

On the 11 year solar cycle signature in global total ozone dynamics

Maria N. Efstathiou* and Costas A. Varotsos

Climate Research Group, Division of Environmental Physics and Meteorology, University of Athens, Greece

ABSTRACT: The main aim of the present study is to investigate further the association between total ozone (TOZ) and the 11 year solar cycle (SC) during the period 1979–2010, by employing satellite observations of TOZ made by Nimbus-7, Meteor-3, Earth Probe Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) instrumentation. A statistically significant correlation between the annual mean TOZ over both hemispheres and sunspot number (SN) is found. On the contrary, focusing on the January and February mean monthly TOZ fluctuations from the equator to the high latitudes of the Northern Hemisphere, no association between TOZ and SN is derived. This is attributed to the existence of the quasi-biennial-oscillation (QBO) and the El Niño–Southern oscillation (ENSO) in the TOZ time series. The latter oscillation is herewith expressed by the recently introduced Ozone ENSO Index (OEI). However, when considering the TOZ zonal means centred at 17.5 and 27.5°N during the east phase years of the QBO in the equatorial zonal wind at 50 hPa, a statistically significant correlation between TOZ and SN is revealed. It is an indication that the quasi-periodic fluctuations (i.e. QBO, ENSO) strongly contaminate the relationship between TOZ and solar activity. Plausible mechanisms are discussed, exploring the momentum flux (MF) measurements between 45 and 75°N, in the periods of increased dynamical variability. The findings obtained point to the conclusion that the 11 year solar cycle response in TOZ is caused by dynamical changes which are caused by solar activity. These are of crucial importance because solar radiation is a major driving force of the climate system. Copyright © 2012 Royal Meteorological Society

KEY WORDS Total ozone; zonal wind; solar activity

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1. Introduction

Several studies have shown that variations in the 11 year solar irradiance and subsequent ultraviolet absorption by ozone cause changes in temperature and wind in the upper stratosphere (Varotsos *et al.*, 1995; Kondratyev and Varotsos, 1995, 1996; Katsambas *et al.*, 1997; Alexandris *et al.*, 1999; Crooks and Gray, 2005). These relatively weak direct changes could alter the atmospheric dynamics giving rise to indirect feedbacks in the lower atmosphere. The latter can be achieved *via* the upward propagation of planetary-scale waves through a change of the stratospheric mean circulation (i.e. Brewer–Dobson circulation) (Varotsos, 1989, 2002, 2003, 2004, 2005a, 2005b; Varotsos and Cracknell, 1993, 1994; Varotsos *et al.*, 1994, 2000; Cracknell and Varotsos, 1994, 1995; Gernandt *et al.*, 1995; Koder and Kuroda, 2002; Efstathiou *et al.*, 2003; Varotsos and Kirk-Davidoff, 2006; Tzanis and Varotsos, 2008).

Matthes *et al.* (2010) indicated that the solar response in the upper stratosphere does not depend on the quasi-biennial oscillation (QBO) of the equatorial wind. However, this is not the case in the middle to lower stratosphere where the solar response depends on the QBO phases. More specifically, during QBO east, the combination of production and advection resulted in a net ozone increase.

Lu *et al.* (2009) proposed some insights on the modulation of the 11 year solar cycle signals by the QBO, especially in the Northern Hemisphere (NH) winter temperatures and zonal

winds. They used daily ERA-40 Reanalysis and ECMWF Operational data for the period of 1958–2006 in order to examine the seasonal evolution of the QBO–solar cycle relationship at various pressure levels up to the stratopause. The results showed that the solar signals in the NH winter extratropics are indeed QBO-phase dependent, moving poleward and downward as winter progresses with a faster descent rate under westerly QBO than under easterly QBO.

Sitnov (2009) using TOZ data that were collected at 10 ground-based European stations during the period 1957–2007 investigated the effects of the QBO and 11 year solar cycle, manifesting in total ozone (TOZ). One of the results obtained by Sitnov (2009) is that solar activity modulates the phase of the QBO, so that the quasi-biennial total ozone signals during solar maximum and solar minimum are nearly in opposite phase.

Titova and Karol (2010), having applied the method of discriminant analysis to the TOMS data of satellite sounding of TOZ each March from 1979 to 2008, attempted to make a new estimate of the TOZ field variability in the NH and inter-longitudinal regularities of its changes under the action of climatic variability. The effects of temperature variations in the polar stratosphere, El Niño–Southern Oscillation (ENSO) and QBO seemed to be comparable and reached 80 DU in some regions. Titova and Karol (2010) also proposed that the regions of TOZ variations and their location and dimensions change depending on the phases of QBO and ENSO. Three regions of increased TOZ, over Europe, Eastern Siberia and the Pacific Ocean, are formed in years with a warm stratosphere. A compensating TOZ decrease takes place in the tropics and over Greenland. In the years of El Niño and the easterly QBO phase, the TOZ increases over Europe and drops over the central Pacific, as well as to the south from 45°N.

* Correspondence to: M. N. Efstathiou, Faculty of Physics, Climate Research Group, Division of Environmental Physics and Meteorology, University of Athens, University Campus Bldg. Phys. V, Athens 15784, Greece. E-mail: efstathiou@avgouleaschool.gr

Ziemke *et al.* (2010) have recently established an ozone ENSO index (OEI) using TOZ data measured in tropical latitudes from Nimbus 7 TOMS, Earth Probe TOMS, NOAA SBUV and Aura OMI satellite instruments from 1979 to the present. In more detail, the OEI was developed by calculating first the western and eastern Pacific TOZ monthly mean averages and taking their difference. The combined Aura OMI and MLS ozone data confirmed that zonal variability in TOZ in the tropics imposed by ENSO events in the troposphere. The latter reveals that OEI can be calculated by considering TOZ instead of tropospheric TOZ.

Soukharev (1997), studying the TOZ monthly means from January to March between 1973 and 1995 at five stations in northeastern Europe, indicated statistically significant correlations between the variations of TOZ in February/March and the SN during the different phases of the QBO. A similar correspondence was established between the index of stratospheric circulation and SN considering the QBO phase. Assuming the correlations between the ozone and stratospheric circulation index, Soukharev (1997) concluded that a connection between solar cycle, QBO and ozone occurs through the dynamics of stratospheric circulation.

More recently, an extensive description for the stratosphere/solar cycle relationship was given by Gray *et al.* (2010) studying observations and mechanisms for the Sun's variability and solar irradiance variations on both decadal and centennial time scales. They also described corresponding observations of variations of the Earth's climate on associated time scales, including variations in ozone, temperatures, winds, clouds, precipitation and regional modes of variability such as the monsoons and the North Atlantic Oscillation. The solar component of lower stratospheric (column) ozone variability was earlier discussed in Chapter 3 of WMO 2006 and was updated in Section 2.4.3.2 of WMO 2010 (WMO, 2006, 2010). Identification of the solar cycle signal in observed ozone was improved due to the absence of major volcanic eruptions over the past 15 years. The deduced solar cycle variation in column ozone appeared to have a mean amplitude of 2–3% (from minimum to maximum) in low to mid-latitudes from the extended data series. Model estimates and measurements suggested that the amplitude of the solar cycle in ozone concentration is less than 4% throughout the stratosphere, although there are apparent differences between the models and observations at some altitudes. Finally, the lower stratospheric solar cycle in tropical ozone appeared to be caused indirectly through a dynamical response to solar variations (Chattopadhyay and Chattopadhyay, 2007, 2009).

During the last three decades the role of the winter Arctic temperature and its modulation by the phase of the equatorial quasi-biennial oscillation wind has been an attractive issue. The first observational evidence for effects of the QBO on the Arctic stratosphere was given by Labitzke and van Loon (1988), while Labitzke (2004) showed that the lower stratospheric temperature response to the solar cycle at low to middle latitudes is strongest during the east phase of the QBO. More recently, Xu *et al.* (2011) based on the Aura-MLS (Microwave Limb Sounder) observations, showed that the wintertime Arctic temperature is modulated by the phase of the equatorial QBO wind. In particular Xu *et al.* (2011) claimed that the 40 hPa QBO easterly phase corresponds to a warmer (colder) northern polar stratosphere (mesosphere) and *vice versa*. Moreover, Xu *et al.* (2011) pointed out that the intensification of the planetary waves in the winter Arctic stratosphere and lower mesosphere

coincides with the equatorial 40 hPa QBO easterly phase. In this respect, Salby and Callaghan (2000) suggested that changes in the polar-night vortex are consistent with the solar signature observed in winter records of polar temperature that have been stratified according to the QBO. In addition, the substantial role of the winter QBO to the excitement of the 'northern annular mode' (NAM) (also called the Arctic Oscillation) (Thompson and Wallace, 1998, 2000) has been discussed by Baldwin *et al.* (2001).

The investigation of the plausible relationship between the QBO phase and the northern winter polar vortex is of special interest. In this context, Lu *et al.* (2008) discussed the fact that observational studies tend to suggest a colder and stronger polar vortex during westerly QBO, and a warmer and more disturbed polar vortex during easterly QBO (Holton and Tan, 1982).

It has long been known that the interplay between radiative and dynamical mechanisms that involve QBO and the solar cycle affect the ozone layer. For example, Varotsos (1989) studying the global TOZ, during the period 1958–1984, suggested that there was not any evident connection between TOZ and 10.7 cm solar flux (F10.7). However, when the data were separated according to the east or west phase of the QBO in the equatorial stratosphere, it was found that the TOZ was correlated (inversely correlated) with the solar cycle, during the west (east) phase of QBO.

In the light of the above-mentioned very important conclusions the main aim of this paper is to explore further the association between TOZ and solar activity, from the equator to the high latitudes in both Hemispheres over the last three solar cycles.

2. Data and analysis

The TOZ data set used in the analyses came from several different satellite instruments: Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) for January 1979 to May 1993, Meteor-3 TOMS for June 1993 to November 1994, Earth Probe TOMS for July 1996 to May 2004 and the Aura Ozone Monitoring Instrument (OMI) for June 2004 to present (with measurement gaps for several months of the years 1994, 1995 and 1996). Also, measurements from the 'merged' total column ozone record of TOMS, OMI and National Oceanic and Atmospheric Administration (NOAA) 9 Solar Backscatter Ultraviolet Instrument (SBUV/2) (for May 1993 to July 1996, with data gaps for several months of the years 1995 and 1996, at 5° latitude resolution) were incorporated (http://acdb-ext.gsfc.nasa.gov/Data_services/merged/). The merged total ozone data sets are monthly-mean zonal and gridded average products constructed by merging individual TOMS/OMI (total ozone) and SBUV/SBUV/2 (total and profile ozone) satellite data sets. An external calibration adjustment has been applied to each satellite data set in an effort to calibrate all the instruments to a common standard.

Momentum Flux (MF) measurements between 45 and 75°N, through 1979–2010, obtained by the NASA Goddard Space Flight Center, were also used (http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data.html). The momentum flux averaged between 45 and 75°N, at 50 hPa, is an indicator of a disturbed stratosphere. The correlation between the meridional wind (north–south wind) and the longitudinal asymmetries of the zonal wind (east–west wind) yields the momentum flux. While the heat flux is almost always poleward, the momentum

flux is more variable in direction, albeit that the momentum flux is generally poleward.

Finally, Ozone ENSO index measurements obtained by the NASA Goddard Space Flight Center, Code 613.3 (Chemistry and Dynamics Branch), in the tropics during 1979–2010, were employed (Ziemke *et al.*, 2010). Column ozone measured in tropical latitudes from Nimbus 7 TOMS, Earth Probe TOMS, NOAA SBUV, and Aura OMI satellite instruments were used to derive an ENSO index. This index, which covers a period from 1979 to the present, is defined as the Ozone ENSO Index (OEI) and is the first developed from atmospheric trace gas measurements. Using a data mining technique with existing ENSO indices of surface pressure and sea-surface temperature, the OEI was constructed by first averaging monthly mean column ozone over two broad regions in the western and eastern Pacific (15°S to 15°N, 70–140°E, and 15°S to 15°N, 110–180°W, respectively) and taking their difference. A self-calibrating ENSO index, calculated by this differencing, is independent of individual instrument calibration offsets and drifts in measurements over the long record (http://acdb-ext.gsfc.nasa.gov/Data_services/cloud_slice/). Ziemke *et al.* (2010) indicated a high correlation (inverse correlation) with $r = 0.83$ ($r = -0.81$) between OEI and Niño 3.4 index (Southern Oscillation Index). For clear-sky ozone measurements a +1 K change in Niño 3.4 index appeared to correspond to +2.9 DU change in the OEI, while a +1 hPa change in Southern Oscillation Index coincided with a -1.7 DU change in the OEI. For ozone measurements under all cloud conditions these numbers were reduced to +2.4 DU and -1.4 DU, respectively (see figure 9 in Ziemke *et al.*, 2010). QBO data used in the present paper were calculated at the NOAA Earth System Research Laboratory-Physical Science Division (NOAA/ESRL-PSD) from the zonal average of the 50 hPa zonal wind at the equator. Those data were computed from the NCEP/NCAR Reanalysis (<http://www.esrl.noaa.gov/psd/data/climateindices/list/#QBO>) (Kalnay *et al.*, 1996). Additionally, the mean

monthly sunspot numbers (SN) derived from the datasets of the National Geophysical Data Center (NGDC), during the period January 1749 to October 2009, were employed.

All time series presented in this study were normalized (the long-term mean subtracted and then divided by the standard deviation) and detrended.

3. Discussion and results

Several studies argued that when the solar UV radiation is stronger, more ozone *via* the photolysis of O₂ would be formed in the upper stratosphere, so that the maximum ozone level would occur at the maximum solar activity (WMO, 2006, 2010; Gray *et al.*, 2010; Haigh *et al.*, 2010).

Therefore, it is interesting to re-visit the investigation of the influence of the solar activity to the column ozone variability on a global and hemispheric basis.

3.1. The total ozone and solar cycle on a global and hemispheric basis

According to the above-mentioned purpose, the 11 year solar cycle and the TOZ annual mean fluctuations over the globe, the NH and the SH, during the last three solar cycles are shown in Figure 1(a)–(c), respectively. It is worth mentioning that all measurements that depend on backscattered sunlight are effectively limited to latitudes less than about 65° in the winter hemisphere. Global averages of monthly or seasonal data are therefore restricted to latitudes less than about 65° in both hemispheres. Inspection of Figure 1 shows that an apparent solar cycle signal is prominent in the TOZ data. It should be mentioned that repeating the analysis by using the TOZ annual mean fluctuations derived from the merged ozone dataset, the results obtained do not change (Figure 2). To quantify this association, the correlation coefficients were calculated. These

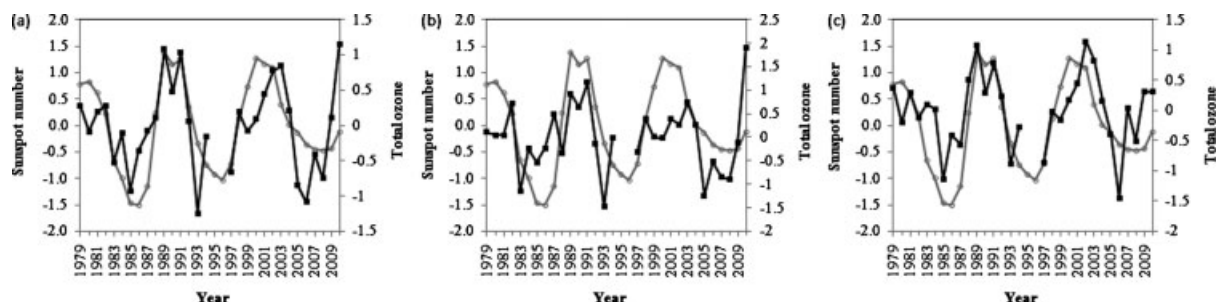


Figure 1. Annual mean TOZ and sunspot number (as a proxy for the 11 year solar cycle) over (a) the globe, (b) the northern hemisphere, (c) the southern hemisphere, during 1979–2010. The black and the grey lines present the TOZ and the SN, respectively. TOZ and SN time series have been normalized and detrended.

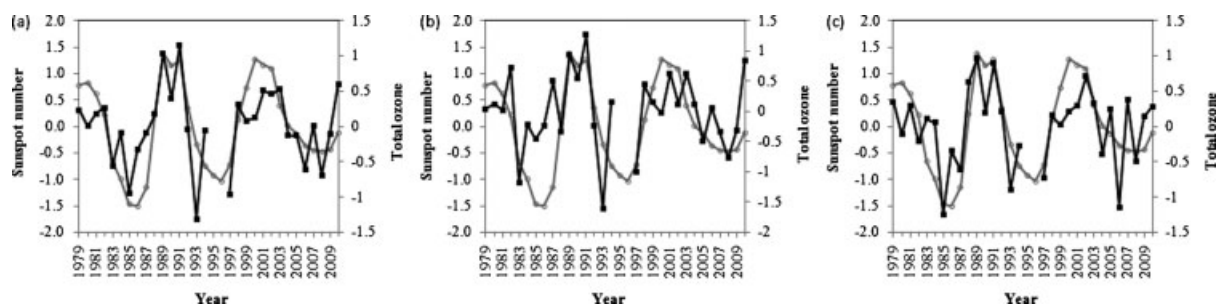


Figure 2. Same as Figure 1, but with annual mean TOZ derived using total column ozone from the merged ozone dataset.

were derived statistically significant (with range 0.5–0.7, at the 95% confidence level) by using the non-parametric Spearman method.

This in-phase march of TOZ and solar activity is not surprising because it is quite consistent with the current understanding about the solar forcing in TOZ dynamics. According to this, the upper stratospheric ozone response (2–3% between solar minimum and solar maximum) is a direct radiative effect of heating and photochemistry. The lower stratospheric solar cycle in tropical ozone appears to be caused indirectly through a dynamical response to solar ultraviolet variations. However, the origin of such a dynamical response to the solar cycle is not fully understood (WMO, 2010).

3.2. The total ozone on the wintertime Northern Hemisphere and solar cycle

To obtain a better understanding of the afore-mentioned dynamical TOZ response, the investigation of the plausible relationship between TOZ and solar activity would be performed at the wintertime regime of the atmosphere. There is no doubt that during winter months, the solar cycle signal is weak compared to large atmospheric variations and the signal is therefore more difficult to extract (Labitzke and van Loon, 1988). In an attempt to explore this problem further, the fluctuations of the mean TOZ over the NH during January/February and the corresponding SN values during the period 1979–2010 are plotted in Figure 3(a).

The conclusion deduced from Figure 3(a) is that quasi-periodic components (2–5 years) in the NH TOZ time series reduce remarkably the correlation between TOZ and SN fluctuations. To investigate whether this contamination of the association of the TOZ and SN fluctuations by the QBO is a function of solar activity, the method of running correlations was employed (Kodera, 1993). The results obtained are shown in Figure 3(b) where the running correlations (r_i) for year i between the equatorial zonal wind at 50 hPa and the mean TOZ for January and February do not show an 11 year signal (Figure 3(b)). Therefore, the above-said contamination by the QBO of equatorial wind is independent of the solar cycle, disturbing any apparent association between TOZ and SN.

3.3. The latitudinal dependence of the association between the wintertime TOZ and solar cycle at the Northern Hemisphere

Next, the investigation of the possible association between the TOZ and SN is explored as a function of latitude. In this

regard, Haigh (1994) has reported that due to the seasonality, the stratospheric ozone changes due to solar flux variation are largest at middle to high latitudes in the winter hemisphere. Figure 4(a)–(f) presents the January/February mean TOZ and SN from the equator to the high latitudes during 1979–2010. All these figures do not show any apparent correlation between TOZ and solar activity, due to the contamination by the quasi-periodic oscillations (QBO and ENSO) in the TOZ time series. It is worth noting that the selected latitudes and the January and February averages gave higher correlations compared to other latitudes and combinations of months.

However, the solar response in the winter TOZ at 17.5 and 27.5°N seemed to differ significantly under the two QBO phases.

Other studies have also identified solar influences on the strength and extent of the Walker circulation which is a cell circulation in the zonal and vertical directions in the tropical troposphere caused by differences in heat distribution between ocean and land. In this context, Meehl *et al.* (2008) and van Loon *et al.* (2007) showed a strengthening of the Walker circulation, at years of the maxima of the 11 year solar cycle. It should be remembered that when the Walker cell weakens or reverses, an El Niño results, and when the Walker cell becomes strong, a La Niña results.

3.4. The association between the wintertime TOZ and solar cycle at the Northern tropics; the role of the QBO and ENSO

Next, the January/February mean TOZ and SN data were grouped according to the QBO phases of the equatorial zonal wind at 50 hPa and were plotted against the OEI at 17.5 and 27.5°N (Figure 5(a)–(d)). During the west phase of QBO, a statistically significant inverse correlation between TOZ and OEI time series is apparent, resulting in a quasi periodic component that coincides with ENSO (Ziemke *et al.*, 2010) and causes no correlation between TOZ and SN. On the other hand, during the east phase of the QBO, the TOZ time series exhibits the 11 year signal which is consistent with the results presented in Labitzke (2004). Repetition of the above mentioned analysis using alternate indices did not change the results.

In the following, Figure 6(a) presents the February mean TOZ and SN at 17.5°N, during 1979–2010, while Figure 6(b) and (c) show the February TOZ, SN and OEI when the data were grouped in the west and east phase of the QBO, respectively. Inspection of these figures shows an apparent correlation between TOZ and the 11 year solar cycle, during the QBO east (a statistically significant correlation at the 95%

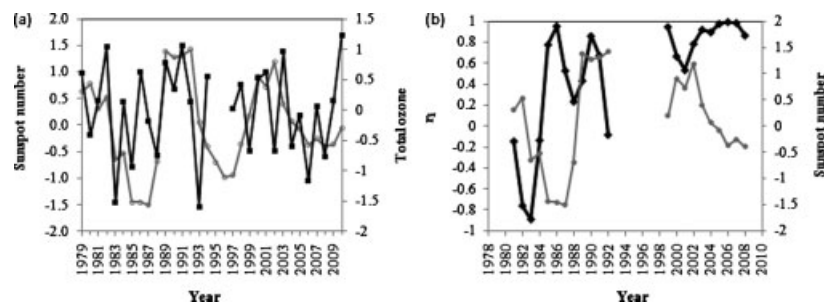


Figure 3. (a) January/February mean TOZ and SN over the northern hemisphere, during 1979–2010. The black and the grey line present the TOZ and the SN, respectively. (b) Running correlations (r_i) for year i between the equatorial zonal wind at 50 hPa and the January/February mean TOZ against SN. The black and the grey line present the r_i and the SN, respectively. TOZ and SN time series have been normalized and detrended.

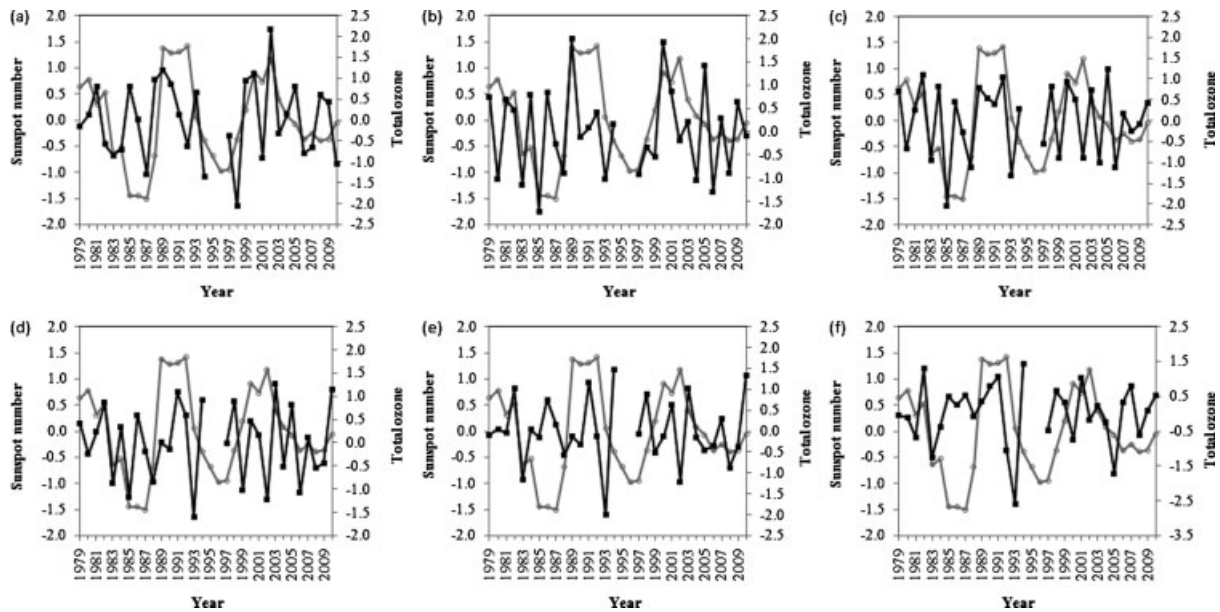


Figure 4. January/February mean TOZ and SN at (a) 7.5°N , (b) 17.5°N , (c) 27.5°N , (d) 37.5°N , (e) 47.5°N , (f) 57.5°N , during 1979–2010. The black and the grey lines present the TOZ and the SN, respectively. All time series have been normalized and detrended.

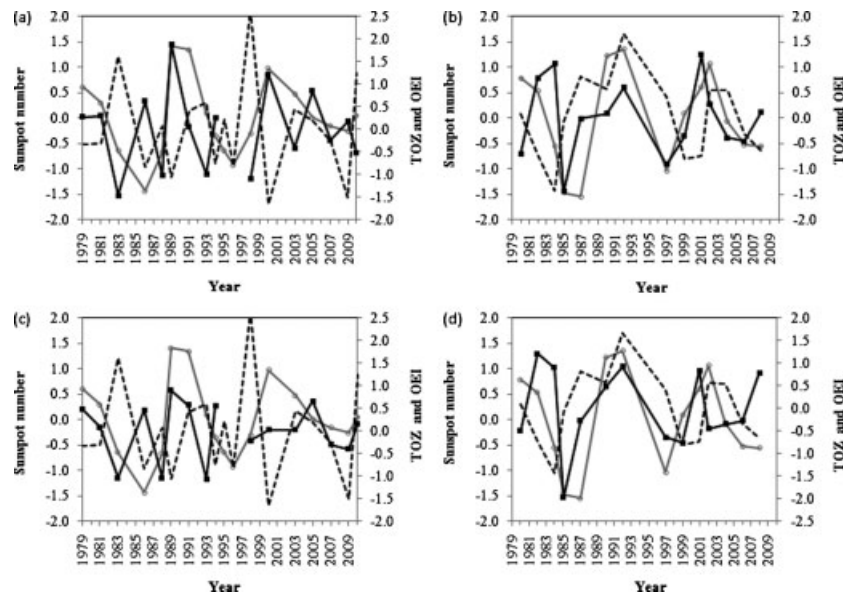


Figure 5. January/February mean TOZ and SN at 17.5°N during (a) the west phase of QBO and (b) the east phase of QBO. January/February mean TOZ and SN at 27.5°N during (c) the west phase of QBO and (d) the east phase of QBO. The black and the grey lines present the TOZ and the SN, respectively. The dashed lines present the OEI through 1979–2010 in the west and east phases of QBO. All time series have been normalized and detrended.

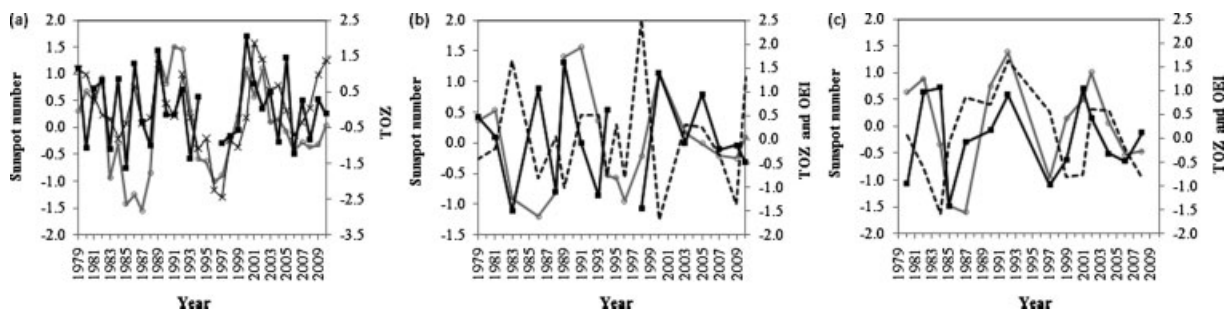


Figure 6. February mean TOZ and SN at 17.5°N , through 1979–2010 (a) independently of the QBO phases, (b) for the west phase of the QBO and (c) for the east phase of the QBO. The black and the grey lines present the TOZ and the SN, respectively. The thin line with the symbol x , in (a), corresponds to the smoothed time series of the February mean TOZ. The dashed lines present the OEI in the west and east phases of the QBO. All time series have been normalized and detrended.

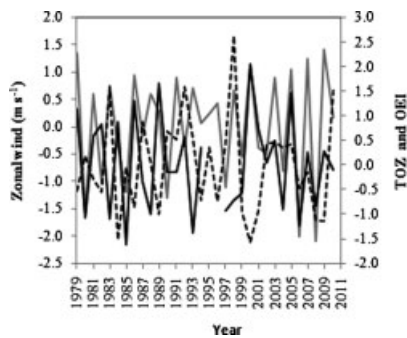


Figure 7. February mean TOZ at 17.5°N and OEI against the equatorial zonal wind at 50 hPa, through 1979–2010. The black and the grey line present the TOZ and the zonal wind, respectively. The dashed line corresponds to the OEI.

confidence level). The ENSO component is apparent once more in the TOZ time series, when the data were grouped in the west phase of the QBO and it is inversely correlated with OEI (Figure 6(b)). It is worth noting that February values gave higher correlations compared to other winter months or combinations of them.

To examine further the contribution of the QBO in the equatorial zonal wind at 50 hPa to the association between the February TOZ at 17.5°N and OEI Figure 7 is shown. Figure 7 shows the statistically significant inverse correlation between OEI and TOZ, but no association of TOZ with the QBO. The latter can probably be explained by the fact that TOZ exhibits the ENSO signal and it is modulated by the temporal evolution of the QBO maxima and minima. It should be noted that repetition of the analysis, replacing OEI with Niño 3.4 time series, did not show any significant change to the results obtained.

3.5. The association between the wintertime TOZ and solar cycle at the Northern high latitudes; the role of the QBO and ENSO

Finally, in order to explore the role of the atmospheric dynamics in the relationship between the TOZ and solar cycle, the interannual variability of the February mean momentum flux (MF) between 45 and 75°N at 50 hPa, during 1979–2010 was studied. Figure 8(a) illustrates the time series of MF and SN for February, while Figure 8(b) and (c) shows the MF and SN when the data were grouped according to the QBO phase. According to Figure 8(c), during the years of the east phase of the QBO an apparent inverse correlation between MF and the

11 year solar cycle is observed, which seems to be statistically significant, using the Spearman's rank correlation test, at the 95% confidence level. It is worth noting that MF was chosen because it gives a larger inverse correlation than eddy heat flux.

A plausible explanation for the statistically significant inverse correlation between MF and the 11 year solar cycle, during the QBO east phase, could be traced by studying the Brewer–Dobson circulation (BDC), which is driven by planetary and gravity wave breaking in the stratosphere and consists of a meridional cell in each hemisphere with air rising across the tropical tropopause, moving poleward, and sinking to the extratropical troposphere. Thus, BDC is considered to be driven by extratropical wave forcing in the winter hemisphere and it should be weakened during the solar maximum (Holton *et al.*, 1995; Koder and Kuroda, 2002). On the other hand, an acceleration of the vortex and a weakening of the BDC coincide with negative MF at the northern high latitudes (Fischer and Tung, 2008; Fu *et al.*, 2010). Moreover, according to planetary wave theory, large-scale asymmetries in the release of latent heat in the tropics is an important source of planetary waves. Planetary waves are accompanied by a convergence of eddy momentum flux across the Equator from the winter to the summer hemisphere in agreement with observation. Geller *et al.* (1997) showed the importance of an observational study of the momentum fluxes of equatorial waves, which are driving the QBO oscillations in the equatorial lower stratospheric zonal winds. The variations in the flux values of the equatorial waves change the forcing of the stratospheric mean zonal wind, which ultimately changes the QBO period. A statistically significant intensification (weakening) of the polar vortex during the westerly (easterly) phase of the QBO has been observed in numerous modelling studies (Marshall and Scaife, 2009).

Another conclusion drawn from Figure 8 is that the increased dynamical variability occurs during the west phase of the equatorial QBO and the winter vortex is significantly weakened during solar maxima and western phase of QBO. The dynamical association between the equatorial stratospheric QBO at 30–70 hPa during austral late winter and spring and the solar dynamic parameters was very recently studied by Lu and Jarvis (2011).

4. Conclusions

In this study, a statistically significant correlation between the annual mean total ozone (TOZ) and sunspot number (SN) over the globe, the northern and the southern hemisphere, through the period 1979–2010 was derived. The apparent 11 year signal in TOZ was obtained without any

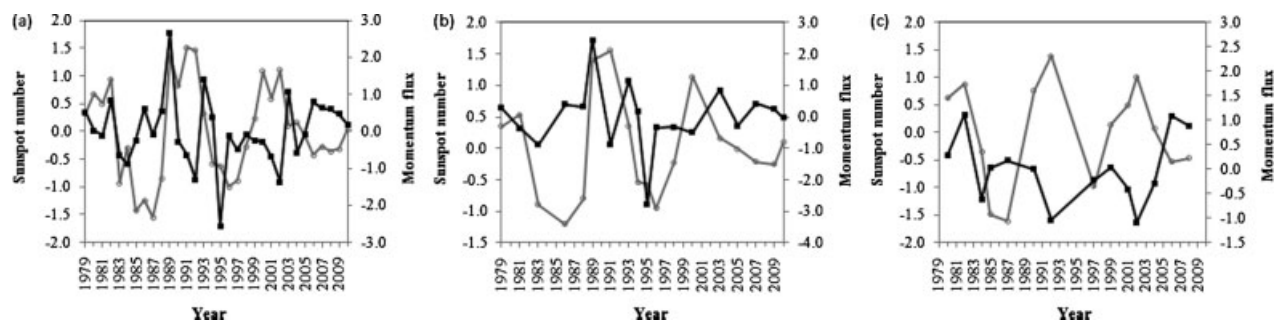


Figure 8. February mean MF and SN between 45 and 75°N , through 1979–2010 (a) independently of the QBO phase, (b) for the west phase of QBO and (c) for the east phase of QBO. The black and the grey lines present the MF and the SN, respectively. All time series have been normalized and detrended.

grouping of TOZ data (i.e. according to the quasi-biennial oscillation (QBO) phases of the equatorial wind). Moreover, the study of the January/February mean TOZ and SN over the northern hemisphere (NH) reveals that the quasi-periodic components in the TOZ time series reduce noticeably the above-mentioned correlation between TOZ and the 11 year solar cycle. In addition, no correlation was derived studying the January/February mean TOZ and SN from the equator to the high latitudes, due to the quasi-periodic components in the TOZ time series, stemming from the QBO and ENSO.

Focusing on the January/February mean TOZ and SN at 17.5 and 27.5°N, the TOZ time series contains an 11 year signal during the east QBO phase and an ENSO signal (expressed by the recently proposed Ozone ENSO Index) during the west QBO phase. The correlation between TOZ and the 11 year solar cycle, in the east phase of QBO becomes higher for February.

Finally, studying the February mean momentum flux between 45 and 75°N at 50 hPa, during 1979–2010, a statistically significant inverse correlation between momentum flux and the 11 year solar cycle is observed, when the data were grouped in the east QBO phase. The latter may be attributed to the increased dynamical variability (i.e. the disturbing factor) that occurs during the west phase of the equatorial QBO, as well as to the fact that the winter vortex is significantly weakened during solar maxima and QBO western phase. Therefore, the main conclusion drawn from the analysis is that the solar cycle response in TOZ is caused by dynamical changes which are caused by solar activity.

List of acronyms

ENSO: El Niño–Southern oscillation
 MF: Momentum flux
 MLS: Microwave Limb Sounder
 NGDC: National Geophysical Data Center
 NH: Northern Hemisphere
 OEI: Ozone ENSO Index
 OMI: Ozone Monitoring Instrument
 NOAA: National Oceanic and Atmospheric Administration
 SBUV: Solar Backscatter Ultraviolet
 QBO: Quasi-biennial-oscillation
 SC: Solar cycle
 SN: Sunspot number
 TOMS: Total Ozone Mapping Spectrometer
 TOZ: Total ozone

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