Modeling the Zonal Drift of Equatorial Plasma Bubbles

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ABSTRACT

Equatorial plasma bubbles are the most significant disturbances in the nighttime low-latitude ionosphere and cause radio scintillation. Quantification of the zonal drift of plasma bubbles with respect to local time, solar radio flux, longitude, season, and geomagnetic activity is urgently needed for the purpose of forecasting bubble locations and scintillation, but such quantification has not been established. In this study, we create an empirical model of the zonal drift of plasma bubbles based on measurements of the Jicamarca incoherent scatter radar and the C/NOFS satellite. The model provides local-time distribution of the zonal bubble drift at any longitude and latitude. The model output is in a good agreement with observations.

1. INTRODUCTION

Equatorial plasma bubbles are mostly generated near the post-sunset terminator and then move eastward. This movement of plasma bubbles in the east-west direction is termed the zonal drift. The typical zonal drift speed is 50-200 m/s before midnight. Plasma bubbles can last for several hours and move over hundreds of kilometers (even more than 1000 km) in the zonal direction. Ionospheric irregularities within equatorial plasma bubbles produce radio signal scintillation which causes degradation or disruption of communication, navigation, and surveillance systems. The zonal drift determines the location of plasma bubbles after they are generated and is the key factor for predicting where scintillation will occur at a later time.

The objective of this effort is to develop an empirical model of the zonal drift of plasma bubbles. We use measurements of the Communication/Navigation Outage Forecasting System (C/NOFS) satellite to determine the zonal drift velocities of plasma bubbles. C/NOFS is a low-inclination satellite that flies along, or close to, the magnetic equator and can detect the same plasma bubbles over successive orbits if the bubbles last many hours [*Huang et al*., 2011, 2013]. The drift speed of plasma bubbles can be accurately determined from the change of the longitude of the bubbles. The statistical patterns of the zonal plasma drift measured by the Jicamarca incoherent scatter radar [*Fejer et al*., 2005] are also used for the model development.

2. Examples of Zonal Drift of Plasma Bubbles

We first present examples of plasma bubbles observed by C/NOFS. Figure 1a shows the case on 23 August 2011. In the top panel, the solid blue line represents the magnetic equator, the red lines represent the latitude of C/NOFS during three successive orbits, and the dashed magenta lines, labeled on the right, represent the corresponding C/NOFS altitude. The next three panels depict the ion density measured by the planar Langmuir probe on board C/NOFS. Three plasma bubbles, marked by B1, B2 and B3, were detected by C/NOFS in the given longitude range during each orbit. The ion density is plotted as a function of geographic longitude to show the change of the location (longitude) of the plasma bubbles during different orbits. The plasma bubbles moved eastward from one orbit to next. Figure 1b shows the case on 12 April 2011. There are nine plasma bubbles in this case. The direction of the bubble drift depends on local time. In Figure 1a, the plasma bubbles were in the evening sector and moved eastward. In Figure 1b, the plasma bubbles were in the post-midnight sector, and the drift velocity was relatively small. In particular, when bubbles B1-B5 approached dawn, they started to move westward.

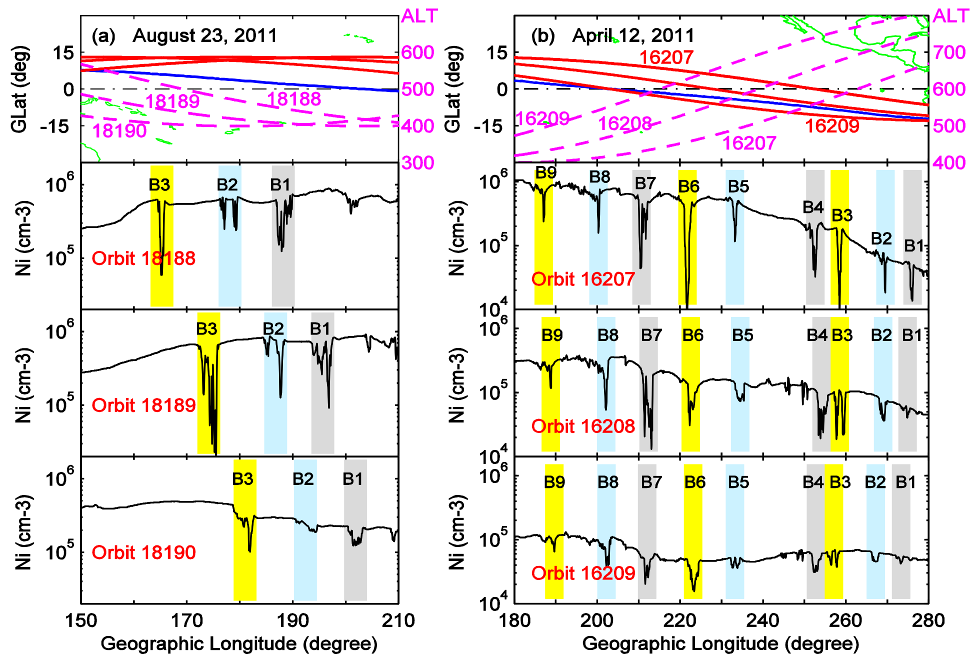

Figure 1. Equatorial plasma bubbles detected by the C/NOFS satellite over three successive orbits on 23 August 2011 and 12 April 2011, respectively.

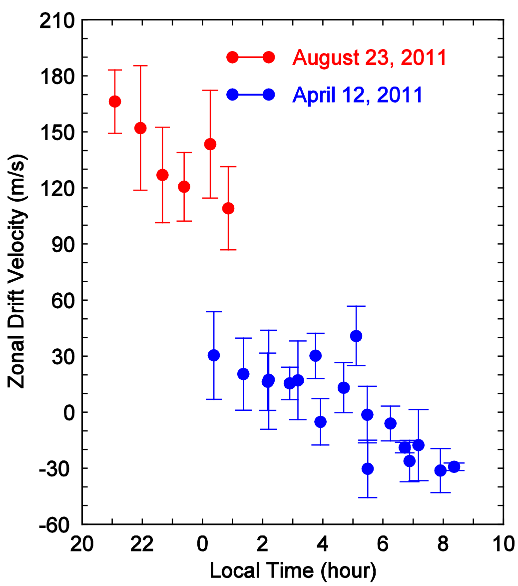

Figure 2. Zonal drift velocity of plasma bubbles measured by C/NOFS on 23 August 2011 and 12 April 2011.

We have created a computer program to make correlation analysis of a bubble between two orbits and calculated the drift velocity and standard deviation. We have used the IGRF model to map the drift velocity to the magnetic equator. All drift velocities given below are the values at the magnetic equator. Figure 2 shows the drift velocities of the bubbles in the cases of Figure 1. The drift velocity was large in the evening sector and decreased at later time. The plasma bubbles still existed near dawn but drifted westward.

3. Model Output and Comparison with Observations

We have searched C/NOFS ion density data over May 2008-June 2013 and visibly examined each orbit of the ion density plots. We only select the plasma bubbles that are well defined and have clear correspondence between successive orbits, similar to those shown in Figure 1. We use the C/NOFS data to determine the variation of the bubble drift on longitude and season. Beside C/NOFS data, we have also used other data in the model development. The dependence of the zonal drift on solar radio flux is taken from the study of *Fejer et al*. [2005], and the dependence of the zonal drift on magnetic latitude is taken from the study of *England and Immel* [2012].

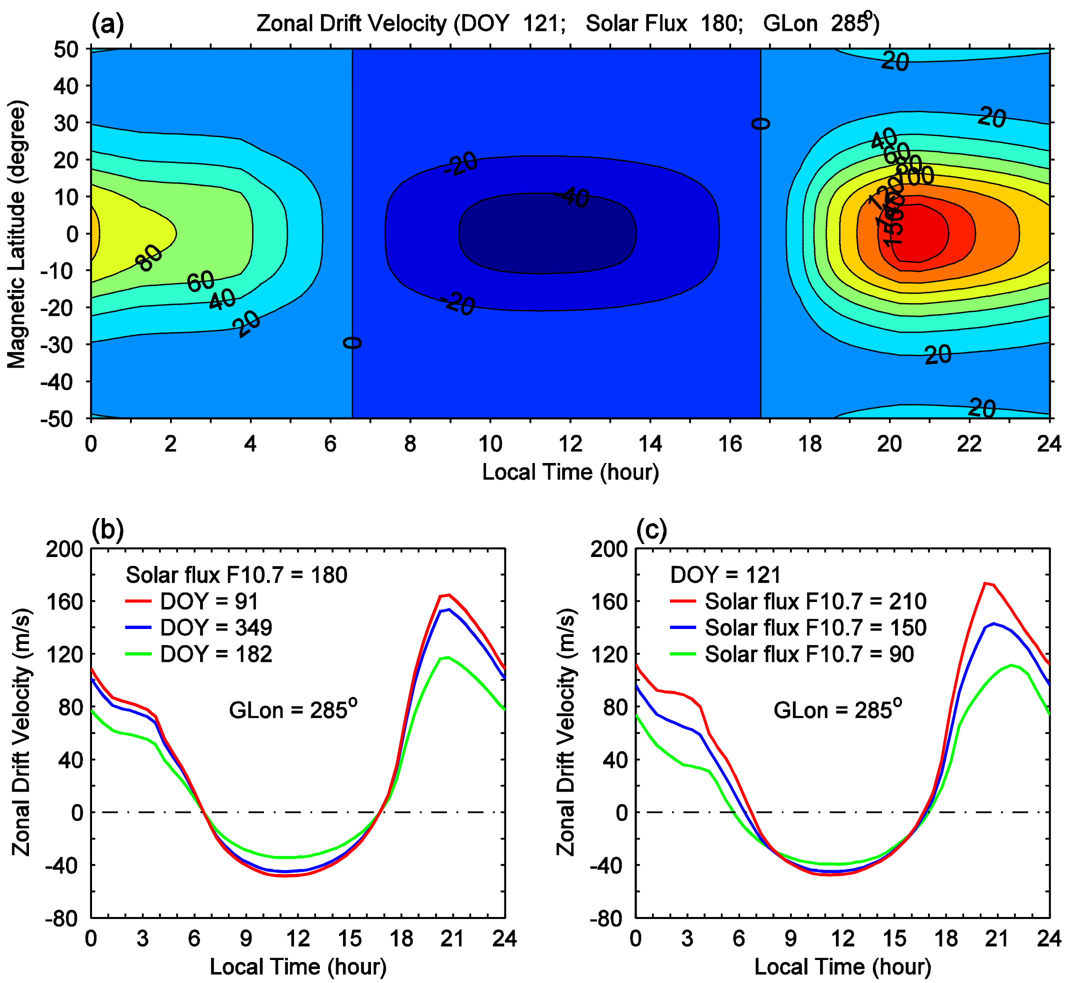

Figure 3. Output of the empirical model of the zonal drift velocity of plasma bubbles. (a) Latitude-LT distribution of the zonal bubble drift. (b) Dependence of the zonal bubble drift on season. (c) Dependence of the zonal bubble drift on solar flux.

The input parameters of the drift model are solar radio flux at 10.7 cm, day of year (DOY), geographic longitude, and magnetic latitude. Figure 3a shows the variation of the zonal bubble drift with local time and magnetic latitude. The drift velocity is westward during daytime and eastward at night and decreases toward higher magnetic latitude. Figures 3b and 3c show the dependence of the drift velocity at a given longitude (285^{o} at Jicamarca) on season and on the solar flux, respectively. In Figure 3b, the solar flux is taken to be 180. The drift velocity is large on April 1 (DOY=91) and December 15 (DOY=349) and small on June 1 (DOY=182). In Figure 3c (on May 1, DOY=121), the drift velocity increases with the solar flux, and the reversal of the zonal drift near dawn shifts towards later local time with higher solar flux level.

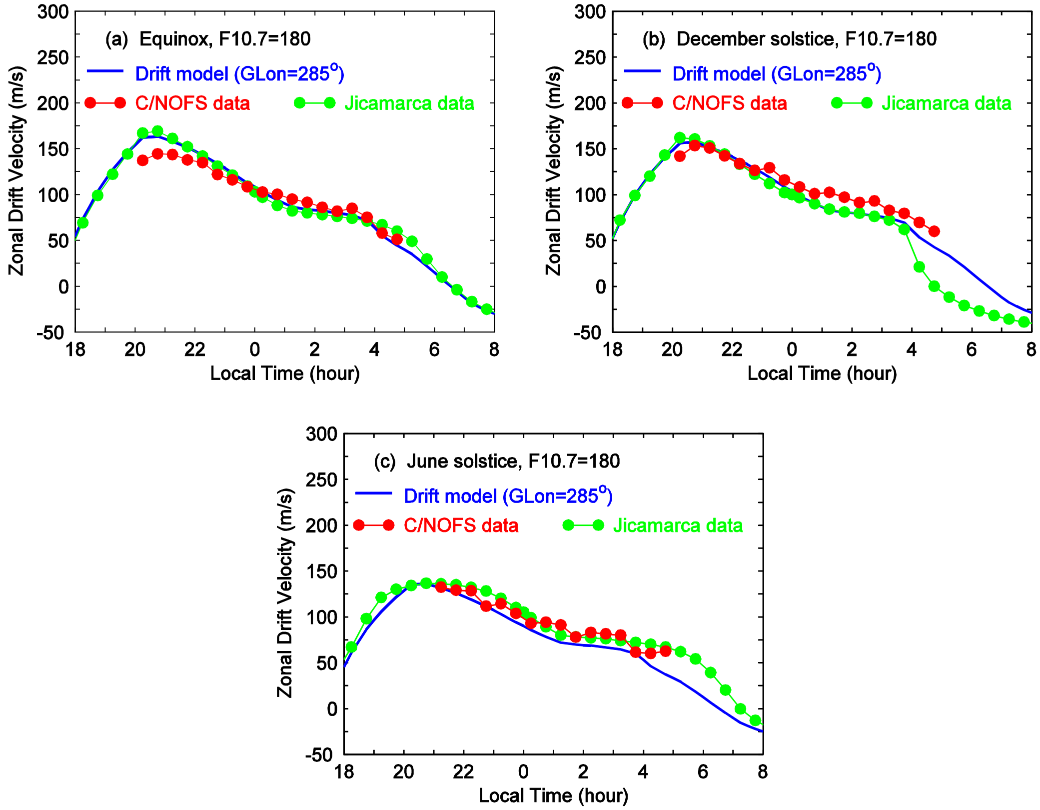

Figure 4. Comparison of the zonal bubble drift of the empirical model with observations from the Jicamarca incoherent scatter radar and the C/NOFS satellite.

We now compare the drift model with observations. The drift velocity data of plasma bubbles observed by C/NOFS are averaged over three seasons: Equinox (March, April, September, October), June solstice (May-August), and December solstice (November-February). Because we want to compare with Jicamarca radar measurements, we normalize the bubble drift velocity to the solar flux level of 180. The drift velocity of the empirical model is taken at the same solar flux level and also averaged over the three seasons. The longitude is taken to be 285^o, the Jicamarca longitude. The blue solid line in Figure 4 represents the model output, the green dots represent the average plasma drift at Jicamarca [*Fejer et al*., 2005], and the red dots represent the C/NOFS data. It is clear that the model zonal drift coincides well with the observations.

4. Summary and Discussion

We have constructed an empirical model of the zonal drift velocity of equatorial plasma bubbles on the basis of observations of the C/NOFS satellite and the Jicamarca incoherent scatter radar. The input parameters of the model are solar radio flux, day of year, geographic longitude, and magnetic latitude. When the input parameters are specified, the model produces the local-time distribution of the zonal bubble drift in the magnetic latitude range of ±50^o. The variations of the zonal bubble drift with solar radio flux, season (DOY) and magnetic latitude are well reproduced. The model output is in good agreement with observations.

On the other hand, some discrepancies between the model and observations exist. As can be seen in Figures 4b and 4c, the modeled drift velocity departs from the radar data between 0400 and 0800 LT for December solstice and June solstice. The zonal drift of plasma bubbles is in general very close to the zonal drift of the background plasma, but difference may occur under some conditions. The bubble drift velocity (the red dots in Figure 4) is not exactly the same as the zonal plasma drift (the green dots in Figure 4). One possible cause is that the C/NOFS data plotted in Figure 4 are taken at all longitudes but not specifically near Jicamarca. Longitudinal variations of the zonal plasma drift and the zonal bubble drift are poorly understood, and different patterns are derived [*Huang et al*., 2010; *Fejer et al*., 2013]. The longitudinal variation of the zonal bubble drift used in the current version of the model is based on the average distribution of the C/NOFS data over all seasons, and the dependence of the longitudinal variation on season has not been considered. In addition, the effect of geomagnetic activity on the zonal bubble drift has not been included. We plan to study these issues in the future.

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