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Electrodynamics of the Low-latitude Thermosphere by Comparison of Zonal Neutral Winds and Equatorial Plasma Bubble Velocity

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ABSTRACT

The coincident observations of nighttime thermospheric zonal neutral winds and equatorial plasma bubble (EPB) drift velocities over Brazil during the October–December,2009 and 2010 are used to examine the coupling relationship between the thermosphere and ionosphere. The EPB zonal drift velocities are estimated using the airglow images recorded by optical imaging system, while the neutral winds are measured by using a bi-static Fabry–Perot interferometer (FPI) experiment deployed at two stations from Brazil. The results reveal the similar pattern in the EPB drift velocities and zonal neutral winds motion during the nighttime and night-to-night thereby illustrating a fully developed F-region dynamo. However, background natural winds also exceed EPBs velocities especially during the development phase of EPBs illustrating that F-region dynamo is not fully activated.

Key words: Equatorial plasma bubble, neutral winds, drift velocity, Fabry-Perot Interferometer, F-region dynamo.

INTRODUCTION

The equatorial ionosphere-thermosphere structure is governed by the geometry of the Earth's magnetic field and the mutual interactions between the plasma, electrodynamics, and the neutral atmosphere (Kelley 1989, Rishbeth 2000). The large horizontal pressure gradients in the early evening produce the strong neutral wind velocities in the evening to midnight period. So the nighttime thermospheric neutral wind becomes particularly important to thermospheric and ionospheric dynamics through the F-region dynamo, which has been described by the several authors based on observations obtained from ground-based experiments (Martinis *et al.* 2001, Meriwether *et al.* 2011).

Rishbeth (1971) reported that the zonal neutral winds during the post-sunset in the low-latitude F-region ionosphere create nearly vertical polarization electric fields that cause the zonal plasma drift with a velocity nearly equal to the winds. As a result, the ion drag on the wind reduces so that high wind speeds can be increased. The presence of plasma in perpendicular to the magnetic field lines can greatly influence the motion of the neutral atmosphere (Maruyama *et al.* 2003). The ion drags thus produced on the naturals can have far reaching consequences in the upper atmosphere.

The plasma zonal drifts at low-latitude F-region ionosphere have been measured using a variety of ground-based and satellite-based techniques (Mendillo & Baumgardner 1982, Taylor *et al.* 1997, Kudeki & Bhattacharyya, 1999, Fejer *et al.* 2005, Makela 2006, Chapagain *et al.* 2011, 2012a). Many of these studies have focused on the magnetic-zonal motion of the ionospheric large-scale irregularities, or equatorial plasma bubbles (EPBs). Since the bubbles are strongly aligned along the magnetic field lines and their zonal drifts depend on magnetic flux-tube integrated ionospheric parameters. Therefore, the EPB zonal motion is important to the study the electrodynamics of the thermosphere. The nightglow emission of 630.0 nm measurements is important to study the electromagnetic coupling along the magnetic field lines and understanding the electrodynamics of the thermosphere (Otsuka *et al.* 2005). In addition, Chapagain *et al.* (2012b, 2013) reported a similar pattern of nighttime and night-to-night variations in the EPB zonal drift velocities and zonal neutral winds motion.

In this paper, we compare the nocturnal zonal drift velocity of EPBs with the background thermospheric wind through the co-located observations of the OI 630.0-nm nightglow emission and thermospheric wind measurements. The main purpose of this work is to address how neutral dynamics control the electrodynamics of the low-latitude thermosphere by comparing the neutral winds motion with EPBs drifts velocity.

INSTRUMENTATIONS AND METHODOLOGY

The data used in this study is obtained from the part of the research project when working as a postdoctoral research associate in University of Illinois at Urbana-Champaign with collaborative research project with Clemson University, USA. The neutral winds data are measured from a bi-static Fabry–Perot interferometer

(FPI) to study the neutral dynamics in thermosphere where as optical imaging data are used to study two-dimensional spatial and temporal properties of ionospheric depletion structure. This combined data set from these co-located instruments is used for a detailed study of the low-latitude thermosphere/ionosphere (TI) system including estimation of the conducive conditions to the development of irregularities as well as their effects on the nighttime equatorial F region ionosphere.

The zonal neutral winds were obtained from a bistatic Fabry-Perot interferometer (FBI) deployed at Cajazeiras (geographic: 6.87°S, 38.56°W; geomagnetic: 7.11°S, 33.24°E) and Cariri (geographic: 7.38°S, 36.53°W; geomagnetic: 8.34°S, 34.96°E) from Brazil, while the EPBs were measured using by an all-sky imager located at Cajazeiras during October 2009-December 2010. Fig. 1 shows the map of location of the sites of the instrumentations from Cajazeries (Caj) and Cariri (Car), Brazil near the geomagnetic equator. The circle represents the field of view (FOV) covered by the imager at a reference altitude of 250 km, which is the assumed altitude of airglow emissions. The separation between these two sites is ~230 km, which is comparable to the 630.0-nm nightglow centroid height of ~250 km. The details of the instruments and analysis procedure used to estimate neutral winds is given in Meriwether *et al.* (2011) and Makela *et al.* (2011), respectively, and is only briefly summarized here.

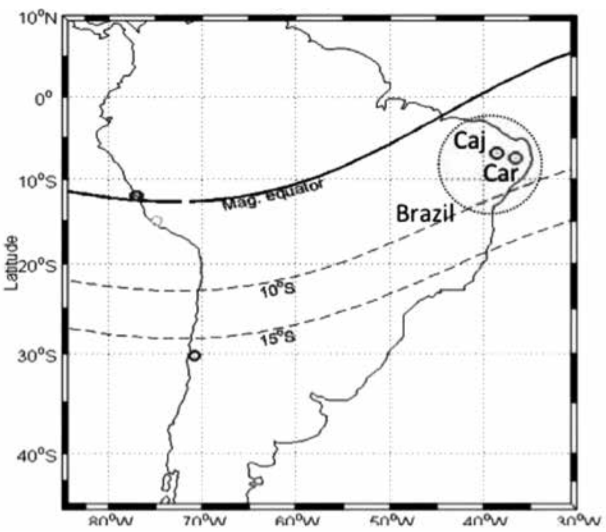

Fig. 1. Map showing the sites locations near geomagnetic equator from Brazil at Cajazeries (Caj) and Cariri (Car). The circle represents the field of view covered by the optical imaging system.

Wind Measurements

The nighttime thermospheric winds are determined from the estimation of the Doppler shifts in the observed 630-nm interference image pattern (Chapagain *et al.* 2012a). This nighttime OI airglow emission is generated through the dissociative recombination of O_2^+ (Link & Cogger 1988) to O + O(^{1}D) with a peak emission altitude of 250 km. This emission rate depends on both the electron density and the neutral O_2 density. The FPI measurement of the line-of-sight Doppler shift requires a pointing system mounted within the dome.

The interpretation of the wind data for the meridional and zonal wind motions depends on the observing mode implemented at the two FPI stations. In the first mode, the two stations operate independently from one another. Each FPI makes sequential observations in the cardinal directions (north(N), east(E), south(S), and west(W)). The spatial separation between the N and S or E and W directions for each cardinal direction of zenith angle of 45° for a nightglow layer with a centroid altitude of 250 km is ~500 km. The geographic locations of the east look direction measurements were used for the analysis (Chapagain *et al.* 2012a). The second observing mode implemented relies on the two FPI systems operating in tandem, making bi-static measurements of the same common volume in the thermosphere. The common-volume measurement points to the north (CVN) and south (CVS) are measured at an zenith angle of 34.4º. The look directions from the two sites at the CVN and CVS points are orthogonal to one another, allowing for the estimates of the vector horizontal wind at each point (assuming zero vertical wind).

In this study, we want to compare the neutral wind velocity to the drift velocity of equatorial plasma bubble (EPBs). EPBs typically drift in the geomagnetic zonal direction. However, the horizontal wind motions estimated from the FPIs are typically presented in the geographic coordinate system (Chapagain *et al.* 2012a). To obtain the neutral winds along the geomagnetic latitudes, we estimated the averaged meridional winds from north and south look directions and its components along the geomagnetic latitude were taken at the point in the east look direction.

EPB Velocity Measurements

In order to calculate the EPB drift velocity, we use OI 630.0-nm airglow images collected by imager deployed to Cajazeiras. The individual images were processed by first spatially registering the images using the star field. After removing the stars from the images using a point suppression methodology, the images were projected onto geographic coordinates assuming an airglow emission altitude of 250 km. It provides the coverage of the spatial structure in the ionosphere over both sites for comparison to the neutral wind measurements provided by the FBI instruments.

Once the images were projected into geographic coordinates, a Keogram representation of the sequence of images obtained on a given night was constructed by taking slices through the images along a line of constant geomagnetic latitude. The geomagnetic latitude used was chosen to match the geomagnetic latitude of the FPI measurements being used (either the cardinal east point or the CVN point when the common volume mode was used). The intensity along this line for each image obtained on a night under study was then stacked up in time to create the Keogram representation. The average intensity of the images as a function of time was removed from the Keogram to enhance the EPB structures, which appear as dark bands in the Keogram representation. A correlation analysis was run on the resultant data to estimate the drift velocity (Yao & Makela 2007).

RESULTS AND DISCUSSION

A coincident observation of OI 630.0-nm airglow image measurements and FPI wind observations during September 2009 - December 2010 were selected. Only 57 of these nights had coincident measurements with imager and FPI out of 78 total nights of observations. We have presented here only the selected nights of observations, to compare the EPBs drift velocities with neutral winds, which are representative of the overall observations.

Consistency of Wind and EPB Velocity

We plot zonal neutral wind and EPBs zonal drift velocities as a function of local time for four selected nights of measurements as shown in Fig. 2. These comparisons illustrate the general result that the zonal drift velocity of the EPBs matches well with the zonal neutral wind speeds. In these plots, positive values correspond to eastward speed, while the error bars are the uncertainty in the measurements of the wind speeds determined by the analysis routine (Makela *et al.* 2011). The largest controlling factor of this uncertainty is the intensity of the 630.0-nm airglow emissions.

These plots are the examples of consistency of winds and EPB drift velocity. The results clearly show the similar pattern of night time variations of winds and EPB drift velocity, they excellent match to each other with increasing early evening hour (from ~18:30 to 21:30 LT), attaining peak values of range of ~100-150 m/s at ~20:00-21:00 LT and then rapidly decrease after ~22:00 LT with minimum around midnight and thereafter remain close to zero near the predawn hours on the most nights. The EPBs sometime disappear after local midnight and all will completely disappear around early morning hours.

The next interesting feature of these plots is night-to-night variations, for examples, peak values of both winds and EPBs velocities are ranges from ~100 m/s to ~150 m/s. The dynamics of neutral wind exactly followed by the plasma bubbles suggesting that F-region dynamo is fully developed. Such consistencies between these two velocities were observed around 40% of total coincidence measurements.

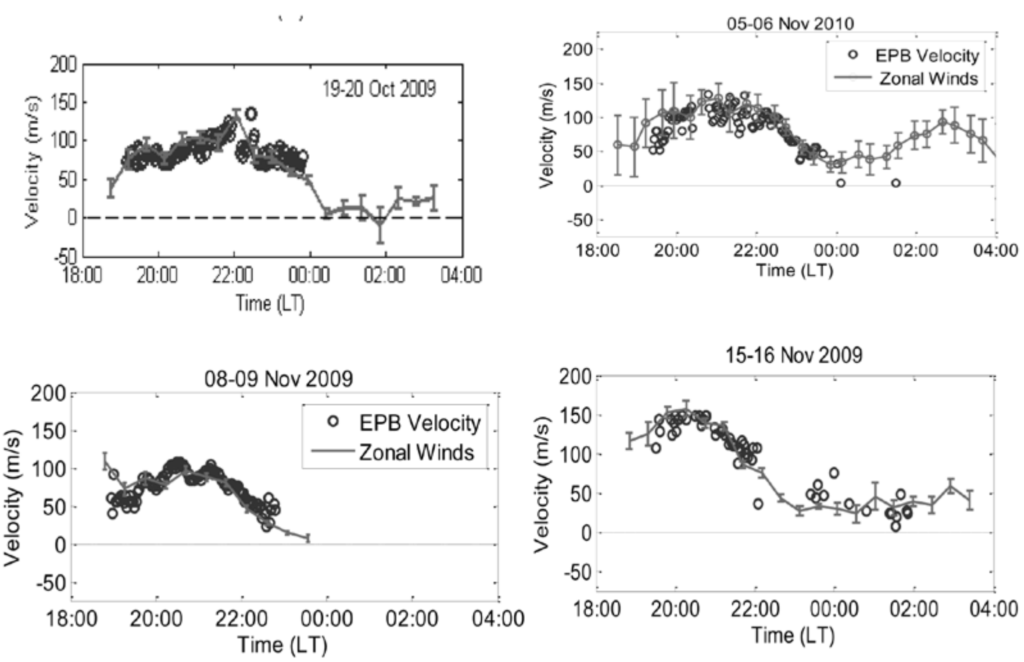

Fig. 2. Comparisons of zonal neutral winds and EPBs drift velocity as a function of local time (LT) from selected 4 nights of the measurements.

The increase in early evening eastward zonal speeds from nearly zero to ~160 ms^{-1} between 18:30 LT and 22:00 LT can be understood to be caused by the reduced ion drag arising from the lower plasma density caused by the recombination of the *F* region ionosphere that is also combined with the uplift of the *F* layer to higher altitudes due to the dynamo electric field. The neutral winds in the *E* and *F* regions produce electric fields that drive plasma drifts in the ionosphere. During the nighttime, the *E* region dynamo is neglected as the ionosphere decays rapidly and only the *F* region dynamo contributes significantly, particularly during the post-sunset local time period. The *F* region dynamo developed during the nighttime plays a key role to produce an enhanced eastward plasma drift by the action of the eastward neutral winds.

As previous studies have reported (Eccles 1998, Martinis *et al.* 2003), the eastward plasma drift is nearly the same in speed as the neutral wind, resulting in a negligible ion drag force. This causes the nighttime neutral wind speed to increase as the plasma density decays due to the combined effects of recombination and uplift. Our finding from coincident observations indicates that the behaviours of night-to-night variations of the neutral dynamics are very closely followed by the EPBs suggesting that the state of the *F* region dynamo is close to being fully activated. This suggests that the drift velocity of the large-scale plasma depletion structures observed off the geomagnetic equator is indicative of the background plasma motion. This exemplifies that the nighttime *F* region dynamo mainly due to the contribution of the local neutral winds is expected to dominate the electrodynamics off the magnetic equator. However, it should be remembered that the dynamo polarization electric fields are mapped along the entire magnetic field line and are also generated by the neutral wind in the geomagnetic conjugate hemisphere connecting the geomagnetic field. Hence, the neutral wind in the conjugate hemisphere is required in order to fully characterize the dynamo polarization electric field all along the flux tube.

Discrepancy in the Early Evening Velocities

Fig. 3 reveals examples of discrepancies between the early night EPB drift velocities and zonal neutral winds. For instance, during the nights of 17-18 December 2009, and 6-7 November 2010, the magnitudes of the early night EPBs drift velocities are smaller than those of the neutral winds. On 17-18 December, the neutral winds are ~100-175 m/s between 19:30 to 21:30 LT, while the EPBs drift speed during this same time period are ~60 -130 m/s, lagging behind to the neutral winds by ~30-60 m/s.

Similar discrepancies were observed on 6-7 November 2010, when EPBs exhibit velocities of ~5-130 m/s in the early evening (before ~20:00 LT), while the neutral wind peaks at a value of ~150 m/s. Such early night discrepancy of EPBs velocities from the neutral winds at least for one hour have been observed about 30-35% of total nights of observations. These discrepancies range from ~10 m/s to 100 m/s. However, after midnight, these parameters exhibit consistent characteristics and magnitudes. Such discrepancy is especially during the development phase of EPB, where the zonal velocity lags behind the neutral winds with significantly with large values.

Several examples of EPB speed being slower than wind in the evening especially during the explosive development phase of the depletion structures, the motion of the EPBs and the ambient plasma drift velocities are not equal and that is the zonal speeds of the EPBs lag behind the ambient plasma zonal drifts or the zonal neutral wind motions. Similar variations of the plasma drift velocity with the background zonal neutral winds, but with different magnitude, in the early evening was reported by Liu *et al.* (2009) from a study of DE-2 satellite data. They showed that the zonal neutral wind and plasma drift velocities increased eastward between 19:00 LT and 22:00 LT with the peak value of plasma drift velocity in the order of 100 ms^{-1}, while the speed of the winds were up to ~150 ms^{-1}. Our results also exhibit smaller drift velocities of the EPB than that of the neutral winds before 22:00 LT on several nights.

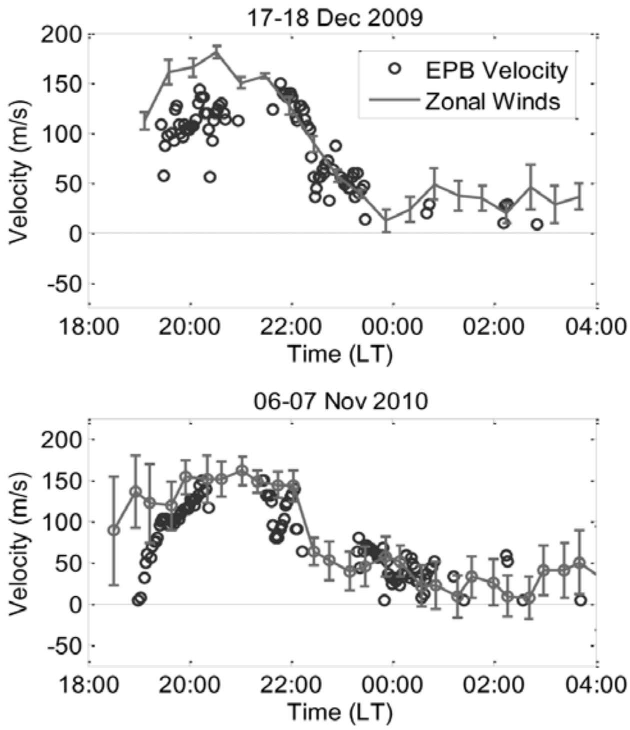

Fig. 3. Comparisons of zonal neutral winds and EPBs drift velocity as a function of local time (LT) from selected 2 nights of the measurements illustrating the discrepancies of early night of EPBs from neutral winds.

The lag of the EPBs velocity compared to the background neutral winds can be ascribed mainly due to vertical polarization electric fields created inside of the EPB during its development phase (Huang *et al.* 2010) or by the *F*-region dynamo not being fully activated in the early evening hours. If the F-region dynamo would not be fully developed, causing the EPB drift velocity to be smaller than that of the background neutral winds.

Latitudinal Gradient of Zonal Neutral Winds

The zonal wind speeds were estimated from CVN and CVS mode from two latitudes as shown in Fig. 4 (top) in processed image of optical imaging system. The neutral winds estimated from two latitudes were plotted in Fig. 4 (bottom). The results clearly shows that the wind measured from the CVN mode closer to the magnetic equator are slightly larger than that from CVS mode, away from geomagnetic equator, especially before midnight period illustrating the latitudinal gradients of the zonal neutral winds. The regions of CVS lies in the Appleton anomaly region, where concentration of ambient plasma is maximum, consequently, the neutral winds motion reduces due to the ion drag forces experienced by the neutrals.

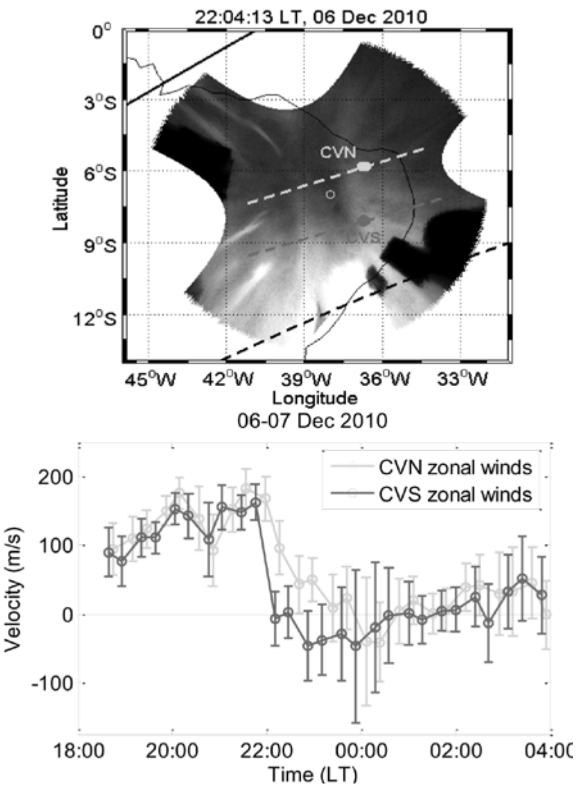

Fig. 4. Processed image measured by optical imaging system illustrating the points of CVN and CVS mode of winds calculations (Top). Comparisons of zonal neutral winds measured in CVN and CVS mode at two different latitudes (Bottom).

CONCLUSIONS

The coincident measurements of the thermospheric zonal neutral winds and EPB zonal drift velocities over northeastern Brazil provide the relationship between the thermosphere and ionosphere near the equatorial regions. The results illustrate a number of interesting features as followings:

- The magnitudes of the EPBs drift velocities and the neutral winds show an excellent agreement (~80% of the total events), especially after 23:00 LT, illustrating that the *F*-region dynamo is generally fully activated.
- The early evening observations on several nights show that the EPB drift velocities are typically slower than that of the background neutral winds implying that the *F* region dynamo is not fully activated during the development phase of EPBs.
- The results reveal the latitudinal gradients of the zonal neutral winds motion with decreasing the wind motion at the higher latitudes.
- The coincident measurements of optical imaging system and FPI neutral winds can be used to examine the change in behaviour of the *F* region dynamo with the solar cycle. It is also a potential field to study latitudinal gradients of neutral winds using data derived from North or South look directions FPI measurements.

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