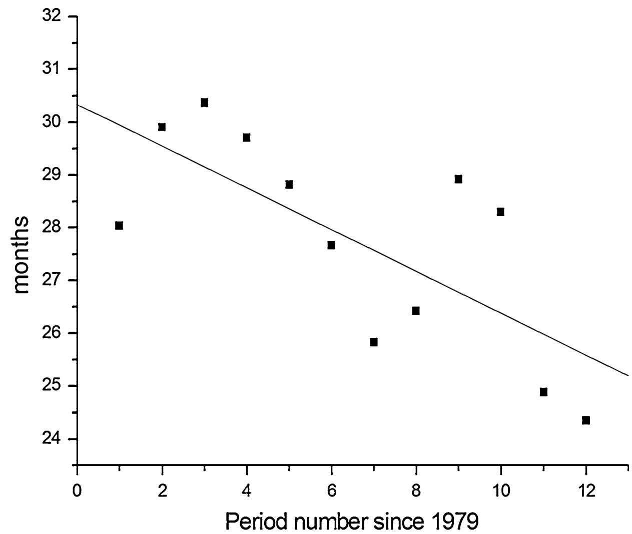

Fig. 9 The calculated consecutive periods for zone 1sV of Fig. 8

In Fig. 3a there is a clear increase of the amplitude of the westerlies at 10 hPa over the 30 years from about 5 m/s to around 20 m/s. This might be a true inter-decade variability or could be the consequence of an evolving bias due to a change in time of the relative weight of radiosonde and satellite information or the increasing aptitude of the former to reach higher altitudes. If we inspect in Fig. 3b the zonal wind at lower altitudes (30 and 70 hPa), it may be seen that the amplitude of the QBO shrinks with decreasing heights, but in addition the amplitude trend virtually disappears. Therefore the amplitude tendency at 10 hPa could be an artifact. The inter-decade change in zonal wind periodicity (1sV) that we found is less likely being due to this kind of possible bias because it is also observed in temperature (1sT) and in addition at other heights (Table 3). The variation range of the magnitude of the decreasing trend of the QBO periods against the considered variable (temperature or zonal wind) or against height is not very significant (considering the slopes and their uncertainties) and may be due to the different strength of the phenomenon in terms of variable or analyzed region and to the interference of other phenomena away from the Equator or close to the tropopause. The reduction of the QBO period for all considered variables, heights and latitudes roughly intersects in the range 10–14 days per cycle. Even though the signal almost disappeared at ± 20°, the reduction in the cycle still appears from the data at ± 15°. From Table 3 the QBO is more detectable in zonal wind than in temperature, tends to disappear towards the tropopause and no clear hemispheric asymmetries emerge. It must be emphasized that the possible decrease of the QBO period over time stems from a statistical power that should be considered fair at least, as it has been obtained over 12 cycles and just in two different atmospheric variables. Also, the trend may reflect a variation over the 30 years studies and may not be a very long term tendency. Although some previous studies in the atmosphere have followed similar procedures, we must caution that any trend emerging only from reanalysis data may be dubious. However, there is no credible long term global coverage alternative data source.

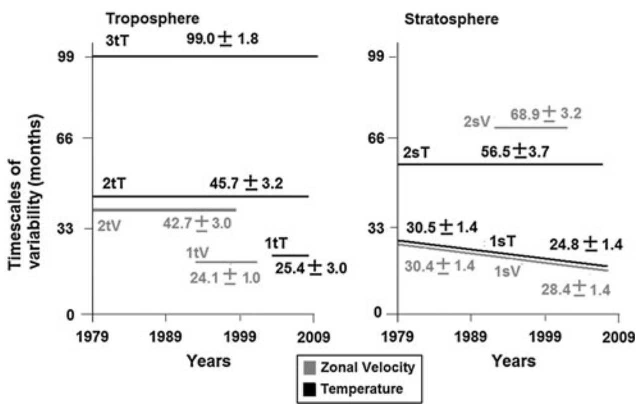

Fig. 10 A summary of the cycles detected at 400 and 10 hPa in zonal mean equatorial temperature and zonal wind reanalysis data over 30 years and their uncertainties

Quiroz (1981) using rocket and radiosonde observations from 1951 to 1979 pointed out that there is a decadal variation in the QBO period, possibly related to solar activity. Past and present models still exhibit difficulties in adequately representing typical QBO periods, so they could hardly reproduce that kind of behavior. The first roughly realistic simulations of QBO-like oscillations in general circulation models were made by Takahashi (1996) with a period of 1.5 years, Horinouchi and Yoden (1998) with a period of 1.1 years, Hamilton et al. (1999) with a period of 1 year and Takahashi (1999) with a period of 2.3 years. Using 44 years of ERA-40 data from 1958 to 2001 Pascoe et al. (2005) did not detect any decreasing tendency in the QBO period. Fischer and Tung (2008) analyzed lower stratosphere wind data from the Free University of Berlin spanning 1953 to 2007. When inspecting these results from 1978 to 2007 a reduction of the QBO period averaged over about three cycles becomes clear since 1986, in basic accordance with our findings. Other studies exhibit diverse possible future scenarios, e.g. Kawatani et al. (2011) found through numerical simulations that global warming may cause longer QBO periods and lower amplitudes. Possible extra-tropical QBO effects (e.g. Holton and Tan 1980) may be too subtle to be detected due to the limited consistency of long-term data-sets. The variability of the extra-tropical stratosphere is possibly affected by many superposing factors as for example the variability of the tropospheric forcing, the solar cycle, volcanic eruptions, and sea surface temperature anomalies (Baldwin et al. 2001).

Nearly 8 years oscillations like 3tT have already been observed by Appenzeller et al. (1998), da Costa and de Verdiere (2002), Gámiz-Fortis et al. (2002), Pisoft et al. (2004), Jevrejeva et al. (2005), Barbosa et al. (2006) in association with the North Atlantic Oscillation, by García et al. (2000) in relation to the Southern Oscillation and by Palus and Novotná (2007) in connection with geomagnetic activity. Quasi-quadrennial oscillation (periods within a range of 3–4 years) like 2tT and 2tV was detected as a distinct and stable oscillation in the troposphere (Pisoft et al. 2011). The 2tT, 2tV and (may be) 3tT cycles are within the range of variability of ENSO, which essentially lies in the 3–7 years broad band, but they are unlikely its outcome because they exhibit a small variability (compare in Fig. 10 the average periods and their uncertainties). In other words, there is apparently no period drift along the 3–7-year interval in each of these quasi-periodic features in each data-set, but there are rather preferred values with a limited dispersion in each case. Similar arguments apply to signatures 2sT and 2sV (4–6 years) in the stratosphere. The fact that the stratosphere may be affected by ENSO has been recently shown by Randel et al. (2009). Previous studies on this issue were hindered by the disturbing volcanic eruptions of El Chichón and Mount Pinatubo respectively during years 1982 and 1991, which occurred both during a similar phase of ENSO.

The TBO appears in meteorological series, but it is not as distinct as the QBO. This signal is observed in the tropical zone, specially over the Indo-Pacific region, but according to our study it may leave some globally visible imprint at 400 hPa. In this work it has been detected only partially throughout the 30 years studied, but this phenomenon is known to be irregular in time (Baldwin et al. 2001). We repeated the calculations for both atmospheric variables at 600 hPa but there was no trace of this cycle. The period varies around 2 years in a manner that cannot be directly linked to the QBO and it is often viewed as a tendency of the Asian monsoon to alternate between strong and weak years. When analyzing NCEP reanalyses from 1956 to 2004 Wang et al. (2008) observed that the TBO was more evident prior to 1979. Thereafter it was weaker and mainly revived in relation to full turns from warming to cooling during the three major ENSO events in the studied time interval: 1982–1983, 1994–1995, and 1997–1998. The former case is not detected in our findings for the TBO in Fig. 10, but the latter two may be associated with what is seen there respectively for zonal wind and temperature (1tV and 1tT). Meehl and Arblaster (2011) recalled evidence that shows that dynamically coupled processes in the Pacific and Indian Oceans can act to produce stronger or weaker TBO, whereas decadal variability in either basin, can lead to changes on decadal scale in the biennial oscillation amplitude. Then they showed through global ocean atmosphere coupled climate model simulations how changes of some of those factors in the mid-1970s could explain a shift towards a lower amplitude TBO at that time. There is still difficulty in establishing whether the QBO and the TBO are manifestations of a common dynamical phenomenon or reflect separate physical processes (Oliver 2005; Mohanakumar 2008). The result of our work that the TBO does not mimic the QBO period reduction over time supports the argument that both phenomena are independent, as advocated by some previous studies (e.g. Baldwin et al.2001).

Weak signatures of the 11-year solar cycle variability through the processed reanalysis data may have been detected in the troposphere and stratosphere, but no clear conclusion may be extracted due to the low statistical power for this kind of phenomenon in the used data-set time interval. Therefore, no atmospheric signature lag can be additionally inferred in the results, which would represent a direct linear response that simply tracks solar activity. Some works did find subtle contributions in limited altitude intervals (see e.g. Mayr et al. 2009). No significant short periodicities, which could be for example attributed to solar wind activity variations were here observed (e.g. Hocke 2009).

We evaluate in the following lines any possible effects on our results due to particular differences of NCEP/NCAR reanalysis with other data-sets, mainly through comparisons made in previous works with ERA products from the European Centre for Medium-Range Weather Forecasts (ECMWF). Pawson and Fiorino (1998a) analyzed low-frequency oscillations in the tropical temperature with both reanalyses. They exhibited good agreement, in particular both showed strong positive anomalies at 30 hPa following El Chichón and Mt. Pinatubo eruptions. In relation to the QBO, Pawson and Fiorino (1998b) found that when compared to rawinsonde measurements, ERA temperature anomalies and winds at 30 and 50 hPa were weak, but NCEP ones were even smaller, whereas both performed even worse at 10 hPa. However, we must remark that our results rely on the time evolution rather than on the intensity of the available data-sets. Trenberth et al. (2001) found that NCEP/NCAR temperatures show fairly good agreement with satellite data overall in the troposphere, but deviate from ECMWF ERA-15 temperatures in the Tropics, which appears to be the consequence of spurious offsets and variabilities in the latter data-set. Kistler (2001) have shown that NCEP/NCAR and ERA-15 reanalyses agree in general quite well, except in the Tropics. The two reanalyses agreed in general in the assessment of inter-annual temperature variability in the troposphere. There was also a good agreement regarding long term trends of temperature in the troposphere, but the patterns in the Tropics were quite different. ERA-15 indicated a significant warming, which was not present in NCEP/NCAR. A comparison of temperature anomalies with reanalysis from the Data Assimilation Office of the Goddard Laboratory for Atmospheres showed very good agreement only with the NCEP anomalies. In brief, considering all these works, the reanalysis data from NCEP/NCAR seems to be the most appropriate set in the geographical and altitude region of our study.

5 Conclusions

The NCEP/NCAR reanalysis data-set, by covering three decades of homogeneous data over time, provides a valuable long-term global record in the troposphere and stratosphere. Significant results in the search for recurrent behavior were obtained only near the equator. Apart from the well-known annual and semi-annual cycles, the data capture the essential nature of different phenomena. Because of the inherent noisiness of the time series and the variability from phase to phase exhibited by the QBO, it is difficult to draw quantitative conclusions about a typical cycle. However, because of the relatively long time series, the global coverage and the homogeneity of data (only satellite era information was used), two possibly previously undetected QBO characteristics may be considered features to be further monitored in future work: a period reduction over time during the 30 years studied (about 12 days per cycle) and oscillations that mimic QBO harmonics in the troposphere and stratosphere. The period reduction over time may not be a very long term trend, but just an effect over the time interval of analyzed data. Evidence found in this work favors the scenario that the QBO and the TBO are unrelated phenomena. Effects of the 11-year solar cycle variability through the studied reanalysis data are just noticeable. Short-term solar variabilities leave apparently no significant signature. Some of the observed recurrent signatures in the troposphere and stratosphere lie within the known range of variability of ENSO, but we evaluate this correspondence as unlikely.

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