A New Prediction Capability for Post-sunset Equatorial Plasma Bubbles

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ABSTRACT

The occurrence of Equatorial Plasma Bubbles (EPBs) has become an important research topic in the field of space science in recent years, due to the adverse influence of EPBs on many important technological applications. One such application is the use of Global Navigation Satellite System (GNSS) signals, such as the Global Positioning System (GPS). The seasonal/longitudinal variability in EPB occurrence is relatively well understood, following decades of EPB observations spanning around the globe. A key unresolved issue is the daily variability in the occurrence of EPBs. To address this issue, an analysis of the daily GPS scintillation occurrence variability in several locations was conducted, and was complimented by coupled ionosphere-thermosphere modeling. It was found that the coupled ionosphere-thermosphere model, which was run independently of ionospheric observations, exhibited a daily variability that closely matched the observations. Further investigation found that the model's high-latitude ion convection pattern, which was driven by the Kp index, was the primary source of this variability. The ionosphere-thermosphere modeling revealed that the neutral winds at the equator are influenced by rather small changes in geomagnetic activity, and therefore the high-latitude convection within the model, from several hours prior. It is understood that neutral wind perturbations caused by enhanced ion convection, and the associated Joule heating, propagate towards the equator and subsequently suppresses the upward plasma drift shortly after local sunset, which prevents EPB growth. An EPB prediction trial using solar wind data to forecast Kp hours in advance shows that one can reliably forecast EPB occurrence during peak EPB season with up to 95% accuracy. EPB occurrence prediction during off-peak seasons, on the other hand, remains a significant scientific challenge.

1. INTRODUCTION

Equatorial Plasma Bubbles (EPBs) are regions of low electron density that rise into the high electron density regions at higher altitudes in the night time hours. Their occurrence gives rise to an entire spectrum of plasma waves/irregularities that are known to cause ionospheric scintillation on trans-ionospheric radio applications; e.g., satellite communications and Global Navigation Satellite

Systems. As such, a prime motivation for space weather forecasting agencies around the world is to develop the capability to accurately forecast the occurrence of EPBs.

The plasma instability that is known to cause EPBs is the Generalized Rayleigh-Taylor (R-T) Instability, in which a vertical plasma density gradient and a zonal electric field (which drives plasma vertically at the equator) destabilizes the plasma in the bottomside ionosphere. The flux-tube integrated linear growth rate of this instability is given by *Sultan* (1997) as:

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(V_p - U_n^P - \frac{g_L}{\nu_{in}^{eff}}\right)\frac{1}{L_n} - R_T$$

where Σ_P^F and Σ_P^E are the F- and E-region flux-tube integrated Pederson conductivities, V_p is the upward plasma drift, U_n^P is the Pederson conductivity weighted neutral wind strength in the direction perpendicular to the magnetic field in the meridional plane, g_L is the altitude-corrected acceleration due to gravity, ν_{in}^{eff} is the electron density weighted ion-neutral collision frequency, L_n is the vertical plasma density gradient scale length and R_T is the recombination rate. In order for the instability to grow, this γ must be positive, and stay positive long enough for the EPB to grow.

If the growth is strong, then the EPBs grow nonlinearly in the vertical direction, crossing the magnetic field lines as they grow. The high electron mobility along the field lines means that as the EPBs grow in altitude, so does their extent in magnetic latitude. As a result, EPBs that reach more than ~ 800 km in altitude above the equator tend to spread out to ~ 20° from the equator in both North and South directions, therefore influencing a collective 40°-wide band that runs along the magnetic equator during the night.

Following decades of observations and research, the long-term seasonal/longitudinal climatology of EPBs is relatively well understood [e.g., *Carter et al.,* 2013 and references therein]. As such, the current challenge lies in being able to predict EPB occurrence on a day-by-day basis. This short paper summarizes our recent efforts to meet this challenge, which has collectively been published in three adjacent works [*Carter et al.,* 2014a;b;c].

2. RESULTS AND DISCUSSION

Our analysis began using GPS scintillation observations from Vanimo in Papua New Guinea, the top panel of Figure 1. In analyzing this period, the question is asked – why were their EPBs on some days, but not others? The second panel shows both the F10.7 solar flux and the Kp index, which do not appear to show any clear correlation with the EPB occurrence. In addition, it is important to note that the solar flux was relatively stable and geomagnetic activity was mostly low throughout this interval.

By analyzing the R-T growth rate expression shown above, it is clear that in order to investigate this issue some modelling is required because of the large number of unmeasurable quantities. The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) [*Qian et al.*, 2014], a 3-dimensional physics-based self-consistent model of the Earth's ionosphere and thermosphere, was used. This model was primarily driven throughout this observation period using the F10.7 solar flux and geomagnetic Kp index shown in Figure 1b. The results were then used to calculate the R-T growth rates.

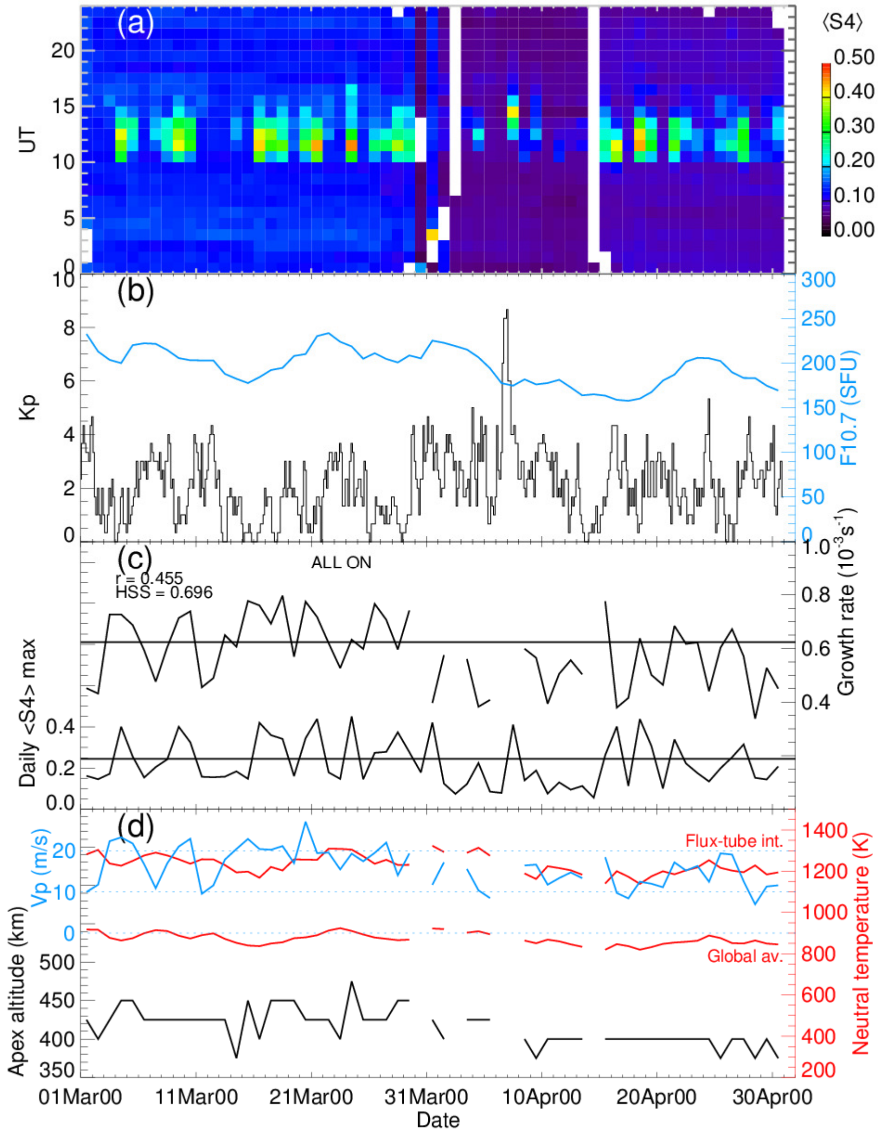

Figure 1. (a) GPS scintillation data showing the presence of EPBs throughout March and April 2000. (b) The F10.7 solar flux and geomagnetic Kp index throughout this period. (c) The daily maxima of the GPS scintillation data and the calculated R-T growth rates. (d) The modeled apex altitudes and the upward plasma drift values contributing towards the R-T growth rates in (c), in addition to the globally averaged and flux-tube integrated thermospheric temperatures. Figure published by *Carter et al.* [2014a].

The maximum R-T growth rates for each day are plotted in Figure 1c, along with the daily maximum GPS scintillation level, to better indicate the daily variability. Surprisingly, the TIE-GCM R-T growth rates show a similar daily variability compared to the GPS scintillation levels, indicating that the model drivers are inducing a daily variability that closely resembles the observations. Figure 1d shows that the upward plasma drift is well correlated with the R-T growth rates. In fact, it was found that the primary driver of the daily variability in the R-T growth rate was the V_p term and that the Kp index was the quantity that controlled the changes in V_p [*Carter et al.*, 2014a].

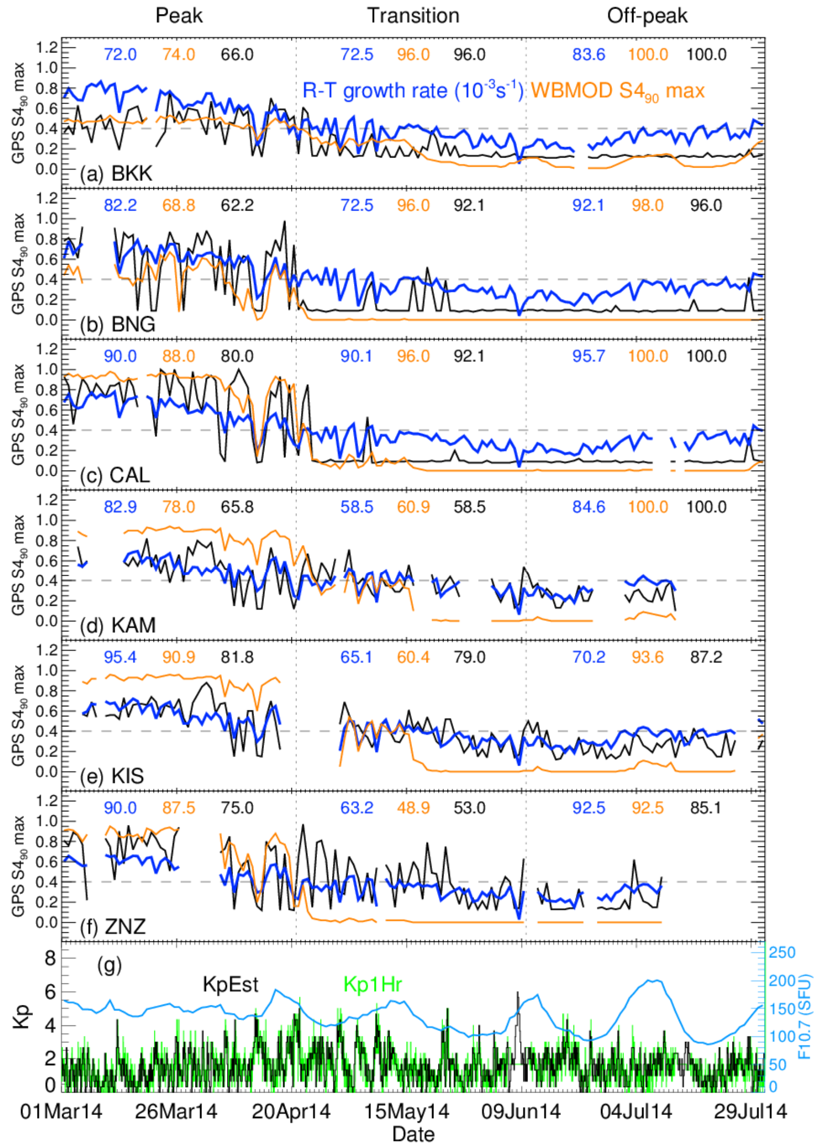

Figure 2. (a)-(f) The daily maxima of the GPS scintillation levels, the R-T growth rates calculated from the TIE-GCM outputs and the WBMOD scintillation levels between March and July 2014, in black, blue and orange, respectively. The digits indicate the percentage of correct EPB occurrence predictions using the TIE-GCM R-T growth rates, WBMOD and "persistence" forecasts. (g) The F10.7 solar flux and the unverified measured Kp index KpEst (black) and the Wing model 1-hr predicted Kp index Kp1Hr (green). Figure published by *Carter et al.* [2014c].

Very similar results were then found for a completely different dataset (five other GPS stations across different longitude sectors) and it was confirmed that small changes in Kp influenced the zonal wind strength at the equator, and subsequently the strength of the upward plasma drift, V_p [*Carter et al.*, 2014b].

Given that Kp was found to be a primary driver of the daily EPB occurrence variability during EPB season, we tested the idea of predicting EPB occurrence by driving the TIE-GCM with predicted Kp values from the Wing Kp model [*Wing et al.*, 2005] and using the TIE-GCM outputs to calculate the

R-T growth rates. For this EPB prediction trial, we employed six stations, three in Africa and three in South-east Asia.

Figure 2 shows the results of this trial, which commenced during peak EPB season and finished during off-peak season for the African and South-east Asian longitude sectors. The results from the TIE-GCM were compared to the scintillation forecast model WBMOD [*Secan et al.*, 1995] results and the "persistence" forecast (i.e., what happened yesterday will happen today). Using the constant thresholds indicated by the horizontal dashes, the percentage of correct EPB occurrence predictions were calculated and shown by the digits in each period. In other words, an EPB day was classified as a day in which the maximum hourly GPS scintillation level reached above 0.4. Similarly, an EPB day was successfully predicted when the TIE-GCM R-T growth rate was calculated to be above 0.4 x 10^{-3} s^{-1} and when WBMOD predicted an S4 value above 0.4. The result is either a "yes" or "no" prediction as to whether EPBs will form or not. A prediction accuracy of 100% is achieved when the predictions accurately forecast both EPB days and non-EPB days throughout a given period.

From Figure 2, it is clear that the TIE-GCM R-T growth rate performs best during peak EPB season, when EPB occurrence is largely dominated by EPB suppressions; the best result is for the KIS station at 95.4% accuracy. However, WBMOD and persistence forecasts perform best during both transition and off-peak periods, when EPB variability from day-to-day is much lower.

A common issue for all EPB prediction models/techniques analyzed in this work is their collective inability to predict unseasonal EPB events, i.e., EPBs during transition and off-peak seasons. This issue is subject to continuing research efforts.

3. CONCLUSIONS

In this brief paper, we have summarized our recent efforts aimed at predicting the daily occurrence of EPBs at several locations around the world. Following the discovery that the TIE-GCM model exhibited a daily variability that resembled the observed GPS scintillation data, it was found that the model's parameterization of the Kp index influenced the low-latitude regions in a way that impacted EPB occurrence. This influence manifests itself in the daily changes in the upward plasma drift, which are caused by changes in the zonal wind, which then subsequently affects the daily variability of the R-T growth rate. In light of these results, an EPB prediction trial using Kp index predictions was performed and compared with other EPB prediction techniques. The TIE-GCM driven by Kp predictions performed best during peak EPB season, when daily EPB occurrence variability is governed by EPB suppressions by relatively small increases in geomagnetic activity. The prediction of un-seasonal EPBs during transitional and off-peak seasons remains a significant challenge.

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