Comparison of the linear Rayleigh-Taylor instability and equatorial plasma bubbles using WAM-IPE and ROCSAT-1

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Abstract: The prediction of the equatorial plasma bubble (EPB) has been one of the most important issues in space weather forecasting. The Rayleigh-Taylor (R-T) instability mechanism is fundamentally linked to the generation of EPBs in the ionosphere. Previous studies have showed that the global morphology of the evening prereversal enhancement (PRE) of vertical ion drift have a good agreement with the global morphology of EPB occurrence probability. The growth rate of R-T instability is primarily influenced by the ambient zonal electric field, which correlates with vertical drift, thus enabling the potential linkage between R-T instability and EPB occurrence probability. This study aims to explore the predictability of EPB occurrence by correlating the R-T instability growth rate with EPB occurrence probabilities. We utilize the coupled Whole Atmosphere Model and Ionosphere Plasmasphere Electrodynamic (WAM-IPE) model, incorporating a new integrated R-T instability growth rate formulation based on the Quasi-Dipole Coordinates and the modified electrodynamics equations. The variations and the distributions of EPB occurrence probability are observed by ROCSAT-1 during 2000–2002. A comprehensive analysis comparing these two aspects is presented.

Introduction and Motivation

1. Several studies demonstrated that pre-reversal enhancement (PRE) vertical drift and equatorial plasma bubble (EPB) occurrence rate have a nearly linear relationship (e.g., Kil et al., 2009; Huang et al., 2012)
2. Rayleigh-Taylor instability (RTI) growth rate is mainly driven by eastward electric field.
3. Is it possible to establish the relationship between RTI growth rate and EPB occurrence rate?

Expression for Rayleigh-Taylor Instability

$$\gamma = \frac{(\Sigma_x^F E_x + K_x^{DF} - \Sigma_c^F E_y)}{K^{gF}\Sigma_x B_{e3}\cos^2\lambda_m}\frac{\partial K^{gF}}{\partial y}$$

$$K_x^{DF} = B_{e3}\cos\lambda_m \int_{S(150)}^{N(150)} \left[\frac{\sigma_P d_1^2}{D} u_{e2} + \left(\sigma_H - \frac{\sigma_P \vec{d_1}\cdot\vec{d_2}}{D}\right) u_{e1} + \frac{n m_i \vec{e_2}\cdot\vec{g}}{B_{e3}B}\right] ds$$

$$K^{gF} = \cos\lambda_m \int_{S(150)}^{N(150)} \frac{n_0 m_i \vec{e_2}\cdot\vec{g}}{B} ds$$

γ: growth rate
Σ_c: integrated meridional/downward Pedersen conductivity
Σ_x: integrated eastward Pedersen conductivity
E_y: vertical electric field
u: neutral winds
K_x^{DF}: dynamo current
K^{gF}: gravity-driven current

- The field line integrated parameters can be output by WAM-IPE, allowing for direct calculating the R-T growth rate. The lower boundary for Σ_x is 90 km, for other parameters is 150 km.

Methodology

ROCSAT-1

January 27, 1999~June 17, 2004
Velocity: 7545 m/s
Altitude: ~600 km
Inclination: 35 °
Period: 2000~2002

Extracted Irregularities Caused by RTI

$$A(t) = \int_\omega H(\omega, t)d\omega$$

Focus on the scale size shorter than 200 km by Hilbert-Huang transform (Huang et al., 2020)

EPB Selection Criteria

$$\sigma = \frac{\left[\frac{1}{10}\sum_{i=1}^{10}(log_{10}N_i - log_{10}N_{oi})^2\right]^{1/2}}{\frac{1}{10}\sum_{i=1}^{10} log_{10}N_{oi}}$$

where N_i is the ion density at each second, and N_{oi} is the linearly fitted value of 10-sec data.

Picked up Data Manually

- The satellite orbit should cross the magnetic equator.
- PRE vertical drift should occur before 20 LT
- EPB event should be observed between 17 and 22 LT and exhibit significant depth.
- The σ index should greater than 0.3 % and the HHT total amplitude should greater than 1×10^4.

Study Goal

Establish the relationship between PRE vertical drift, EPB occurrence rate observed by ROCSAT-1, and RTI growth rate simulated by WAM-IPE.

RTI Growth Rate and Vertical Drift Distributions

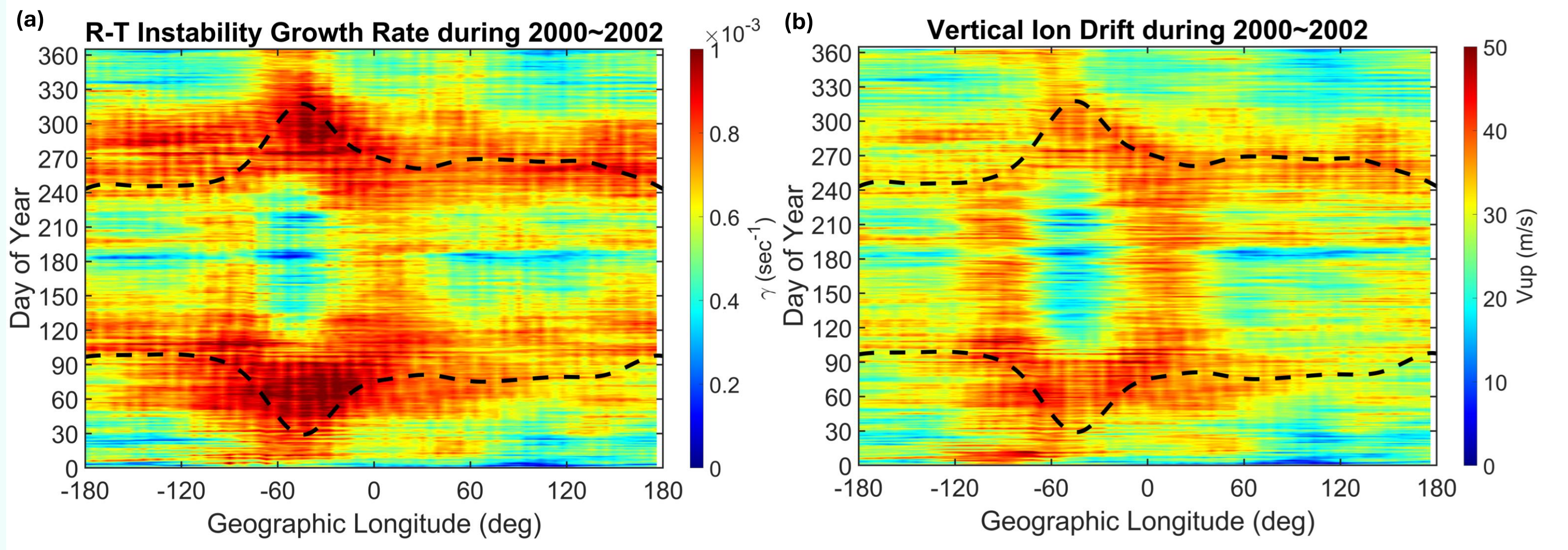


Figure 1. Seasonal and longitudinal variations of (a) R-T growth rate and (b) vertical ion drift during 2000~2002 driven by observed solar and interplanetary parameters. The dashed lines represent the days when the solar terminator aligns with the magnetic field line.

- The 30-min derived solar and observed interplanetary parameters are used to drive the WAM-IPE. The values in this figure are calculated based on the maximum values between 200 and 400 km altitude and within the local time range of 18 to 20 LT.
- The most significant growth rates are predominantly observed in the longitude range spanning from 90°W to 60°E during the periods of day 0 to 90 (from January to March) and day 270 to 330 (from September to November).

Contribution Analysis of RTI Growth Rate

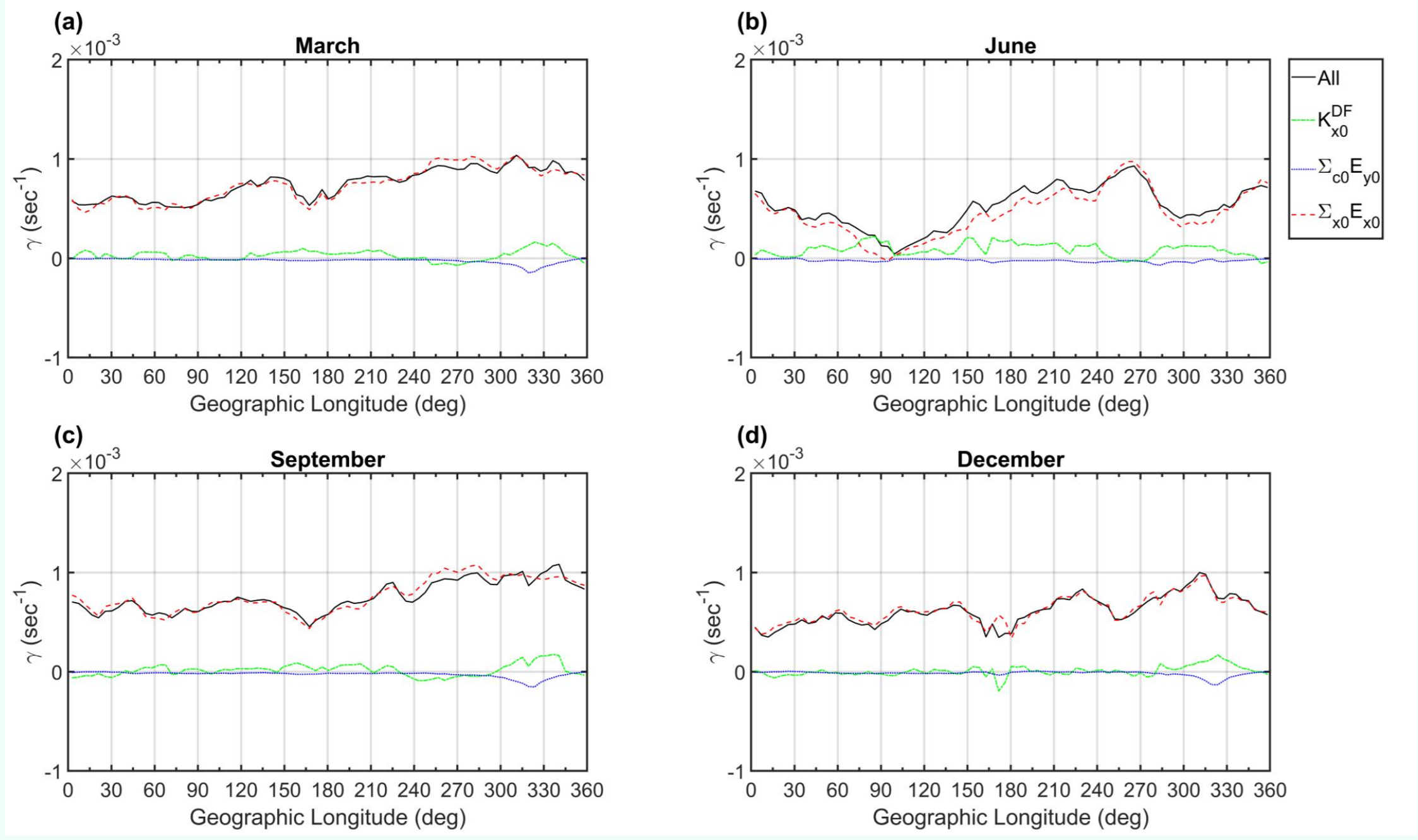
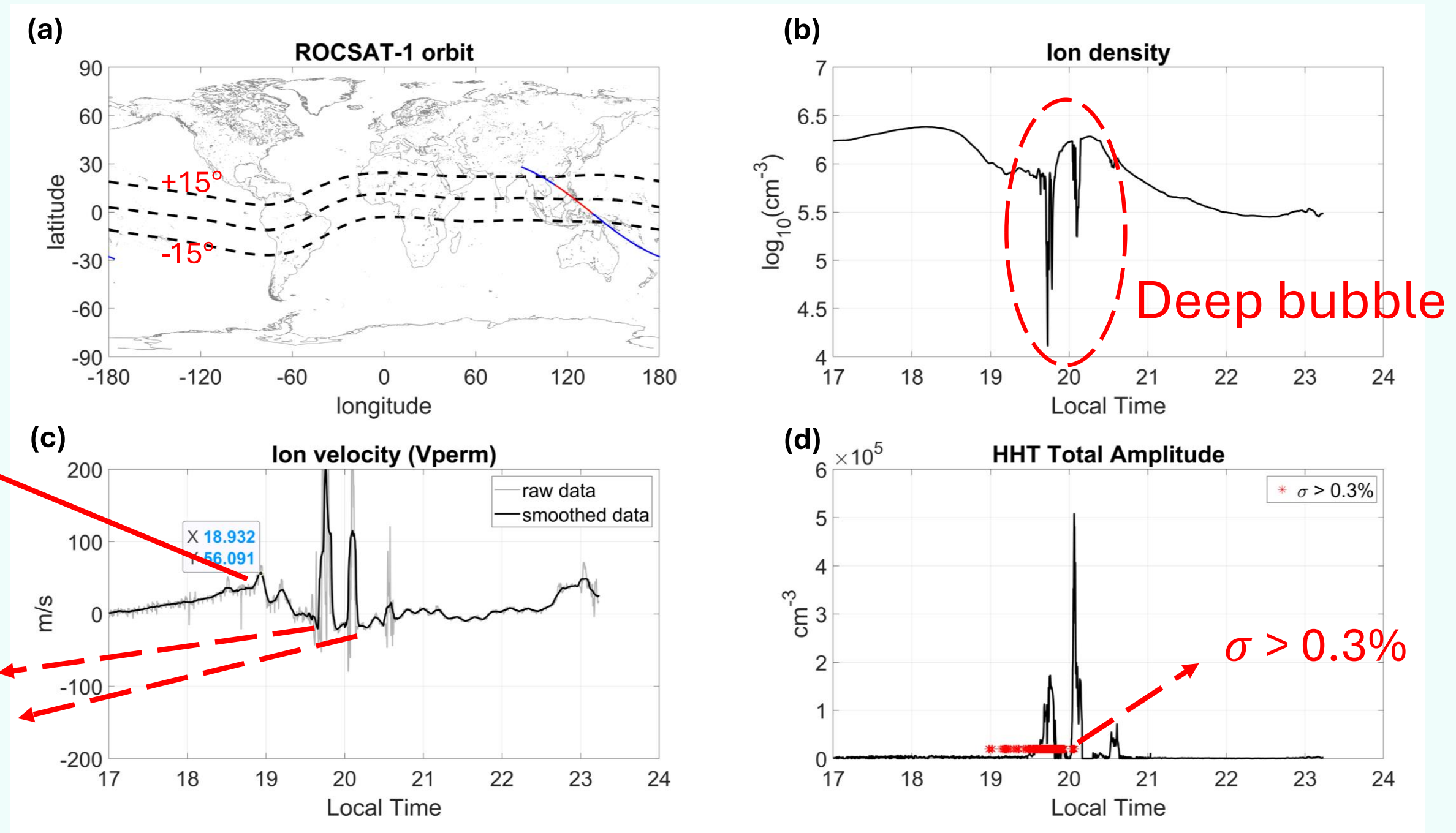


Figure 2. . R-T growth rate driven by various parameters at different longitude on (a) March 20, (b) June 20, (c) September 20, and (d) December 20.

- We further analyzed the contributions from each term of the growth rate expression. The result show that $\frac{(\Sigma_x^F E_x)}{K^{gF}\Sigma_x B_{e3}\cos^2\lambda_m}\frac{\partial K^{gF}}{\partial y}$ have the most significant contribution to the growth rate in almost all seasons and longitudes, indicating that vertical drift is the key factor.

Example of PRE and EPB Events



PRE feature

Uplifting EPBs are caused by the polarization electric field inside the EPBs.

Figure 3. Ionospheric irregularities observed by ROCSAT-1 on 20th March 2002. (a) ROCSAT-1 ground track (b) ion Density (c) ion velocity, and (d) HHT total amplitude.

Statistical Result of PRE and EPB

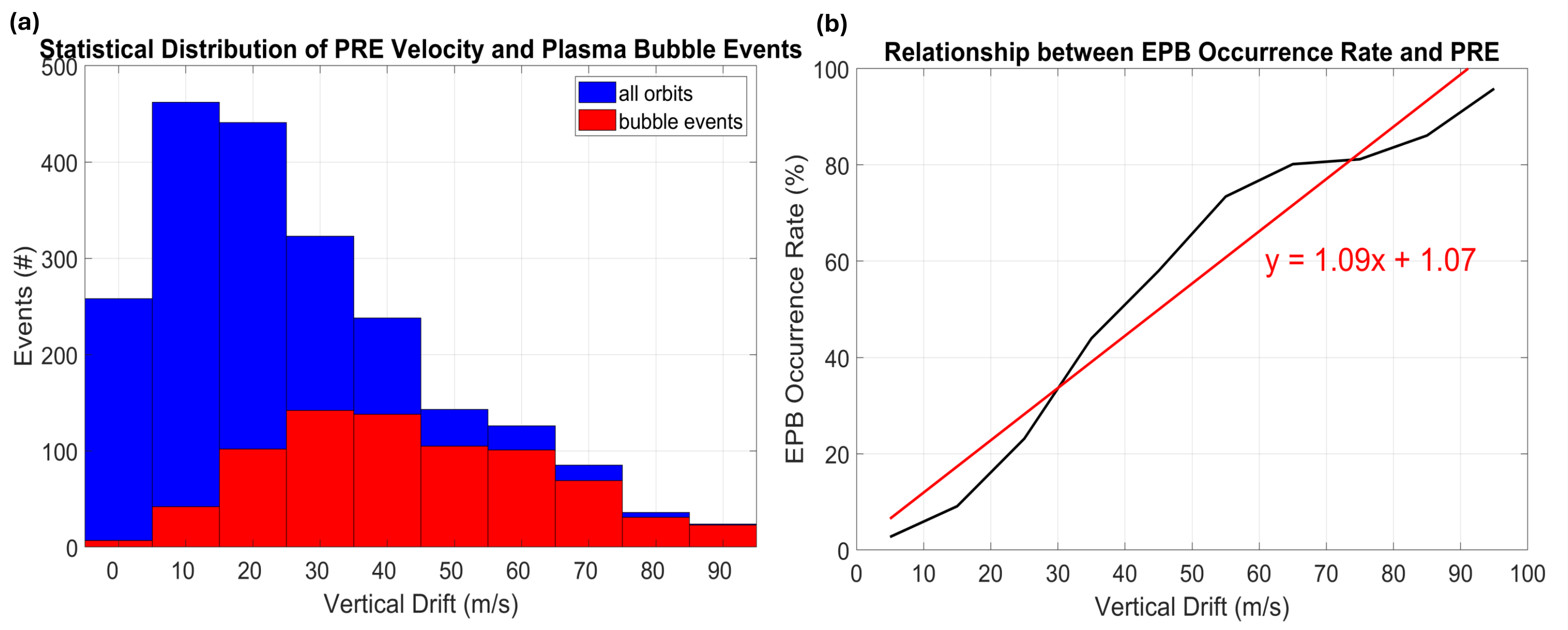


Figure 4. Statistical analysis of PRE velocity and EPB occurrence. (a) equator-crossing PRE velocity and EPB event (b) relationship between EPB occurrence rate and PRE velocity. The blue bars indicate all PRE events, while the red bar represents events where both PRE and EPB were observed. The red line in (b) is linear fit to the data.

- The statistical results show that not every occurrence of PRE will lead to the formation of plasma bubbles.
- When the PRE vertical drift reaches as high as 60 m/s, there is nearly an 80% EPB occurrence rate.

Connection between EPB Occurrence Rate and RTI Growth Rate

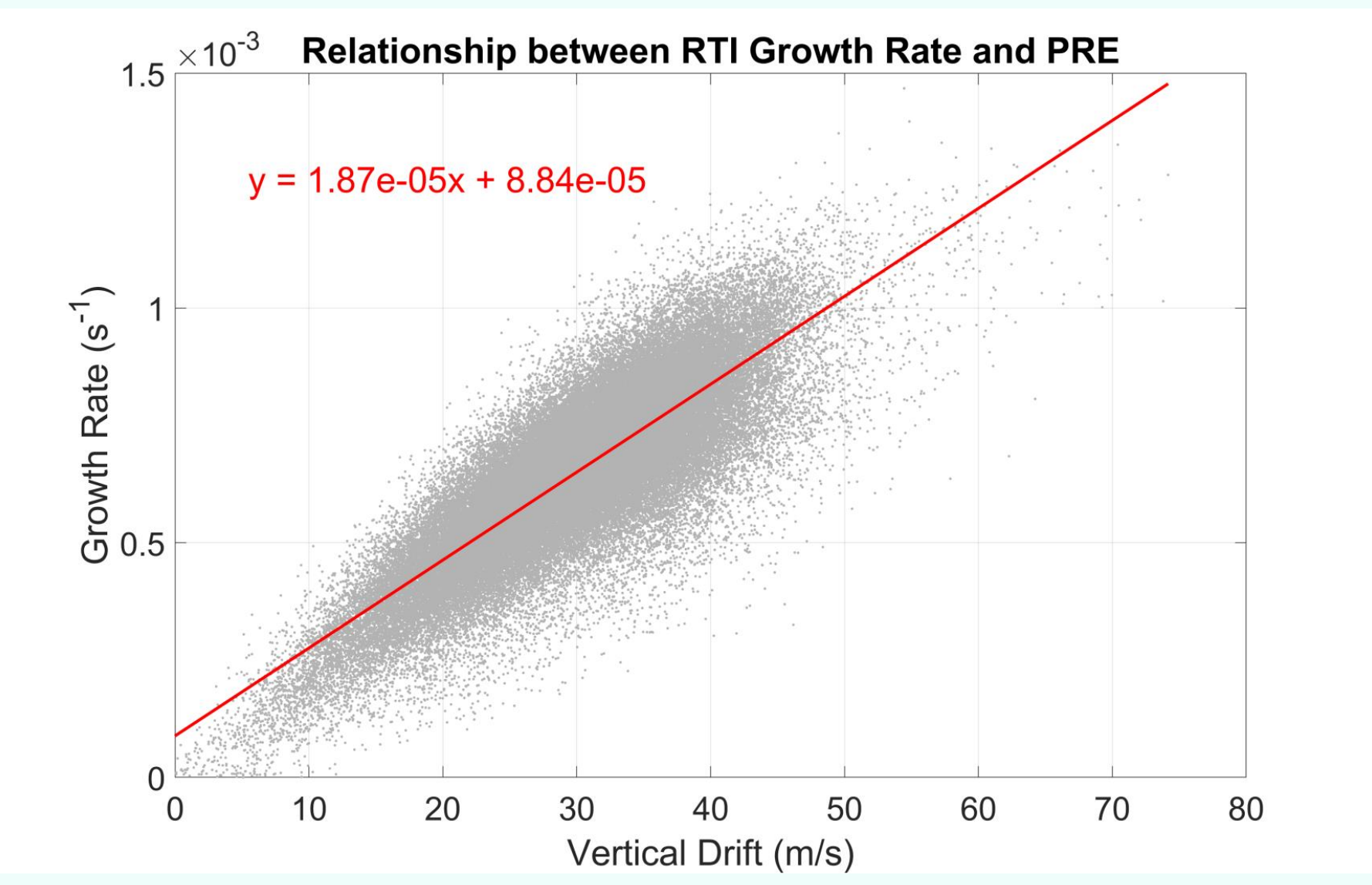


Figure 5. Statistical analysis of RTI growth rate and PRE vertical drift.

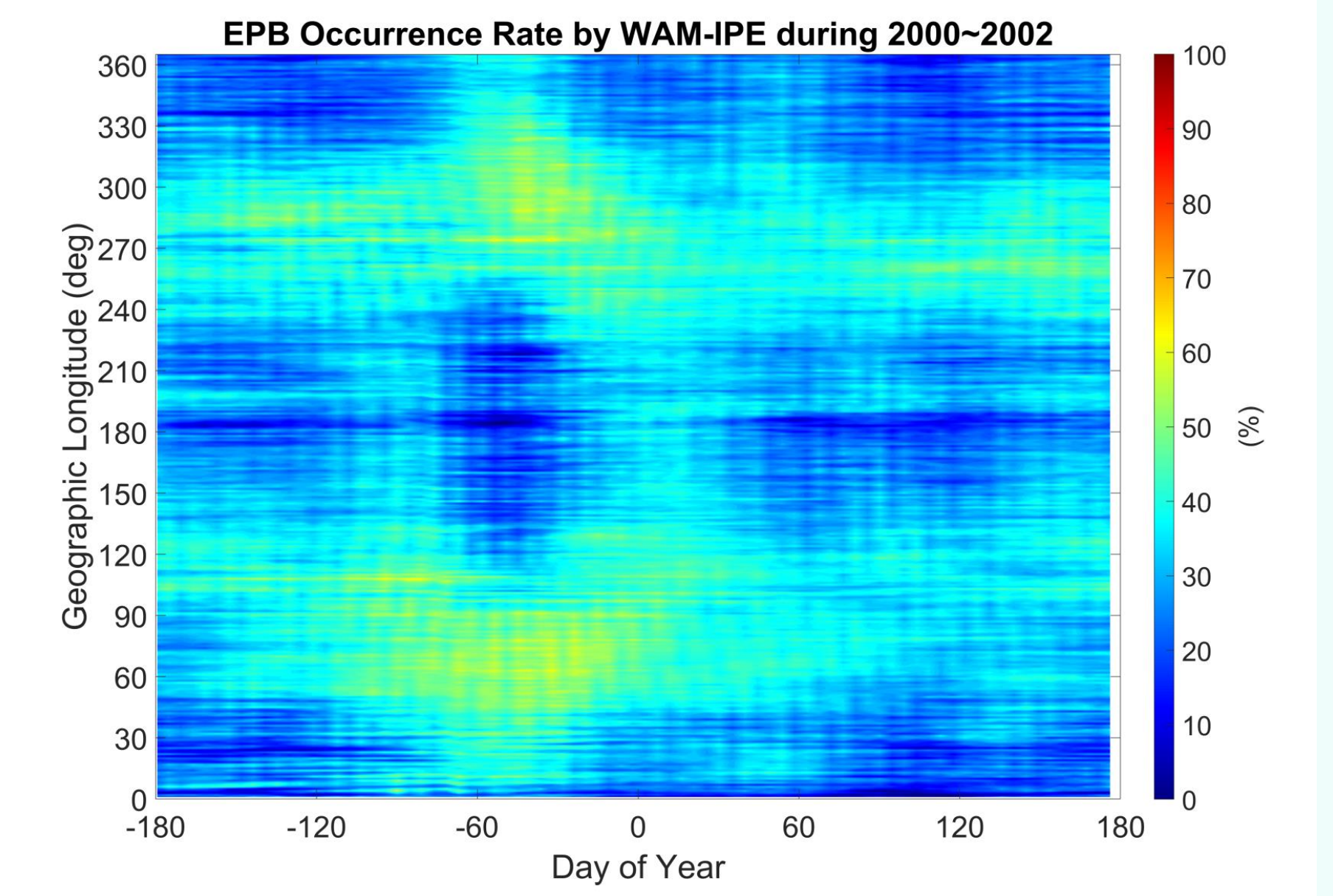


Figure 6. Estimated EPB occurrence for 2000~2002 based on the growth rate.

- Based on the two linear equations, the correlation between RTI growth rate and EPB occurrence rate can be expressed as,

$$EPB\ rate = 5.828 \times 10^4\gamma - 4.08$$

- Figure 6 reveals that the regions with the fastest growth rate shown in Figure 1 has an EPB occurrence probability of approximately 60 %.

Summary and Future Work

- The statistical results show that PRE vertical drift is related to both EPB occurrence rate and RTI growth rate. Therefore, we can establish a relationship between EPB occurrence rate and RTI growth rate.
- When the growth rate reaches 1×10^{-4}, the probability of a deep EPB event occurring is approximately 55%.
- The next step will involve studying the differences across various longitudes and the PRE velocity at various altitudes for the construction of an EPB alert system.

Acknowledgment

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