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Modeling study of the ionospheric responses to the quasi-biennial oscillations of the sun and stratosphere

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ABSTRACT

The Quasi-biennial Oscillation (QBO) is a persistent oscillation in the zonal mean zonal winds of the low latitude middle atmosphere that is driven by breaking planetary and gravity waves with a period near two years. The atmospheric tides that dominate the dynamics of the mesosphere and lower thermosphere region (MLT, between heights of 70–120 km) are excited in the troposphere and stratosphere, and propagate through QBO-modulated zonal mean zonal wind fields. This allows the MLT tidal response to also be modulated by the QBO, with implications for ionospheric/thermospheric variability. Interannual oscillations in solar radiation can also directly drive the variations in the ionosphere with similar periodicities through the photoionization. Many studies have observed the connection between the solar activity and QBO signal in ionospheric features such as total electron content (TEC).

In this research, we develop an empirical model to isolate stratospheric QBO-related tidal variability in the MLT diurnal and semidiurnal tides using values from assimilated TIMED satellite data. Migrating tidal fields corresponding to stratospheric QBO eastward and westward phases, as well as with the quasi-biennial variations in solar activity isolated by the Multi-dimensional Ensemble Empirical Mode Decomposition (MEEMD) analysis from Hilbert-Huang Transform (HHT), are then used to drive the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM).

The numerical experiment results indicate that the ionospheric QBO is mainly driven by the solar quasi-biennial variations during the solar maximum, since the solar quasi-biennial variation amplitude is directly proportionate to the solar cycle. The ionospheric QBO in the model is sensitive to both the stratospheric QBO and solar quasi-biennial variations during the solar minimum, with solar effects still playing a stronger role.

1. Introduction

The Quasi-Biennial Oscillation (hereafter referred as the QBO) is one of the most prominent phenomena in the tropical middle atmosphere (Baldwin et al., 2001). This long-term oscillation with period varying from 22 to 34 months (averaging ~28 months) dominates the equatorial variability of the stratospheric zonal wind field. It was identified in 1960s for the first time by Reed et al. (1961) and by Veryard and Ebdon (1961) in the equatorial zonal-mean zonal wind. The stratospheric zonal-mean zonal wind alters between westward wind and eastward wind phases with an average period of 28 months, and the serial regimes propagate downward continuously with a rate of ~1 km/month (Fig. 1). The amplitude of the wind regimes tends to be constant between 40 and 10 hPa, but decreases quickly below the 50 hPa level. The westward winds of the QBO can reach a maximum of 40 m/s; on the other hand, the maximum QBO eastward wind regimes are smaller by a factor of 2, about 20 m/s. It has been widely believed that the QBO is generated mainly by equatorial Kelvin waves and other small-scale gravity waves (Holton and Lindzen, 1972; Sato and Dunkerton, 1997).

The interconnection between the stratospheric QBO and the

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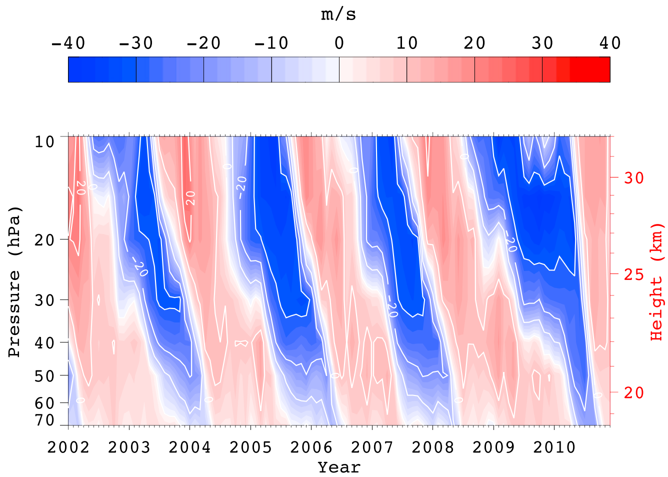

Fig. 1. Monthly-mean zonal wind component at Singapore as a function of isobaric pressure level and time (1°N/104°E) for 2002–2010. The contour interval is 10 m/s.

mesosphere is one of long-standing subjects of interest in the middle-atmospheric community. The QBO signature in the mesosphere was first observed in UARS (Upper Air Dynamics Satellite) HRDI (High Resolution Doppler Interferometer) observations by Burrage et al. (1996). It was out-of-phase with the stratospheric QBO, with an amplitude of about 30 m/s. It has been suggested that the mesospheric QBO is driven by the selective filtering of small-scale gravity waves by the prominent stratospheric QBO (Burrage et al., 1996). Garcia et al. (1997) also used HRDI observations to find that the westward phase of the mesospheric semi-annual oscillation is much stronger during the westward phase of stratospheric QBO, though the same feature could not be observed by MF radar.

The residual of zonal wind measured by HRDI with the amplitude of the annual and semiannual oscillations removed also has a striking relationship with the migrating diurnal tide (DW1) in the meridional wind at 95 km altitude, 20°N (Hagan et al., 1999); however, the tidal modulation by the QBO wind retrieved from the HRDI observations has opposite effect during April 1993 and 1994 in the Global Scale Wave Model (GSWM) simulations. Forbes et al. (2008) showed the migrating tidal temperature retrieved from the SABER observations had QBO-like signatures in the mesosphere and lower thermosphere (MLT) region, with variations of order ±10∼15%. Wu et al. (2008) also found comparable results retrieved from TIDI in the zonal and meridional wind DW1 in the MLT region during 2002∼2007. This result showed that during the DW1 March equinox maximum, the DW1 amplitudes were larger in even years (stratospheric eastward phases) compared to the amplitudes during odd years (stratospheric westward phases). The zonal mean zonal wind in the MLT was also more westward at the equator during the eastward phase of the stratospheric QBO, accompanied by the enhancement of eastward winds in the mid-latitude regions. This latitudinal wind distribution further increases the meridional gradient of the zonal mean zonal wind (Wu et al., 2008), and it can result in the interannual variations in the migrating diurnal tide (McLandress, 2002). Moreover, the magnitude of the QBO in the diurnal tidal amplitudes observed by SABER and TIDI on TIMED has been reported by Xu et al. (2009). The QBO signal in DW1 has an amplitude of 3K in temperature, as well as 7 m/s (9 m/s) in meridional wind in the Northern (Southern) hemisphere, with a period of 24–25 months. The DW1 amplitudes were found to maximize when the eastward winds of the stratospheric QBO maximized at 20 hPa.

The aforementioned results suggest influences on the propagation of atmospheric tides by the stratospheric QBO. Numerical model simulations by Mayr et al. (2011) also revealed this mechanism for QBO-modulation of the migrating diurnal tide, revealing the importance of tide-zonal mean flow interaction through linear advection. The results also showed that the QBO-modulation of DW1 in the upper mesosphere was driven by modulated gravity wave momentum deposition. Nevertheless, advection produced with the observed QBO can not reproduce the quasi-biennial variations of the migrating diurnal tide in the GSWM (Hagan et al., 1999). Note that the GSWM is a linearized model and is incapable of generating the nonlinear interaction effect with other tidal modes. With regard to the migrating semidiurnal tide (SW2), the QBO effect is much weaker than that on DW1 (Pancheva et al., 2009; Wu et al., 2011).

In addition to the migrating tides, it has been reported that the diurnal eastward-propagating wavenumber 3 (DE3) tidal component also has the potential to be modulated by the stratospheric QBO (Forbes et al., 2008; Oberheide et al., 2009); however, the stratospheric QBO has opposite effect on the DE3. The DE3 is 10–15% larger during the stratospheric QBO eastward phase. Oberheide et al. (2009) reported the temporal variation of DE3 corresponded to that of the stratospheric QBO. By HME (Hough Mode Extension) fits, the temperature and zonal wind DE3 amplitudes corresponding to the first symmetric Hough mode showed variations modulated by the QBO. However, the generation mechanism for QBO-modulation of DE3 was attributed to the mesospheric QBO related changes in tidal vertical wavelength (Oberheide et al., 2009). From numerical simulations, Ekanayake et al. (1997) found that the eastward propagating tides have the tendency to be larger in westward background wind fields. These westward background winds act to Doppler shift the vertical wavelengths of eastward propagating tides to larger values. Tides with longer vertical wavelengths are more resistant to dissipation and can propagate vertically to higher altitudes.

The ionospheric QBO has also been of interest in the ionospheric community. There are many studies showing the strong similarity between the ionospheric and stratospheric QBO (Chen, 1992; Echer, 2007; Wu et al., 2009; Fernández et al., 2014; Tang et al., 2014). For example, Wu et al. (2009) used the FORMOSAT-3/COSMIC data in the ionosphere and the TIDI data in the MLT region to examine the DE3 and DW2 tidal components. The study suggested that the stratospheric QBO signature was being transmitted upward to produce variations in the MLT region and the ionosphere. Tang et al. (2014) provided evidence of the ionospheric response to the QBO using GPS TECs. During solar maximum, there is a QBO-like signal with period of 22–34 months confined at ±20° geographic latitude with amplitudes near 5 TECu, which might be caused by stratospheric QBO modulation of tidal winds in the E-region. However, It had been suggested by Fernández et al. (2014) the ionospheric QBO is attributed by the EUV solar flux. Chang et al. (2016) provided evidence that the ionospheric QBO is related to both the O/N_2 variations driven by tidal breaking in the MLT region, as well as solar activity during solar maximum.

To summarize, further investigations into the source of the ionospheric QBO should be made. As a prominent variation, the primary mechanism driving the ionospheric QBO has not yet been conclusively determined and investigated. Also, there has thus far been relatively little research into this question using numerical experiments. In light of these needs, the two major research questions to be addressed in this study are as follows:

1. What are the effects on atmospheric tides in MLT region from solar activity and the stratospheric QBO?
2. What is the main source contributing to the ionospheric QBO? Is it the solar quasi-biennial variations or the stratospheric QBO?

In answering these questions, we hope to better understand the vertical coupling mechanisms in the ionosphere from sources both below and above. Most specifically, to be able to clarify the coupling mechanisms driving the ionospheric QBO. In this research, a numerical experiment using the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) (Richmond et al., 1992) is carried out to answer these questions.

The paper is structured as follows: the first section is background information on this research and the statement of the specific research