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Role of the phase of Quasi-Biennial Oscillation in modulating the influence of SSW on Equatorial Ionosphere

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Abstract

Understanding the coupling of ionosphere-thermosphere (IT) system from the lower atmospheric forcing is one of the primary challenges for the space weather community. The present paper deals with the role of two lower atmospheric processes over the Indian region ionosphere i.e., stratospheric Quasi-Biennial Oscillation (QBO) and Sudden Stratospheric Warming (SSW). The role of QBO in modulating the response of equatorial/low latitude ionosphere over Indian sector to the major SSW events of 2009 and 2013 has been investigated by using combined measurements from meteor wind radar operating over Trivandrum, Global Positioning System (GPS) derived total electron content (TEC), and magnetic field data. The time variation of Equatorial Electrojet (EEJ)-induced surface magnetic field show that the response of EEJ is distinctly different during different phases of the QBO. The peaking time of EEJ and occurrence time of counter electrojet (CEJ) were found to be shifted towards morning/evening sector during the westward/eastward phase of the QBO during the SSW years. The TEC over both the equatorial and low-latitude ionosphere exhibit a similar feature. The tidal components derived from horizontal winds using a meteor wind radar revealed similar shift in their peaking time. These observations clearly vindicate that the phase of QBO plays a crucial role in structuring the equatorial electrodynamics and electron density distribution over low-latitudes during the SSW evens. These results are unique and achieves significance as we are heading towards solar minimum period where forcing from the lower atmosphere is an import aspect of ionospheric variability.

1. Introduction

The ionosphere is the ionized gas in the earth's upper atmosphere sandwiched between the neutral atmosphere and the magnetosphere. Consequently, it is not only affected by the solar wind-magnetospheric processes but also by the processes occurring in the lower atmosphere. The solar ionizing flux and geomagnetic activity, which are considered as the primary drivers of the ionospheric variability, cannot explain a significant portion of its day-to-day variability. The ionospheric variability, not accounted by these main drivers, is approximately 20% during daytime and 33% during nighttime, and these variability were reported to reach as high as 200% over low-latitudes [Chau et al., 2012]. As a result, understanding and forecasting the day-to-day variability of ionosphere has been a challenging task in spite of the concerted efforts over several years. The situation becomes more complex over low-latitudes as the ionosphere therein is not only driven by the processes taking place in the lower atmosphere locally but also by the processes occurring in the high-latitudes. The SSW, which occurs over high-latitude, is one such process that affects the low-latitude ionosphere through changes in dynamics and energetics. Another atmospheric process driven by the upward propagating waves of lower atmospheric origin is the QBO, which is the oscillating mean flow in the equatorial stratosphere (~16-50 km). The effect of QBO is not only confined to the neutral atmosphere but also affects the thermospheric/ionospheric variability.

It has been shown that the large-scale changes in dynamics and energetics during SSW affect the low and mid-latitude atmosphere in more or less predictable way, and has been reproduced by numerical simulations [Pedatella et al., 2012]. It is to be noted that all the studies regarding the response of ionosphere to the SSW have been treated irrespective to the background stratospheric wind conditions/phase of the QBO. In other words, the role of the phase of prevailing QBO in modulating the variability of equatorial ionosphere during the SSW is not explored so far and not been reported yet. In this context, the present study aims at investigating the role of different phases of QBO on inducing variability on the equatorial ionosphere during special geophysical event like the SSW.

2. Database

The EEJ intensity during November-March for the year 2008-2009 and 2012-2013 is obtained from the difference between the horizontal component of the current induced magnetic field at Tirunelveli (8.73°N, 77.70°E, 0.23°N dip lat.) and Alibag (18.5°N, 72.9°E, 10.33°N dip lat.), which are located on and off the EEJ current region, respectively. The GPS derived TEC data have been used to investigate the ionospheric variability.

The horizontal winds in the MLT region were obtained from a collocated SKiYMET (all Sky interferometric METeor) radar operational in Trivandrum.

In order to examine the nature of stratospheric background wind and phase of the QBO, the zonal mean zonal wind from poles to equator at 10 hPa level (~30 km) obtained from National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) have been analysed.

3. Results

Based on the wind at 10hPa, the phase of the QBO has been described as the westward/eastward during 2009/2013 SSW event.

Figure 1 depicts the temporal variation of EEJ current intensity from November to March for 2009 (a) and 2013 (b) SSW event. In order to discriminate the effect of lower atmosphere from the geomagnetic disturbances, the ap indices has been depicted in upper panel of the figure for both the cases. The red curve represents time variation of the polar stratospheric temperature at 10 hPa. It is clear from figure that the anomalies in the behaviour of EEJ began to appear from December onwards (i.e., after day 30) for both the cases. It is well evident that CEJ occurs in a periodic manner after day number 30. The occurrence time of these periodic CEJ events during 2009 event, marked using ovals, appear to be shifted towards morning sector with the progression of days (Figure 1a). The geomagnetic activity was quiet during and around these three days with ap remained ≤ 10. The peaking time of EEJ also displayed a similar shift towards morning sector during this period, which is highlighted by black arrow in the figure. The peaking time of EEJ appeared at ~13 LT around day 50 which gradually shifted with the progression of the days. After the SSW peak, two intense periodic CEJ episodes occurred, which also exhibited a similar pattern as marked by the dotted arrow.

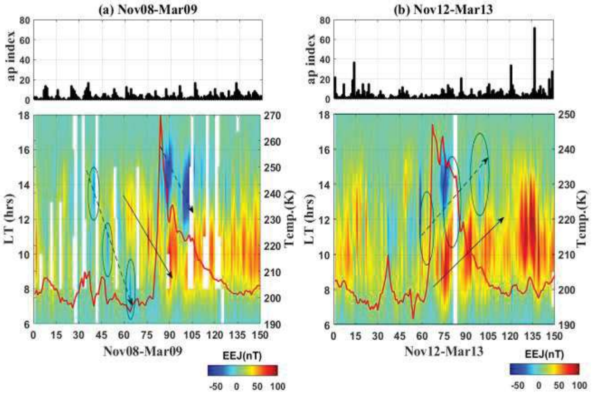

Figure 1. Temporal variation of EEJ current intensity as a function of days from November to March for 2009 (panel a) and 2013 (panel b) SSW event. Arrow depicts the shift in the occurrence time of peak EEJ and CEJ.

In contrast to the SSW event of 2009, a series of CEJ events occurred during the 2013 SSW event, which appeared to be shifting towards evening sector with the progression of the days. The CEJ sets (highlighted by black ovals) began to appear from day 30 onwards, which get intensified during the SSW period. The occurrence of CEJ events exhibited a systematic shift towards evening with day number and indicated by the dotted arrow. It can be noted that the geomagnetic activity was very low during this period with ap<5. Similarly, the peaking time of EEJ is also observed to be shifting gradually towards evening from ~days 75 to 105 (black solid arrow in Figure 1b).

The hourly meridional winds at 94 km are used to estimate the tidal amplitudes and phase in the upper mesospheric region during the period of study. The hourly values of meridional wind at 94 km are subjected to a 4-day running window which is advanced by 1-day so as to construct a composite diurnal cycle. Thereafter, Fourier transform is applied to extract the day-to-day variability of phase and amplitude tidal components. The linearly interpolation has been applied to fill the data gaps present in the meteor radar observations so as to obtain continuous time series of wind. However, the Fourier analysis is not performed for those cases wherein the data gap in the 4-day time series exceed 12 hours. Figure 2 depicts the behaviour of the phase and amplitude of the tidal components (both diurnal and semidiurnal) at 94 km altitudes during November-March period for 2009 SSW event. It is clear from the figure that the phase of the diurnal component showed strong oscillations with a notable feature of phase shifting towards the morning sector. The notable shift in phase of the diurnal tides towards morning sector is observed during days 15-30, 45-70, and 75-105 (highlighted by red dotted lines). Similarly, the phase of the semi-diurnal component also exhibited a shift towards morning from ~day 45-75, but not as clearly as seen in the diurnal component. The amplitude of the diurnal component is reduced considerably from ~day 60-105 and a sudden jump in the semi-diurnal amplitude is observed during days ~75-105. This period, where phase of the diurnal components shows reduced amplitudes and shift towards morning, and enhanced semi-diurnal amplitude is coinciding with the presence of strong CEJ events as seen in Figure 1. Figure 3 depicts the phase and amplitude of the diurnal and semidiurnal tide at 94 km during the SSW event of 2013. The systematic shifting of phase of diurnal and semi-diurnal component towards evening sector during ~day 65-90 can be seen from the figure (marked by red arrows). However, such feature appears more prominently in the diurnal component compared to that in the semi-diurnal components. It is interesting to note that enhanced EEJ and occurrence of CEJ events also display shift towards evening during this time.

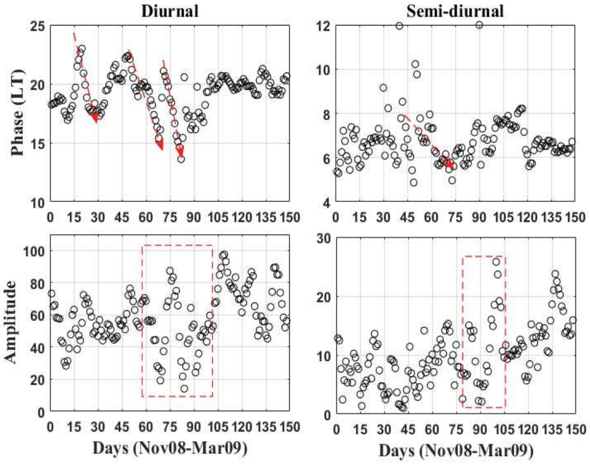

Figure 2. Variation of phase and amplitude of the diurnal and semidiurnal component of meridional wind at 94 km during Nov-Mar for 2009 SSW event.

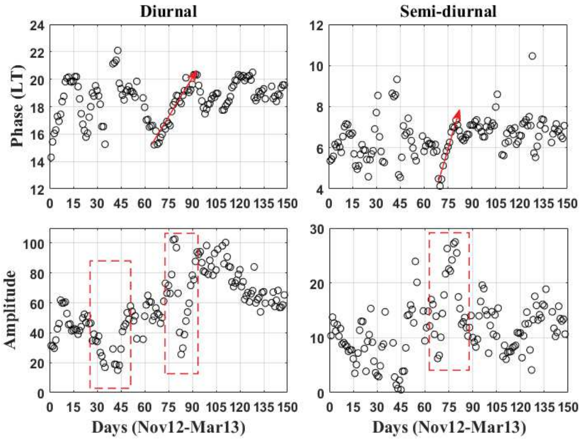

Figure 3. Same as figure 2 but for 2013 SSW event.

Figure 4 depicts the time variation TEC during November to March for 2009 and 2013 SSW event over Bhopal (panel a) and Raipur (panel b). The polar stratospheric temperature at 10 hPa is also depicted over the TEC contour (red line). It is evident from the figure that TEC experienced large perturbations during both the SSW events over the low-latitudes even before the onset of the SSW i.e., from ~day 30. The TEC over Bhopal display shift with the daytime peak and reduced electron density structure appeared to be gradually shifting towards morning sector (shown by black arrow in figure).

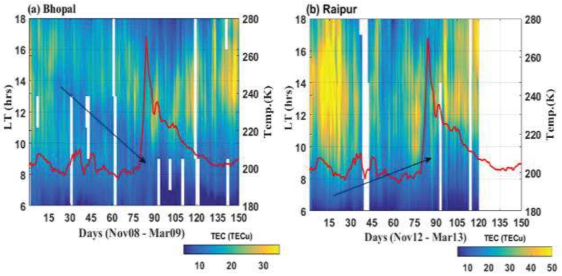

Figure 4. Variation of TEC as a function of the local time and day from Nov to Mar over Bhopal (a) and Raipur (b) for 2009 and 2013 SSW event.

The kind of systematic shift observed in 2009 is not very clearly present during the SSW event of 2013. The shift towards evening sector is more evidently seen during 08-12 LT from ~day 45 (marked by the black arrow). Notably, this effect is just opposite to that observed during 2009 wherein prominent tilt towards morning sector was seen. Further, the effect is seen to be contaminated during 2013 event due to the presence of active geomagnetic conditions after the SSW peak.

3. Discussion and Summary

The novelty of the results presented in this study is the dramatic difference in the response of low-latitude ionosphere to the SSW events of 2009 and 2013, which occurred in different phases of the QBO. The series of CEJ events during the SSW events show systematic shift in their time of occurrence, but opposite in direction during different phases of the QBO. The shift towards early in local time is observed during 2009, whereas, it is directed towards evening sector during 2013 event. The probable causative mechanism for this distinct characteristic during two SSW events is discussed below.

The stratospheric QBO is known to control the upward propagation of gravity waves depending on their phase velocity [Hagan et al., 1999]. The westward/eastward phase of stratospheric QBO filter out the westward/eastward directing waves, providing the passage only to the eastward/westward propagating gravity waves. These gravity waves undergo non-linear interaction with migrating diurnal and semidiurnal tide and modulates the phase and amplitude of the tides [Liu et al., 2008]. Therefore, the enhanced westward waves at upper mesospheric altitudes during the eastward QBO, accelerate the prevailing westward daytime winds therein. This also advances the phase of the semi diurnal tides at this altitude towards evening. The modification in the tides and winds at upper mesosphere due to the increased westward waves will results in an enhancement in the EEJ strength and also shifts its peaking time towards evening. On the other hand, during the westward QBO, more eastward propagating waves reaches at upper mesospheric altitudes and the effect will be exactly opposite to what is observed during eastward QBO. The enhanced strength of the CEJ observed during the SSW event of 2009 supports this argument. Further, the phase shift observed in the diurnal and semidiurnal tide at 94 km towards morning/evening sector during westward/eastward phase of QBO provides credence to this argument. Such a modification in the background winds and tidal structure at upper mesospheric altitudes will cause modification in the ionospheric electric fields and currents therein by the process of ionospheric dynamo [Richmond et al., 1976]. The change in equatorial electrodynamics affect the distribution of entire low-latitude by the process of equatorial ionization anomaly. Thus, the variability of the equatorial and low-latitude ionosphere is closely coupled with the phase of the stratospheric QBO as the latter affects the upward propagation of gravity waves which modulates the lower thermospheric tides.

4. Acknowledgements

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5. References

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