1 **Solar Effect on the Rayleigh-Taylor Instability Growth Rate as Simulated by the**
2 **NCAR TIEGCM**

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10
11 **Abstract**

12 The TIEGCM (Thermosphere Ionosphere Electrodynamics General Circulation Model)
13 is used to investigate the solar effect on the equatorial ionospheric Rayleigh-Taylor (R-T)
14 instability growth rate, which is responsible for the occurrence of the plasma bubbles.

15 The R-T growth rate is calculated for the solar maximum year 2003 and minimum 2009.

16 The growth rate is strongly dependent on the solar activity. During solar maximum, the
17 pre-reversal enhancement is much stronger leading to higher R-T growth rate. The R-T

18 growth rates from the TIEGCM follow the same solar dependence as the observed

19 occurrence of equatorial plasma bubbles by DMSP satellites. The R-T growth rate also

20 enhances when the day/night terminator is parallel to the magnetic field line near the

21 equator. The R-T growth rate does not correlate well with the solar F10.7 index on a

22 short time scale (~ 10 days) because the field-line integrated electron content gradient

23 cancels out the positive correlation between the vertical ion drift with the F10.7 index.

The TIEGCM result shows the importance of the electron content gradient to the R-T growth rate and the plasma bubble occurrence. The bubble occurrence rates were estimated based on the vertical ion drift simulation results.

Introduction

Plasma bubble occurrence changes with season and longitude [Burke *et al.*, 2004a; 2004b; Su *et al.*, 2006; Gentile *et al.*, 2006; Stolle *et al.*, 2006]. They also have a strong solar dependence [e.g., Gentile *et al.*, 2006]. Their occurrence is much higher during solar maximum. The occurrence of the plasma bubbles is related to the R-T growth rate, which is impacted by the vertical ion drift pre-reversal enhancement (PRE) near dusk [Fejer *et al.*, 1999].

Because of the close association between the R-T growth rate and plasma bubbles, the R-T growth rate can be used to assess the occurrence of the bubbles. The R-T growth was calculated using different models [Sultan, 1996; Haerendel *et al.*, 1992; Basu, 2002; Luo *et al.*, 2012; Carter *et al.* 2014a; 2014b; Wu, 2015].

Wu [2015] investigated the nonmigrating tidal effect on the R-T growth rate based on the NCAR TIEGCM simulations. The model calculated R-T growth rate shows similar longitudinal and seasonal distribution as that of the occurrence of plasma bubbles.

Because the TIEGCM uses the solar F10.7 index as a proxy of the solar UV input for the ionosphere calculation, it also allows us to examine the solar effect on the R-T growth rate. The goal of this paper is to have a more qualitative assessment of the R-T growth

rate variation with the solar activity in connection with the zonal winds and PRE. We hope this effort will help to lay the foundation for future forecast capabilities. The paper is organized as follows: in the next section the model calculation is described; then the results are discussed; and finally the findings of the paper is summarized.

R-T Growth Rate Simulation

TIEGCM is a model developed by NCAR [Richmond *et al.*, 1992]. In this study, a resolution of 2.5x2.5 degree is used. The model is driven by the Weimer ion convection model at high latitudes [Weimer, 2005], which is based on 5-minute resolution IMF parameters. The GSWM (Global Scale Wave Model) provides both migrating and nonmigrating tides inputs at the lower boundary near 97 km [Hagan and Forbes, 2002].

The R-T growth rate is calculated by integrating along the magnetic field lines across the equator at the pressure level of 1.75 in the TIEGCM (~ 264 km and ~ 298 km during solar minimum and maximum) as shown by Equ. 26 in Sultan [1996]:

$$\gamma_{RT} = \Sigma P, OF \Sigma P, OE + \Sigma p, OF V_p - ULP - g_{eff} F K F - RT$$

where, $\Sigma P, OF$, $\Sigma P, OE$ are the field line integrated F and E region Pedersen

conductivities, V_p , ULP are the field line integrated perpendicular ion drift and neutral

wind in the upward or downward direction, g , $veff$, are the effective gravity and

effective collision frequency, KF is the flux tube electron content height gradient in the

F region, RT is the recombination rate. More detailed information about each of the terms can be found in *Sultan* [1996].

The model calculation of the R-T growth rate is described by *Carter et al.* [2014a] and *Wu* [2015]. The F region boundary in model calculation is at pressure level -0.75 (183 km in 2009 and 195 km in 2003). The lower boundary is set so that the electron density contribution along the field line in the F-region can be fully captured during both solar maximum and minimum conditions. The recombination rate is set to zero as in *Carter et al.* [2014a] as *Sultan* [1996] pointed out that the field-line-integrated is weighted mostly in the F-region, where it is not important. The model was run for solar maximum (2003) and minimum (2009) conditions. The model uses the daily F10.7 index value as a proxy for solar conditions in the UV heating and ionization calculation in the model.

Results and Discussions

Similar to what was shown in *Wu* [2015], the R-T growth rates at 18 LT for the case of minimum year 2009 (apex of the field line at 264 km) are plotted in Figure 1a. The top scale of $1.4 \times 10^{-3} \text{ sec}^{-1}$ equals to one over 12 minutes. The two black lines in the plot marks the condition when the magnetic field line is parallel to the day/night terminator. *Tsunoda* [1985] predicted larger PRE and higher plasma bubble occurrence along under the condition (hereafter referred as Tsunoda condition). The prediction in general agrees with observations [e.g., *Gentile et al.*, 2006]. The R-T growth map looks similar to bubble occurrence map during solar minimum (1994-1997) [*Gentile et al.*, 2006, Figure 6]. There are some noticeable differences. The bubble occurrence has some high values

between 90W and 10E degree longitudes, whereas the R-T growth rate peaks between 60W and 0 degree longitude. The R-T growth rate also does not always follow the Tsunoda condition, the high R-T growth rate distribution shifted eastward.

The R-T growth rate map for solar maximum (2003) is shown in Figure 1b. Compared to the solar minimum case, the growth rate is much larger. *Gentile et al.* [2006] also showed bubble occurrence during solar maximum (1997-2002, Figure 5). Bubble occurrence is high in the 60W to 40E longitudinal range extending from January to April and September to December, whereas the higher R-T growth rate was discretely distributed between 90W and 0 longitudes. There was no large R-T growth rate beyond 0 degree longitude in the east. The R-T growth rate also appeared to be shifted eastward from the Tsunoda condition. It should be noted that *Gentile et al.* [2006] showed the bubble distribution at ~19 LT, while the R-T growth rate calculation is for 18 LT. It is possible that the lower boundary condition of the TIEGCM at 97 km does not have correct tidal or planetary wave input to the model. Further improvements are needed.

To understand the solar effect on the R-T growth rate, we examine the vertical ion drift during solar minimum and maximum, which are shown in Figure 2a and 2b. During solar minimum, the vertical ion drift is about 10 m/s or less during the two equinoxes. During the solar maximum, the vertical ion drift is larger in general. There are also some large vertical ion drifts along the 30W longitude, which are around 20 m/s. The solar variation of the vertical ion drift is one of the main reasons for solar dependence of the R-T growth rate and bubble occurrence. *Huang and Hairston* [2015] showed that the PRE is

114 directly related to the solar activity changing from 10 m/s for F10.7 of 70 sfu to about 40
115 m/s for F10.7 of 150 sfu. The TIEGCM shows smaller change in the PRE than that
116 observed by C/NOFS (Communication/Navigation Outage Forecast System), it should be
117 noted that there are altitude differences between the simulated the PRE (260 to 300 km)
118 and the observed PRE (400 to 500 km), which may or may not contribute to the
119 difference. PRE varies with altitude during quiet time and less so during geomagnetic
120 active periods [Fejer *et al.*, 2014; Hui, 2015]. Further study is needed.

121
122 The solar activity also affects the importance of the lower thermospheric input to the R-T
123 growth rate. During solar minimum, the nonmigrating tide wave-4 structure is visible in
124 the vertical ion drift with amplitude about 6.2 m/s (at 30W, 40E, and 150E longitudes
125 around day 70, missing one at 120W) with two contour steps in Figure 2a comparing to
126 the global annual peak to peak variation about 22 m/s with seven contour steps, which is
127 ~28% of the overall variation. For the growth rate the wave-4 amplitude is $\sim 17.5 \times 10^{-5}$
128 s^{-1} (two contour steps in Figure 1a) and the global annual peak to peak variations is
129 $\sim 96 \times 10^{-5} \text{s}^{-1}$ (eleven contour steps), which is ~18% of the overall variation. During solar
130 maximum, the effect of the lower thermosphere input becomes less important and the
131 wave-4 feature is not clear in the ion drift and R-T growth rates. The relative
132 contribution from the wave-4 feature in thermosphere decreases with increasing solar
133 activity as reported by Oberheide *et al.*, [2009].

134
135 One of the large differences between the TIEGCM calculated R-T growth rate and bubble
136 occurrence is in the longitudinal range between 0 and 40E. The simulated vertical ion

drift also did not show much enhancement in that longitudinal range, whereas *Kil et al.* [2009] showed strong PRE. That is a deficiency in the TIEGCM, which may again be related to the lack of planetary wave input from the lower boundary at 97 km.

The vertical ion drift map from ROCSAT-1 observations showed strong vertical ion drift covering a larger longitudinal range during March equinox [*Kil et al.*, 2009]. The vertical ion drift map from the TIEGCM has some discrepancies compared to the ROCSAT observations. Further investigation is needed to understand these discrepancies. An oscillation in the zonal wind with amplitude about 30 m/s (e.g., Figure 4 near day 300), will generate roughly 10 m/s oscillation in the vertical ion drift (Figure 5 near day 300) based on the TIEGCM simulation.

To explore the source of the vertical ion drift variation with solar cycle, the TIEGCM modeled zonal winds at pressure level 1.75 at the geographic equator (18 LT) are investigated, because the zonal winds are one of the main drivers for the PRE [*Heelis et al.*, 2012]. By examining the zonal wind, we hope to shed some light on the solar dependence of the thermosphere dynamics and its effect on the R-T growth rate. The zonal winds from solar minimum year 2009 are plotted in Figure 3a. The wave-4 pattern is prominent in the early and later part of the year, which is mostly from the DE3 nonmigrating tide from the GSWM lower boundary condition. Because 2009 is a solar minimum year, there were no major geomagnetic activities and solar heating of the thermosphere was also weaker. Consequently, the nonmigrating tides from the lower atmosphere become a major source for the longitudinal variations shown in Figure 3a,

which lead to the longitudinal variations in the vertical winds and in turn to the R-T growth rate. The zonal winds for solar maximum (2003) are shown in Figure 3b. The wind pattern is much more structured due to geomagnetic activities during solar maximum. The zonal winds are much stronger because of stronger UV solar heating [e.g., *Drob et al.*, 2015].

To examine the issue further, the 2003 solar F10.7 index and zonal winds from several longitudinal sectors are plotted in Figure 4. There is a clear correlation between solar index and zonal winds and both have the similar 27-day periodicity from the solar rotation. Figure 5 shows the solar F10.7 index and vertical ion drift at the same longitudes shown in Figure 4. The correlation between the F10.7 and the vertical ion drift is not as good as that for the zonal winds. The correlation coefficients for each of the longitudinal sections listed in Figure 5 are mostly smaller than those in Figure 4. In the later part of the year, the ion drift shows a strong correlation with the solar index. During other times, the ion drifts from different longitudes react differently to the F10.7 index. While zonal wind is a major driver for the vertical ion drift, the ion drift can also be affected by other factors, which may have different solar response. We plot the F10.7 index with the line-integrated R-T growth rate in Figure 6. There is a lack of direct correlation between the solar F10.7 index and the R-T growth rate compared to the zonal winds. The correlation coefficients with the F10.7 index are much smaller as shown in Figure 6. While the zonal wind increase during solar maximum contributes to the overall increase of the R-T growth rate, the R-T growth rate did not respond consistently to all solar F10.7 index variations. To investigate the lack of correlation

between the solar F10.7 index and R-T growth rate in short term time scale, we examine other parameters in the R-T growth rate calculation. The vertical neutral winds do not show much correlation with the F10.7 index (not shown here). The flux tube electron content height gradient KF in the R-T growth rate equation, on the other hand, does show a clear negative correlation with the F10.7 index in the short-term time scale (Figure 7) as indicated by the negative correlation coefficients. This negative correlation cancels the positive correlation of the vertical ion drift in the R-T growth rate calculation with the F10.7 index. The KF negative correlation with the F10.7 index is understandable as the solar activity can increase the geomagnetic activity and E-region conductivity, which can lead to greater transport between the field lines and reduction in the KF . In Figure 7, the Kp index also elevated with the F10.7 index indicating strong geomagnetic activity caused by the solar activity.

On an annually basis, the KF is also smaller during solar maximum (2003) compared to minimum (2009). However, the reduction in the KF from solar minimum (2009) to maximum (2003) is not enough to offset the overall increase in the vertical ion drift on the annually basis. Consequently, the R-T growth is larger in general during solar maximum year 2003. We plot the KF annual patterns for 2009 and 2003 in Figures 8a and 8b.

The KF longitudinal and seasonal variations are similar to that of the R-T growth meaning they have the tendency to follow the Tsunoda condition approximately. The effect of the KF on the R-T growth rate and the occurrence of the plasma bubble is less studied compared to the PRE, because KF cannot be easily observed as PRE. The KF is higher under the Tsunoda condition, because the low E-region conductivities on both ends of the magnetic field lines help to maintain larger gradient. The model simulation shows the importance of this parameter.

Another unresolved issue in the simulation results is that the apparent longitudinal shift between the high R-T growth and the Tsunoda condition. We also suspect that the GSWM lower boundary condition did not provide accurate nonmigrating tide and planetary wave for the TIEGCM model. The lower boundary condition in the TIEGCM can have strong impact on the model simulation results in the equatorial region as demonstrated by *Yamazaki et al.* [2014] for the equatorial electrojet calculation

Based on the simulated vertical ion drift, we can estimate roughly the bubble occurrence using the nearly linear relationship between the PRE and plasma bubble shown by *Kil et al.* [2009] (Figure 7, occurrence = $2 \cdot (\text{vertical drift, in m/s}) + 10$). Figure 9 shows the estimate for the 2009 and 2003. Such result would predict a stronger correlation with the F10.7 index than the real bubble occurrence, as we have shown earlier. A better estimate would be based on the R-T growth rate. Since we do not have observation of the R-T growth rate, we cannot establish a linear or other relationship with bubble occurrence directly based observation yet. More study is needed to establish such a relationship.

226

227 **Summary**

228 The TIEGCM simulated R-T growth rate has strong solar dependence due to the changes
229 in the PRE with solar activity. The R-T growth rate showed the nonmigrating tide wave-
230 4 feature during solar minimum and not during solar maximum. During solar maximum
231 the R-T growth rate are in general higher. However, it does not show a strong
232 correlation with short-term changes in the solar F10.7 index, because of the negative
233 correlation of the *KF* with the F10.7 index. The TIEGCM simulations show the
234 importance of the contribution from *KF* to the R-T growth rate and solar effects. It opens
235 up opportunities to examine the R-T growth rate for different solar cycles.

236

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244 **References**

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Figure Captions

Figure 1. Seasonal and longitudinal variations of the field line-integrated Rayleigh-Taylor instability growth rate (10^{-5}s^{-1}) at 18 LT simulated with nonmigrating tides for solar minimum year 2009 (a) and maximum 2003 (b). The peak height for the field lines is at pressure level 1.75, which is ~ 264 (298) km during solar minimum (maximum). The black lines are days and longitudes match the Tsunoda condition.

Figure 2. Same as Figure 1 but for the field line integrated vertical ion drift.

Figure 3. The zonal winds at pressure level 1.75 at 18 LT for solar minimum year 2009 (a) and maximum 2003 (b).

Figure 4. 2003 solar F10.7 index and zonal winds at 18 LT from six different longitudes. The longitudes and zonal wind data are shown in the same colors.

Figure 5. 2003 solar F10.7 index and vertical ion drifts at 18 LT from six different longitudes. The scale for the solar index is on the left and that of the vertical drift on the right.

Figure 6. 2003 solar F10.7 index and field line integrated R-T growth rates from six different longitudes.

Figure 7. 2003 solar F10.7 index, Kp index, and flux tube electron content height gradient from six different longitudes. The scale for the height gradients of different

354 longitudes (colored lines) is on the left side and that for the F10.7 (solid black line) and
355 Kp (dotted black line) indices are on the right.

356

357 Figure 8. Flux tube electron content height gradient at 18 LT and for field lines with
358 peak height pressure level 1.75 for solar minimum year 2009 (a) at ~ 264 km and
359 maximum 2003 (b) at ~ 298 km.

360

361 Figure 9 Estimated plasma bubble occurrence for 2009 (a) and 2003 (b) based on the
362 vertical ion drift PRE.

363

2003 Solar F10.7 index and Equatorial Zonal Winds

2003 Solar F10.7 index and Vertical Ion Drift at 18 LT

2003 Solar F10.7 index and R-T Growth Rate

2003 Flux Tube Electron Content Height Gradient

(a) 2009 Flux Tube Electron Content Height Gradient $10^{-3}/\text{km}$

(b) 2003 Flux Tube Electron Content Height Gradient $10^{-3}/\text{km}$

2009 Estimated Bubble Occurrence Rate

2003 Estimated Bubble Occurrence Rate