Longitudinal and seasonal variation of the equatorial flux tube integrated Rayleigh-Taylor instability growth rate

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Abstract Using the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM), the ionospheric Rayleigh-Taylor instability growth rate is calculated. The seasonal and longitudinal variations of the growth rate from the TIEGCM appear to match that of the spread $F$ observed by various satellite missions. The growth rate is strongly dependent on the angle between the sunset terminator and the geomagnetic field line near the magnetic equator. The TIEGCM simulations with nonmigrating tides show the zonal wave number 4 structure in the Rayleigh-Taylor instability due to the inclusion of the nonmigrating diurnal eastward zonal wave number 3 and semidiurnal eastward zonal wave number 2 tides.

1. Introduction

The Rayleigh-Taylor (R-T) instability is main cause for the occurrence of plasma bubbles in the equatorial ionosphere. Plasma bubbles have strong seasonal dependence and longitudinal variations as shown by satellite observations [Burke et al., 2004a, 2004b; Stolle et al., 2006; Su et al., 2006; Gentile et al., 2006] and ground-based observations. Tsunoda [1985] showed that seasonal and longitudinal variations are closely associated with angle between the sunset terminator and the Earth magnetic field line at the geomagnetic equator. When the terminator is parallel to the field line, the occurrence is highest. That is understandable because when the terminator and field line are parallel, the two conjugate points will fall into the sunlight shadow simultaneous and the $E$ region will disappear at the same time allowing the $F$ region dynamo to maintain a high potential difference and larger upward ion drift near the sunset. Fejer et al. [1999] have shown that the prereversal enhancement (PRE) is directly related to the growth rate of the R-T instability. The geometry of solar location relative to the magnetic field line (declination) can be easily calculated for different seasons and longitudes. As Burke et al. [2004b] have shown that the high occurrence of the spread $F$ mostly coincides with the time when the sunset terminator parallel to the field line.

The occurrence of equatorial spread $F$ also depends on other factors including the neutral winds. Neutral winds are related to tides, planetary waves, gravity waves, and equatorial dynamo. Because of this complexity, the R-T instability can be highly variable. To assess the R-T instability, one can calculate the R-T growth rate [Sultan, 1996; Haerendel et al., 1992; Basu, 2002]. Because of the equal potential along the field line, the growth rate calculations are field-line integrated. Over the years, a variety of the models have been used to estimate the R-T growth rate. For example, Luo et al. [2012] used International Reference Ionosphere and horizontal wind model to calculate the growth rate. Recently, Carter et al. [2014a, 2014b] used the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) to calculate the R-T growth rate and successfully showed that the R-T rate is affected by geomagnetic activity. Because the TIEGCM is a comprehensive ionosphere model with many options, more can be done with the model to calculate the R-T growth rate. In this paper, we use the model to examine the seasonal and longitudinal variations of the R-T growth rate and compare that with the occurrence of the equatorial spread $F$. Because the TIEGCM model has the electrodynamics and ion neutral interaction, it is very suitable for investigating the R-T growth rate and the effects of neutral winds. The seasonal and longitudinal variations of the R-T growth rate can be the key to understanding the occurrence of the spread $F$ in the equatorial region.

2. Model Calculation of Growth Rate

TIEGCM is a three-dimensional first-principles self-consistent model [Richmond et al., 1992]. It uses nonlinear representation of the coupled thermosphere and ionosphere system including a self-consistent solution of the
equatorial electric field. It solves the momentum, energy, and continuity equations in three dimensions for neutral and ion species. It has 57 constant-pressure levels covering from 97 to 500 km. In this study, we use 2.5 × 2.5° resolution.

At high latitudes, the Weimer ion convection model is used [Weimer, 2005]. The model is driven by the IMF parameters and solar \(F_{10.7}\) index. At the lower boundary 97 km, the GSWM (global scale wave model) can provide both migrating and nonmigrating tides are included [Hagan and Forbes, 2002].

Sultan [1996] gives the field line integrated growth rate with both neutral wind and ion drift as follows [Sultan, 1996, equation (26)]:

\[
\gamma_{RT} = \frac{\Sigma^F_{P,0} - \Sigma^E_{P,0}}{\Sigma^F_{P,0} + \Sigma^E_{P,0}} + \frac{q_r}{v_{eff}} K^f - R_T
\]

where \(\Sigma^F_{P,0}\) is the \(F\) region integrated Pedersen conductivity, \(\Sigma^E_{P,0}\) is the \(E\) region integrated Pedersen conductivity, \(V_p^{i}\) is the integrated ion drift perpendicular to the field line in the upward or downward direction, \(U_p^{i}\) is the integrated neutral wind perpendicular to the field line in the upward and downward direction, \(g_e\) is the effective gravity, \(v_{eff}\) is the effective collision frequency, \(K^f\) is the vertical gradient of the field line integrated electron content in the \(F\) region, and \(R_T\) is the recombination rate. More detail can be found in Sultan [1996].

To calculate the field line integrated growth rate, the field lines were traced from the magnetic equator at different longitudes and altitudes both southward and northward until the lower boundary of the TIEGCM at 97 km is reached. In the formula there are quantities integrated in the \(F\) region and those integrated in both the \(F\) and \(E\) regions. The \(F\) region boundary is set at 200 km. The recombination rate is assumed to be zero as in Carter et al. [2014a]. Because the upper limit of the TIEGCM is at about 500 km, the field line can reach roughly 15° magnetic latitudes in both north and south. First we show the R-T growth rate at ~270 km altitude for different longitudes and local time for different seasons in Figure 1. The top scale 1.3 × 10^-3 s^-1 is roughly equal to 1 over 13 min. In this case the GSWM with both the nonmigrating and migrating tide was used. It is clear that the large growth rate occurs near 18:00 LT. That is understandable because of the large upward ion drift related to the PRE. The upward ion drift is directly related to the R-T growth rate. There are large growth rates during local times other than 18:00 LT, which will be investigated in future research. In this work, we will focus on the growth rate near dusk at 18:00 LT.

The next step is to expand the analysis for the entire year of 2006. In Figure 2a, the R-T growth rates at 18:00 LT for different longitudes and day of year are plotted. The TIEGCM is run with both migrating and nonmigrating tides from the GSWM. The map very much resembles satellite observed spread \(F\) occurrence map [e.g., Burke et al., 2004b; Stolle et al., 2006; Gentile et al., 2006]. The bubble statistics from Gentile et al. [2006] is also...
shown in the Figure 2b for comparison. The similarity shows that R-T growth rate plays an important role in the occurrence of the spread $F$. The seasonal and longitudinal variations of the R-T growth rate can be traced to the variation of the angle between the sunlight terminator and magnetic field at the magnetic equator. The large growth rates are mostly found when the angle is close to zero. The zero-angle location was shown by Gentile et al. [2006] as black lines.

There is a general trend of the maximum R-T growth rate related to the condition when the solar terminator is parallel to the magnetic field. The bubble occurrence mostly follows the same trend. The bubble occurrence and R-T growth rate are different in some way in the longitudinal variations. The R-T growth rate has an enhancement between $\pm 60$ and $\pm 30^\circ$ longitudes. The enhancement in the bubble occurrence is mostly between $-60$ and $40^\circ$ longitudes. The longitudinal variations in June and July are not the same. There are two enhancements in the bubble occurrence ($\pm 180$ and $15^\circ$ longitudes). There is only one enhancement in R-T growth rate ($\pm 90^\circ$ longitude). It should be noted that the occurrence of bubble is low during these 2 months.

We do not expect the R-T growth rate be exactly the same as the bubble occurrence rate. Some of the longitudinal and seasonal variations of bubble occurrence may be due to factors other than R-T growth rate.

### 3. Discussion

There are some discrepancies between the seasonal and longitudinal distribution of the R-T growth rate from the TIEGCM and that of the observed spread $F$. As shown by Burke et al. [2004b] and Gentile et al. [2006] the largest occurrence of spread $F$ does not exactly match the zero angle position between the terminator and magnetic field (Figure 2b). Thus, while the growth rate is important there are other factors...
The TIEGCM simulation of R-T growth rate can be used to study the geomagnetic and solar effects on the growth rate and on the spread $F$. Beyond the dependence of the Sun terminator angle relative to the magnetic declination, nonmigrating tides may also affect the longitudinal variation of the R-T growth rate. To examine the nonmigrating tide on the R-T growth rate, a simulation with the TIEGCM without the nonmigrating tides was performed and shown in Figure 3. The R-T rate with the nonmigrating tides has some distinct longitudinal features (highlighted) around equinoxes (Figure 2a) compared to that without the nonmigrating tides. These features may be related to the nonmigrating tides. The features are close to zonal wave numbers 3 or 4. The well-known diurnal eastward zonal wave number 3 (DE3) mostly peaks near the September equinox, which will show up as wave number 4 feature for the same local time representation of the longitudinal variation. The R-T growth rates shown in Figures 2 and 3 are for 18:00 LT. Another strong nonmigrating tide, the diurnal westward zonal wave number 2 (DW2) tide has large amplitudes around both March and September equinoxes [Wu et al., 2008], which will show as a zonal wave number 3 feature at the same local time. The diurnal eastward zonal wave number 2 (DE2) was not strong in the mesosphere and lower thermosphere according to the NASA satellite TIMED observations [Wu et al., 2008], however, was observed by the CHAMP satellite mostly in June and December [Häusler et al., 2010]. Since the R-T rate calculation is field line integrated, the tidal effect can take place between ±15° latitudes. To examine the TIEGCM results further, the equatorial thermospheric zonal wind (270 km) at 18:00 LT are plotted in Figure 4. The zonal wave number 4 features are prominent during most of seasons except the northern summer. Since the TIEGCM nonmigrating tide in this simulation is based on the GSWM, we also plot the equatorial zonal wind at 98 km in Figure 5, which is at the base of the TIEGCM and mostly is the GSWM output. The wave number 4 structure at 270 km mirrors that at 98 km, which is a result of wave propagation. The wave structure is shifted slightly eastward at the high altitude. That is consistent with Häusler et al. [2010] TIEGCM simulation results, which showed strong DE3 and SE2 (semidiurnal eastward zonal wave number 2) tides during March, September, and December. Both DE3 and SE2 will show as a wave number 4 structure in the same local time longitudinal plot. Both are eastward propagating tides consistent with shift in longitude from 98 km to 270 km as shown in Figures 4 and 5. The enhanced R-T rate (in Figure 2a) appeared at slightly westward locations compared to the enhanced eastward zonal wind at 270 km. That probably because the R-T rate is field line integrated, which includes influence from

Figure 4. Same as Figure 2a but for the equatorial zonal wind (270 km) at 18:00 LT (units are in m/s).

Figure 5. Same as Figure 2a but for the equatorial zonal wind (98 km) at 18:00 LT (units are in m/s).
lower altitudes, where the phase structure is more westward.

Figure 6 shows the vertical neutral wind at 270 km. The wave number 4 structure is very apparent in the data indicating the propagation the nonmigrating tides. Figure 7 shows the field-line-integrated vertical ion drift (PRE). The wave number 4 feature is clearly shown as in the case of the growth rate in March. There have been many observations of the PRE in the past [e.g., Kil et al., 2009; Huang and Hairston, 2015]. As Huang and Hairston [2015] have shown that the PRE is highly dependent on the solar activity. We simulated the condition for 2006, which is a solar minimum. Part of the reason for study solar minimum is to see the nonmigrating tide effect. It is known that during the solar minimum the effect of the mesosphere tides on the ionosphere and thermosphere are more dominant.

In Huang and Hairston [2015] Figure 9 (top) (solar minimum), the observed PRE has some similar features also appeared in the calculated PRE (Figure 7). Large values near end of February in longitudinal ranges from $-180^\circ$ to $-150^\circ$ and $90^\circ$ to $180^\circ$ showed in both. The enhanced PRE showed in April in longitudinal range from $-150^\circ$ to $-90^\circ$ in simulation and from $-120^\circ$ to $-90^\circ$ in observation. There are some large differences as well. The observed January and December high PRE values in longitudes from $-90^\circ$ to $0^\circ$ are most absent in the simulation with only a small increase near longitude $-30^\circ$. Some of the observed features in October are not seen in the simulation. The small enhancement in September at longitude $-90^\circ$ may be in the simulation. The large simulated PRE in March at longitude $-30^\circ$ was not in the observed data. Obviously, the TIEGCM even with both migrating and nonmigrating tides cannot capture all the observed features in the PRE at the moment. It will be for a future study to include more inputs from the mesosphere and lower thermosphere to run the TIEGCM simulation.

4. Summary

TIEGCM is a very useful tool to examine the R-T growth rate at various conditions. So far the R-T growth rate seasonal and latitudinal variations resemble the satellite observation of the occurrence spread $F$. The angle between the Sun terminator and the magnetic declination near the magnetic equator plays an important role in determining the R-T growth rate. The simulation with nonmigrating tides shows additional longitudinal wave number 4 structure in the R-T rate, which is a results of nonmigrating DE3 and SE2 tides in the simulation. The results demonstrate the potential for the TIEGCM as an effective tool for studying the equatorial ionosphere, which can lead to a better understanding of the occurrence of the spread $F$.
The occurrence of the plasma bubble has strong longitudinal and seasonal variations as the R-T growth rate. R-T growth rate is one factor among many that determine the occurrence of the plasma bubble. Other factors including gravity wave seeding may also have large impact on the bubble occurrence. We note that the upper boundary of the TIEGCM at ~500 km is a limiting factor for examination of R-T growth rate at higher altitudes.

Future simulations with real data as lower boundary inputs are planned, and calculation with altitude extended model is also under consideration.

References


