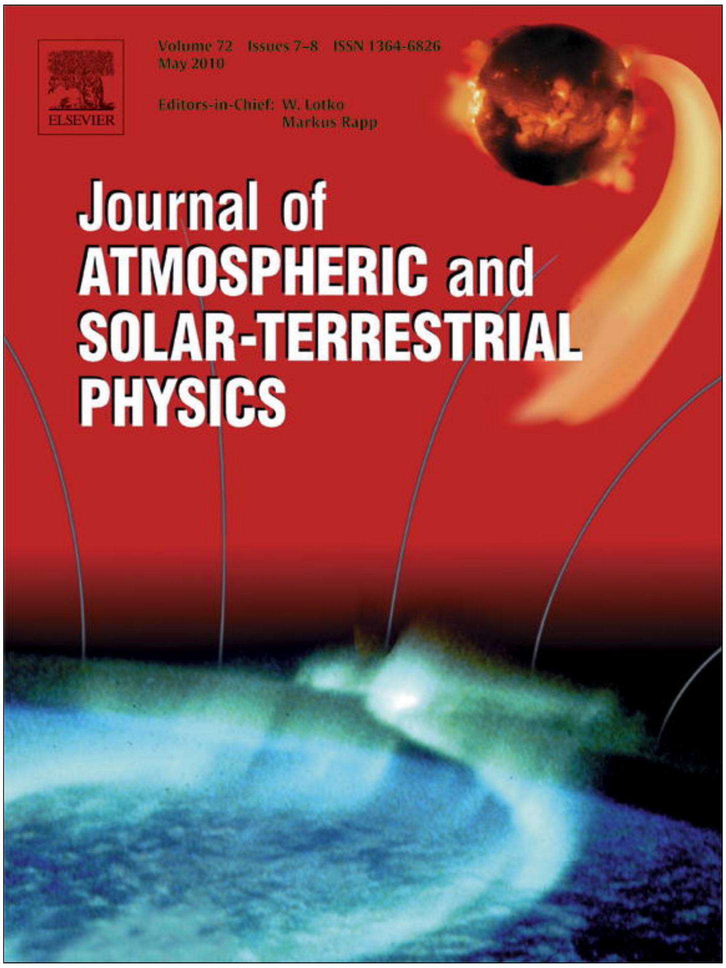
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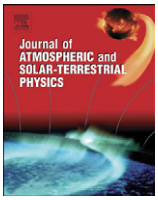

Trends in total ozone and the effect of the equatorial zonal wind QBO

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ABSTRACT

Trends in total column ozone have been analyzed in terms of the equatorial zonal wind. We used zonal monthly mean total ozone from Total Ozone Mapping Spectrometer (TOMS) and monthly mean zonal wind in the equatorial stratosphere at 30 hPa to define the phases of the quasi-biennial oscillation (QBO). Total column ozone trends have been assessed during the period 1979–2004, for both Hemispheres, and for each month, under three conditions considering, all the ozone dataset, ozone values during easterly phase and ozone values during westerly phase of the QBO. When the whole dataset is considered, negative trends are observed. From low to midlatitudes a zonal pattern is noticed with increasing negative values toward higher latitudes. When the data is filtered according to the QBO phase, statistically significant positive trends appear in the westerly case during January to May at low latitudes .The trend pattern in the case of the easterly phase presents more negative values.

1. Introduction

The global stratospheric ozone decay, since1979 to the present is well established. Several authors (Herman and Larko, 1994; Callis et al., 1997; Atkinson, 1997; and Steinbrecht et al., 2003; among numerous others) have studied the global total ozone changes. World Meteorological Organization (WMO) (1995, 1999, and 2003) provides an excellent overview (Malanca et al., 2005).

Several studies (Bojkov et al., 1990; Callis et al., 1991; Stolarski et al., 1991, 1992; Niu et al., 1992; Herman and Larko, 1994) have shown the large midlatitude decay in the total ozone column and in the lower stratospheric ozone between 1979 and 1980 and the mid-1980s. Harris et al. (1997) revised total ozone column seasonal trends at midlatitudes using zonal averages. Harris et al. (2001) have further refined the approach used to determine ozone variability and change.

Furthermore, Fioletov and Shepherd (2003) demonstrated the remnant effect of the Antarctic ozone hole signature in zonal mean total ozone levels over the Southern Hemisphere through the austral summer. In most studies cited above, it had been customary to use zonal mean values, ignoring all longitudinal effects (Malanca et al., 2005).

The quasi-biennial oscillation (QBO) in equatorial stratospheric winds, with a period varying from about 26 to 30 months, prevails over seasonal variation at heights between 18 and 30 km (100 to 10 hPa), descends with time in alternating series of easterlies and westerlies that attain speeds of 20 to 30 m/s. The discovery of the QBO in equatorial stratospheric winds by Reed (Reed et al., 1961) and Ebdon (1960) induced researchers to look for this oscillation in meteorological and geophysical parameters (for a comprehensive review of the QBO see Baldwin et al., 2001). The initial evidence of the QBO in total ozone that came from ground-based observations of two subtropical stations, was reported by Funk and Garnham (1962). Analysis of long time series of global satellite data from Total Ozone Mapping Spectrometer (TOMS) have clearly documented characteristics of global QBO in column ozone (Bowman, 1989; Lait et al., 1989; Chandra and Stolarski, 1991; Randel and Cobb, 1994; Tung and Yang, 1994; Kane, 1994; Echer et al, 2004).

The mechanism by which the QBO modulates ozone column abundance in the stratosphere is well known (Plumb and Bell, 1982; Baldwin et al., 2001; Jiang et al., 2004). The temperature anomalies associated with the QBO winds induce a modification to the normal stratospheric circulation. The normal circulation of the stratosphere, known as the "Brewer–Dobson" circulation, after the pioneering deductions of Brewer (1949) and Dobson (1956) from observations of stratospheric water vapor and ozone. This circulation comprises a two-cell structure in the lower stratosphere, with upwelling in the tropics and subsidence in middle and high latitudes, and a single cell from the tropics into the winter hemisphere at higher altitudes (Plumb, 2002). The QBO circulation is superimposed on the Brewer–Dobson circulation. Depending on which phase, this circulation will either be speeded up or weakened (Cordero et al., 2003).

Shibata and Deushi (2008) described long-term variations and trends that appeared in the REF1 simulation from 1980 to 2004 by

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the Chemistry-Climate Model of the Meteorological Research Institute (MRI-CCM) and in TOMS/SBUV observations. They found a monthly dependence for the QBO signal on column ozone.

In this work, the total column ozone trends have been assessed using minimum least squares, during the period 1979–2004, for both Hemispheres, and for each month, considering all the ozone dataset, ozone values during easterly phase of the QBO, and ozone values during westerly phase of the QBO.

2. Data sources

The monthly average zonal mean of the Total Column Ozone from TOMS (Nimbus 7, METEOR and Earth Probe satellite) measured in 5° bins between 60°N to 60°S, in Dobson units, was taken from http://toms.gsfc.nasa.gov/ozone/ozoneother.html.

The monthly mean zonal wind in the equatorial stratosphere, which defines the phases of the QBO, was taken from a compilation by Naujokat (1986) (http://dss.ucar.edu/cdroms/karin_labitzke_strat_grids/data/qbo/). The dataset, going from 1953 to the present, combines the observations of the radiosonde stations Canton Island (3°S, 172°W), Gan/Maledive Islands (1°S, 73°E) and Singapore (1°N, 104°E).

The ozone data is filtered using the equatorial zonal wind at 30 hPa**.**

Linear tendencies have been assessed for each month. Fig. 1 shows, as an example, scatter plots for February between 0–5°, considering, (a) entire time ozone series; (b) east QBO phase; and c) west QBO phase. The results are tested using the Student's t-test; values not statistically significant (below 80% confidence level) are obtained when all ozone series and east QBO phase are considered. In the case of west QBO phase, 90% confidence level is obtained.

3. Results

When the whole dataset is considered (Fig. 2), the long term trend for every month of the year presents negative values as expected. Shading zones indicate values significant at the 95% confidence level.

Values close to zero are noted at low latitudes between January to May, increasing negative values are observed towards higher latitudes and negative tendencies decrease during winter season in both Hemispheres. A focus, lower than −1.4 DU/year, at around 50° in February can be noticed. Between September to November, the negative tendencies values increase up to −2.86 DU/year in October at around −60°, indicating the intensification of the ozone hole.

Bojkov (1986) and Garcia and Solomon (1987) noted an apparent QBO modulation of the minimum ozone amounts observed in the Antarctic ozone hole that forms in springtime in the Southern Hemisphere. Garcia and Solomon noted that years in which the 50 mb equatorial zonal winds over Singapore were westerly (easterly), the severity of the ozone depletion within the hole was greater (less) than average. Shibata and Deushi (2008) observed the total ozone depletion in southern high latitudes during late winter to early summer and the second maximum ozone decrease in northern high latitudes during early spring, March to April, using data from TOMS/SBUV.

When the data is filtered according to the QBO phase, in East case, a similar pattern with only negative values is observed (Fig. 3a). Shading zones indicate values significant at the 95% confidence level. The increasing of the negative tendency values observed in Fig. 2 between September to November in South Hemisphere is present in this case with higher absolute values (−3.76 DU/year in October).

The pattern observed in both above cases are broken, when west phase years are considered (Fig. 3b). Shading zones indicate

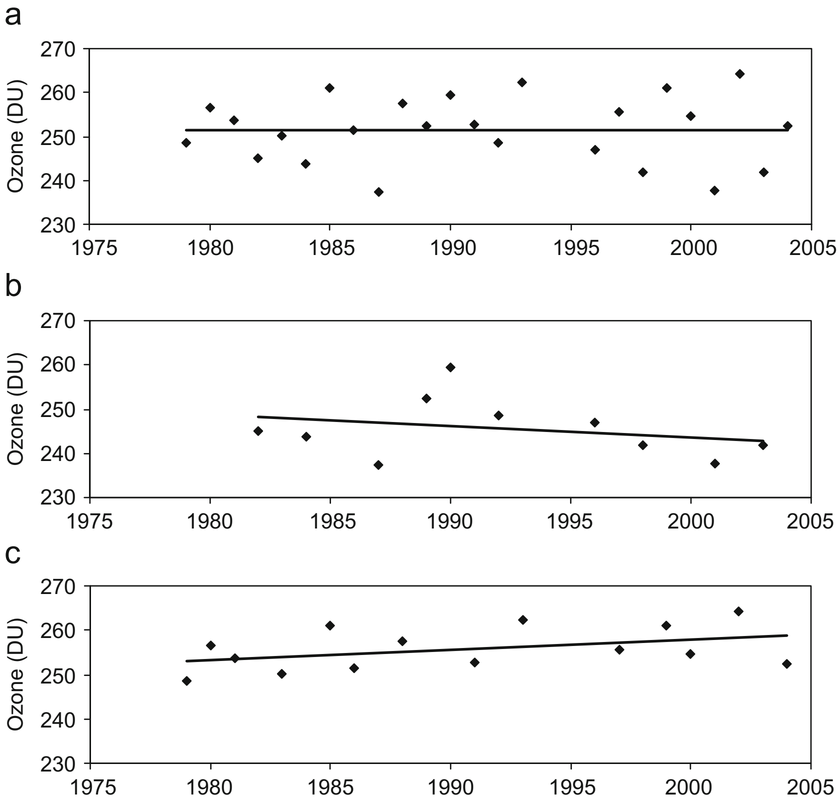

Fig. 1. Scatter plots for February (0–5°), considering, (a) entire time ozone series; (b) east QBO phase; and west QBO phase. Trend lines are included.

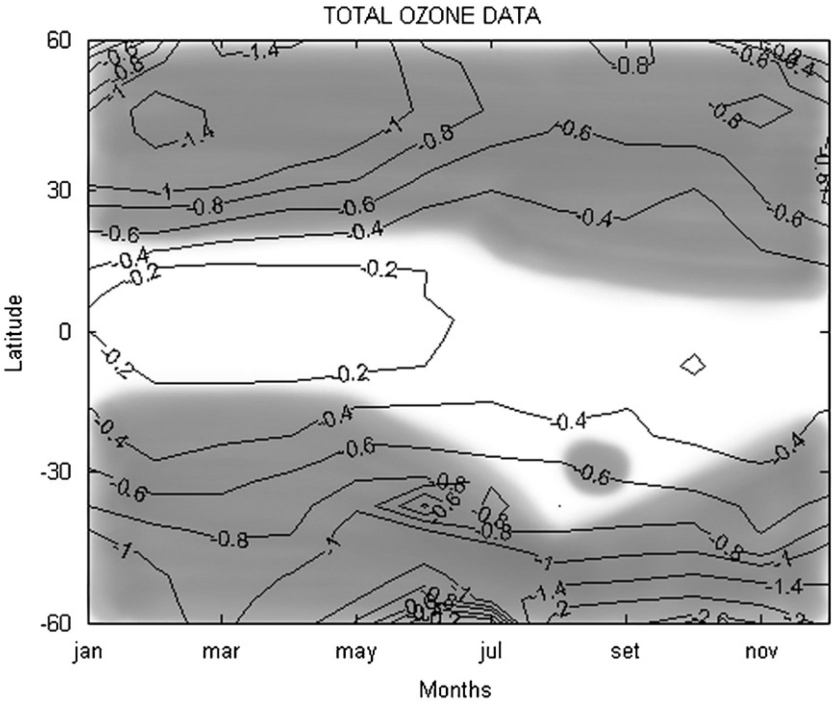

Fig. 2. Latitude-month diagrams of the total column ozone trends in DU/year during the period 1979–2004, considering all the ozone dataset. Shading zones indicate values significant at the 95% confidence level.

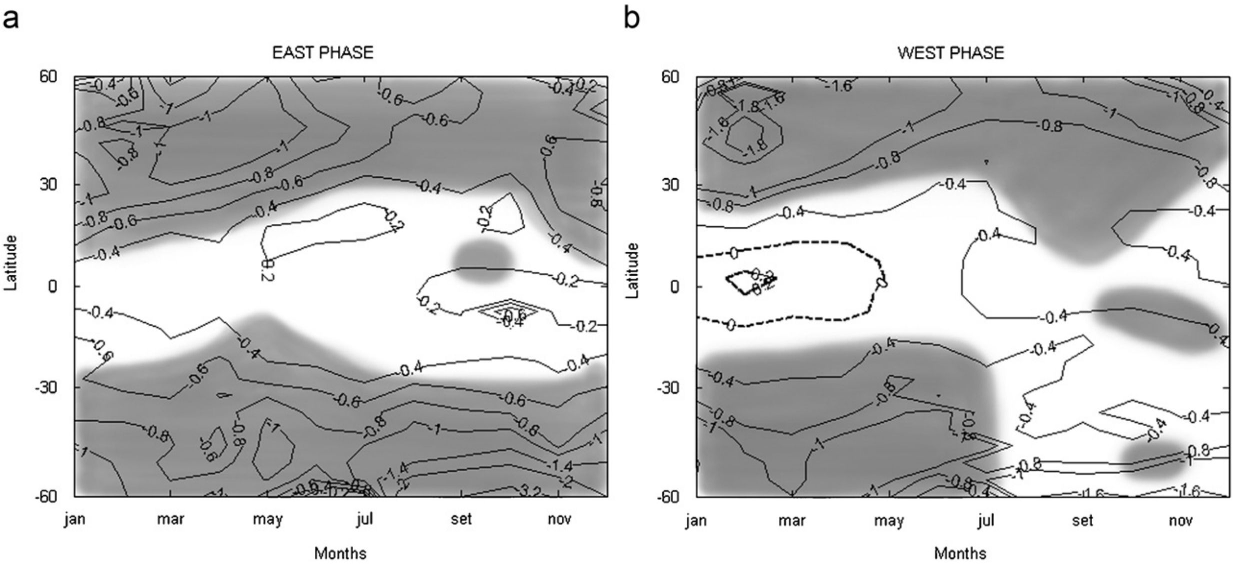

Fig. 3. Latitude-month diagrams of the total column ozone trends in DU/year during the period 1979–2004. (a) Considering ozone values during easterly phase of the QBO and (b) considering ozone values during westerly phase of the QBO. Shading zones indicate values significant at the 95% confidence level.

values significant at the 95% confidence level. At low latitudes, positive trends are observed between January to May, statistically significant at the 90% confidence level, and from June to December tendencies negatives are observed. The increasing negative tendencies do occur in this case, just smaller in magnitude compared with Figs. 2 and 3a. The focus observed at around 50° in February is increased in the case of west phase with a value of around −2.0 DU/year.

The values significant at the 95% confidence level are present for latitudes higher than ±15° for the three cases analyzed.

Gray and Ruth (1993) show that the QBO signal in the severity of the ozone hole may be predicted based on the QBO anomaly in ozone at midlatitudes and they considered this reason to be a better tool for the prediction of the severity of the ozone hole than the sign of the equatorial wind at a particular pressure level.

4. Discussion and conclusion

From the analysis of TOMS long time series, Randel and Wu (1996) noted that the variation of the total ozone column is nearly in phase with the equatorial zonal winds at 30 h Pa at ±10° latitude. An extratropical anomaly out of phase with the tropical signal, over 15–60° latitude, was also observed. The extra tropical ozone QBO is seasonally synchronized, such that the QBO influence is observed only during winter–spring of each respective hemisphere. Randel and Wu (2007) have generated a global ozone profile dataset covering the period 1979–2005 based on a combination of SAGE I and II satellite measurements and polar ozonesondes. They found a large percentage decreases in the tropical lower stratosphere ozone trends.

The relationships between total ozone and selected upper troposphere/lower stratosphere variables using decadal scales over Southern Hemisphere midlatitudes for the period 1980–2000 have been analyzed by Canziani et al. (2008). Their results show that many of the changes in total ozone correspond to processes driven in the lower stratosphere and upper troposphere, which depend on latitude and season. The Brewer–Dobson circulation variability, the planetary wave activity and changes in the tropospheric and lower stratospheric circulation affecting transport are some of the factors that have influence on the total ozone content and its variability (Malanca et al., 2005).

Kodera et al (1991) tested the hypothesis that the Solar/QBO modulation of the stratospheric circulation takes place in the upper stratosphere during early winter through wave-mean flow interaction of planetary waves and showed that the QBO effect propagates poleward and downward during northern winter.

The atmospheric dynamics of the Southern Hemisphere, at low stratospheric heights and at high latitudes, is different from that at the Northern Hemisphere. The Southern Hemisphere circulation is more regular and more zonal, and the atmospheric wave activity is remarkably lower compared with the Northern Hemisphere (Labitzke and van Loon, 1999; Lastovicka and Krizan, 2009). In general, the North Hemisphere observations suggest that the stratospheric polar vortex is weaker, warmer and more disturbed by planetary waves when the lower stratospheric equatorial winds are in the easterly phase of the QBO than when they are in the westerly phase. The correlation between the winter-time average northern hemisphere polar temperature and the phase of the QBO in the lower stratosphere was noted over twenty five years ago by Holton and Tan (1980) (H–T relationship). They found that polar winter stratospheric warmings (and higher polar temperatures) tended to occur mainly during the easterly phase of the equatorial QBO. The explanation was that the QBO winds in the lower stratosphere determine the position of the zero wind line near the equator. This results in enhanced poleward heat transfer during an easterly QBO phase and weaker transfer during a westerly phase. These warming events result in both temperature and ozone increases at high winter latitudes.

Gray et al. (2001) showed, using a stratosphere–mesosphere model (SMM), that the presence of an H–T relationship in late winter would require realistic equatorial winds over an extended height region that includes the upper stratosphere as well as the lower stratosphere.

The QBO-planetary wave mechanism had an important role in the Arctic dynamics during 1958–2006 according to Lu et al. (2008).

During easterly phase years, the modulation of planetary wave forcing by the equatorial wind QBO results in a stronger large scale mean circulation and a relatively larger column ozone anomaly in easterly years than westerly years can be resulted from a stronger downwelling in winter mid-latitudes (Baldwin et al., 2001).

The mean meridional circulation is modulated by the QBO (Jones et al., 1998; Kinnersley, 1999). A significant interhemispheric asymmetry in the timing and amplitude of the subtropical anomalies is present due to the interaction of the QBO with the seasonal cycle (Gray and Dunkerton, 1990). The nonlinear horizontal advection of zonal momentum in the tropics and subtropics by the mean meridional circulation, which is highly asymmetric during solstice periods, induces a seasonal dependence of the circulation. The asymmetry in subtropical ozone anomalies arises primarily through its formation by an asymmetric QBO circulation. This asymmetric anomaly emerges directly through the advection of ozone at the lower levels and indirectly through the advection of NO_y at the upper levels (Baldwin et al., 2001). Chipperfield et al. (1994) have investigated the QBO signals in SAGE II O_3 and NO_2 data using an isentropic 2D model and found that the contours of NO_y bulge upwards in the equatorial lower stratosphere producing the modulation of the horizontal advection on the tracer that dominates the modulation of the vertical advection. The larger horizontal gradient in the case of NO_y accentuates the effect of the induced QBO circulation and consequently also enhances the hemispheric asymmetry in the QBO signal.

When the data is filtered according to the QBO phase, different linear tendencies are found. The differences in the circulation between both phases of the QBO drive the total ozone changes. It would be necessary to analyze the altitude variations of the ozone trends, as well as the trends in temperature and tracers, filtered all by the QBO phase. This would help to elucidate the mechanisms that cause our results.

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