Impact of Anthropogenic Emission Changes on the Occurrence of Equatorial Plasma Bubbles

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Abstract In this work, we examine the impact of increased anthropogenic emissions on equatorial plasma bubble (EPB) occurrence by modeling the growth rate of Rayleigh-Taylor (R-T) instability ($\gamma_{RT}$), which is closely related to EPB generation. Using the global coupled ionosphere-thermosphere-electrodynamics model-institute of geology and geophysics, Chinese Academy of Sciences model, $\gamma_{RT}$ is calculated under three different CO2 emission levels. As CO2 increases, $\gamma_{RT}$ significantly increases at low altitudes (~260 km) and decreases at high altitudes (>~320 km). In the altitudes in between, $\gamma_{RT}$ increases (decreases) before (after) midnight. Longitudinal variability of the $\gamma_{RT}$ change is manifested apparently above ~280 km, while it is insignificant for low altitudes. Term analysis revealed that changes in the gravity term and the electric-field term are the main causes and that the neutral-wind term is insignificant. The investigation indicates that increased anthropogenic emissions can change EPB occurrence and, in turn, the radio-communication system and therefore influence modern technological systems, which is expected to be more serious in the future.

Plain Language Summary Equatorial plasma bubbles (EPBs) are ionospheric plasma irregularities that negatively influence radio propagation and even disrupt communication and navigation systems. In this work, we attempt to elucidate whether increased anthropogenic emissions impact EPB occurrence. To quantitatively characterize the EPB occurrence, the Rayleigh-Taylor (R-T) instability growth rate ($\gamma_{RT}$) defined by Sultan (1996), https://doi.org/10.1029/96ja00682 is used. Based on a thermosphere-ionosphere coupled model, global coupled ionosphere-thermosphere-electrodynamics model-institute of geology and geophysics, Chinese academy of sciences, $\gamma_{RT}$ is calculated for three different CO2 emission levels. The results show that as CO2 increases, $\gamma_{RT}$ significantly increases at low altitudes (~260 km) and decreases at high altitudes (~320 km). In the altitudes in between, $\gamma_{RT}$ increases before midnight but decreases after midnight. Longitudinal variability of the $\gamma_{RT}$ change is manifested apparently above ~280 km but is insignificant at low altitudes. As a first step, this work revealed a possible link between long-term anthropogenic climate change and short-term space weather events that impact modern communication.

1. Introduction

Equatorial plasma bubbles (EPBs) are ionospheric plasma disturbances that primarily occur at night when the ionospheric E-layer disappears (e.g., Kelley, 2009). The nighttime F-layer on top of the disappeared E-layer stimulates Rayleigh-Taylor (R-T) instability, which can cause EPBs. The existence of EPBs influences radio propagation and in turn induces ionospheric scintillations (Basu & Basu, 1981). Space-to-ground communication and global navigation satellite systems are also adversely affected and even disrupted (Panda et al., 2018; Seo et al., 2009). Hence, investigations on the spatiotemporal variability of EPB occurrence have attracted the interest of many researchers and are still a great challenge to date (Abdu, 2001; G. Li et al., 2021).

To our knowledge, whether EPB occurrence has long-term (over decades) changes in response to increased anthropogenic emissions is still unknown. The present global CO2 level is high and increases faster than ever (IPCC, 2021). Communication systems are experiencing explosive development, and the signal is negatively affected by the existence of EPBs in the ionosphere. The increased CO2 emissions could change the ionospheric electron profile and affect the dynamics and electrodynamics in the ionosphere-thermosphere system. Roble and Dickinson (1989) first proposed the cooling effect (~50 K) of doubling CO2 in the upper atmosphere, and then
Rishbeth (1990) theoretically analyzed whether doubling CO2 would lower the ionospheric F2-layer peak by approximately 20 km. Significant effort was then made to explain the relationship between CO2 increases and long-term trends of the upper atmosphere and ionosphere using both long-term observations and novel models (e.g., Cnoseen, 2014; Danilov & Mikhailov, 2001; H. Liu et al., 2020; Laštovička et al., 2006; Qian et al., 2009; Rishbeth & Roble, 1992; Solomon et al., 2018; S. R. Zhang & Holt, 2013; Yue et al., 2006). We naturally ask how the EPB occurrence changes as the I-T system changes with anthropogenic emissions. This problem has become urgent given the simultaneous rapid increase in greenhouse gas emissions and the dependence of modern society on wireless communication in recent years.

Examining the relationship from existing observations is quite difficult due to some limitations: (a) the influence of geomagnetic and solar variations is hard to remove, and (b) the history of continuous EPB observations is limited. Instead, modeling the generalized R-T instability (Sultan, 1996), which has been widely accepted to govern EPB occurrence, should be helpful to answer this question. Using the generalized R-T instability as a proxy to study EPB occurrence has been proven to be an effective method. In general, more EPBs are observed occurring in the solar maximum condition (D. H. Zhang et al., 2010), for which the R-T instability growth rate is also large (Wu, 2017). The observed seasonal dependence and longitudinal variability of EPB occurrence (Burke et al., 2004; Gentile et al., 2006; Kil et al., 2009) agrees well with the modeling R-T instability by Wu (2015). On the daily time scale, the day-to-day variability in the R-T instability growth rate shows some consistency with the daily variation in the observed S4 index (Carter et al., 2020). In addition, a high level of geomagnetic activity is generally associated with the occurrence of more frequent and stronger EPBs (G. Li et al., 2010). Relationship between the variations in the geomagnetic Kp index and the modeled R-T instability growth rate was also revealed (Carter, Retterer, et al., 2014). Hence, to elucidate this question, as a first step, we performed numerical experiments using a thermosphere-ionosphere coupling model to compare differences in the modeled R-T instability growth rate with different CO2 levels.

2. Model Description and Data Processing

The Global Coupled Ionosphere-Thermosphere-Electrodynamics Model developed at Institute of Geology and Geophysics, Chinese Academy of Sciences (GCITEM-IGGCAS; Ren et al., 2009), is a global three-dimensional ionosphere-thermosphere coupling model with an ionospheric dynamo module. The model self-consistently calculates the thermal structure, neutral and plasma density, neutral winds, and plasma velocity at heights of 90–600 km. The hydrodynamic equations are solved by the finite difference method in height coordinates with horizontal grids of $5^\circ \times 7.5^\circ$ (latitude $\times$ longitude). The vertical resolution ranges from $\sim 3$ km in the lower thermosphere to $\sim 30$ km in the upper thermosphere. The ionospheric electric fields at low- and mid-latitudes are solved by a magnetic flux-tube-based dynamo model, TIDM-IGGCAS-II (Theoretical Ionospheric Dynamo Model, Institute of Geology and Geophysics, Chinese Academy of Sciences, Version II; Ren et al., 2008). The TIDM-IGGCAS-II is calculated on the magnetic apex coordinate (Richmond, 1995), of which the geomagnetic field is configured by the International Geomagnetic Reference Field (IGRF; Thébault et al., 2015). At high latitudes, the empirical model Weimer-96 (Weimer, 1996) provides the distribution of electric potential and electric fields. The Weimer-96 model is driven by inputs of hemispheric power (HP), solar wind speed (SWS), interplanetary magnetic field (IMF), and cross polar cap potential (CPCP). The impact of extreme ultraviolet (EUV) radiation is described by an empirical model, EUVAC (Richards et al., 1994), which is driven by the F107 index. The CO2 cooling at 15 $\mu$m is calculated considering the nonlocal thermodynamic equilibrium (NLTE) effect with a cooling-to-space approximation assumed, which followed R. G. Roble et al. (1987) and is also adopted in other thermosphere-ionosphere coupled models, such as NCAR-TIEGCM (Qian et al., 2014; Richmond et al., 1992) and NCAR-TIMEGCM (R. G. Roble & Ridley, 1994). The lower boundary is specified by global thermal tides from temperature observations of the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER).

In this work, 3 cases perpetually run for a whole year with different CO2 emission levels, 315, 417, and 667 ppmv. The first case was in 1958 (Case-1958), when the modern technology detection of CO2 came out. The second case is for the present situation (Case-2021). The third case would be a prediction if the CO2 emissions continuously grew over the next 100 years (Case-2121) at the rate in the past 5 years ($\sim 2.5$ ppm/year). The external forcing of solar activity is held at a low level (F107 = 70 s.f.u). The geomagnetic condition is for a low-to-unsettled magnetic disturbance condition (HP = 50 GW; SWS = 500 km/s; IMF By = 0, Bz = 8 nT; CPCP = 60 keV), which corresponds to a Kp of approximately 4. To exclude the effects of secular geomagnetic field variation on...
the ionosphere-thermosphere system (Cnossen, 2014; Yue et al., 2018; Zhou et al., 2021), the geomagnetic fields in all three cases are conformably set for the same configuration.

The linear growth rate of the Rayleigh-Taylor instability is calculated as

\[
\gamma_{RT} = \frac{1}{\sum_{P}^{E} + \sum_{P}^{F}} \left( V_p - U_L^p - \frac{g_e}{\nu_{eff}} \right) K^F - R_T
\]

\(\sum_{P}^{E,F}\) is the flux-tube integral Pedersen conductivity in the E− and F-layers; \(U_L^p\) is the Pedersen conductivity-weighted neutral wind perpendicular to the magnetic lines in the meridian plane; \(V_p\) is the upward plasma velocity; \(g_e\) and \(\nu_{eff}\) are the height-corrected gravity acceleration and the effective ion-neutral collisional frequency, and \(K^F\) is the vertical gradient of flux-tube plasma content in the F-layer. \(R_T\) is the recombination rate, which is so small that it can be ignored (Carter, Yizengaw, et al., 2014). Detailed information on each term is provided in Sultan (1996). From the equation, we know that the large linear growth rate of R-T instability is determined by a steep vertical gradient of electron density (Ossakow, 1981) and is also provoked by eastward electric fields and down-equatorward neutral winds (Kelley, 2009). In this work, the interface height of the E− and F-layers is chosen to be 200 km, the same as Wu (2015) and Wu (2017). Discrete points in the integral calculation are sampled every 10 km along the magnetic field lines. The apex heights of each magnetic line range from 90 to 600 km, with an interval of 5 km. The value of each discrete point is interpolated from the uniform grids of the one-year averaged GCITEM-IGGCAS outputs.

3. Results and Discussion

Changes in the electron density profiles due to the increased CO2 simulated by the GCITEM-IGGCAS model are illustrated in Figure 1a. As the CO2 concentration increased, the low-latitude nighttime ionosphere shrank with a smaller F-layer peak density (NmF2) and a lower F-layer peak height (HmF2). In the past six decades, NmF2 has decreased by ~6% at night. The low-latitude averaged NmF2 will decrease further by over 10% in the next 100 years (Figure 1b). HmF2 would decrease merely approximately 2–4 km around noon but would decrease ~12 km if CO2 grows by 250 ppmv in the future (Figure 1c). The manifested CO2 modulation on the low-latitude ionospheric profile simulated by the GCITEM-IGGCAS model is similar to previous investigations (e.g., Qian et al., 2009). The changes should also affect the R-T instability growth rate (\(\gamma_{RT}\)), which is closely related to the vertical gradient of electron density. The modeled \(\gamma_{RT}\) generally achieves a large value (~8.0 \times 10^{-4} s^{-1}; the time scale is approximately 20 min) at apex heights of ~260–330 km and is close to 0 in the topside ionosphere (>400 km; Figure 2a). The result confirmed that the bottom of the F-layer should be the most likely place for the EPBs to form and develop. The modeled \(\gamma_{RT}\) begins to be strong after sunset and to diminish at sunrise. Maxima are found at local time (LT) of approximately 19–22 (Figures 2d–2g, and). It is understandable that large vertical drifts generally occurred at that LT due to the pre-reversal enhancement phenomenon (Kelley, 2009). Longitudinal variation clearly revealed that, for a yearly average I-T system, a large \(\gamma_{RT}\) is in the South American sector (0°–90°W), where the geomagnetic field is weakest. This result agrees with previous observations (Burke et al., 2004; Gentile et al., 2006) and simulations (Wu, 2015, 2017).

The increased CO2 emissions would significantly affect the \(\gamma_{RT}\). The \(\gamma_{RT}\) changes vary with height, longitude, and LT. At the lower ionosphere (~200–260 km), the nighttime \(\gamma_{RT}\) would increase ~3.0 \times 10^{-5} s^{-1} and ~6.0 \times 10^{-5} s^{-1}, responding to CO2 increases of 102 ppmv and 250 ppmv, respectively. In contrast, the \(\gamma_{RT}\) change is negative above ~320 km. Due to the CO2 increase, \(\gamma_{RT}\) would decrease ~2.0 \times 10^{-5} s^{-1} and ~4.0 \times 10^{-5} s^{-1} above the ionospheric F-layer peak (Figures 2b and 2c). As a reference, the maximum of the nighttime averaged \(\gamma_{RT}\) at the present level is ~3.0 \times 10^{-4} s^{-1}. The local-time variation of the \(\gamma_{RT}\) change also varies with height. At the lower ionosphere, the increase in \(\gamma_{RT}\) lasts almost all night, while its strength before midnight is larger than that after midnight (Figures 2e and 2f). If CO2 increases by 250 ppmv, the \(\gamma_{RT}\) increase would reach over 1.0 \times 10^{-4} s^{-1} (over 25% of the present value). At the upper ionospheric height (>320 km), \(\gamma_{RT}\) decreases all night instead, especially during LT 17–19 and LT 03–06. The longitudes with large declination during these two periods are
different: 80°W–20°E for the former and 160°E–100°W for the latter (Figures 2k and 2l). At the transition height (260–320 km), the maximum enhancement before midnight is also found at approximately 80°W–20°E and could extend eastwardly to 90°E (Figures 2h and 2i). The decrease after midnight is similar to that in the upper ionosphere. The relevant change in the altitudes in between is important, as the maximum value of the vertical profile has been demonstrated to be a good proxy having a strong correlation with the observed S4 index (Carter et al., 2020; Carter, Retterer, et al., 2014; Carter, Yizengaw, et al., 2014). As CO2 increases by 250 ppmv (102 ppmv), the relative increase in at 280 km height could reach ∼20% (10%). The results indicate that, as anthropogenic emissions increase, more EPBs should occur before midnight, with an increase rate of nearly 0.1% per ppmv, assuming that the EPB occurrence and are linearly correlated.

To examine the exact causes of the change, term analysis in Equation 1 is conducted. Figure 3 illustrates the differences between Case-2121 and Case-2021 at three typical heights (240 km, 280 km, and 360 km). At the lower ionosphere, the differences in are mainly caused by changes in the gravity term, \( \sum \frac{U_i^p K}{\sum \phi} \), and the electric field term \( \sum \frac{U_i^p K}{\sum \phi} \). As the height increases, the changes in the electric field term become increasingly unimportant, and the change is almost solely determined by the change in gravity term. The contribution from the change in the neutral wind term, \( \sum \frac{U_i^p K}{\sum \phi} \), is limited for all heights concerned. The vertical variation in the change in gravity term is mainly followed by CO2 modulation of the vertical profile of electron density. As the ionosphere shrinks (Figure 1a), both NmF2 and HmF2 decrease, and \( K^2 \) becomes large below ∼240 km and becomes small above (not shown). The ratio of \( \sum \phi \) and \( (\sum \phi)^p \) also changed differently with altitude: the ratio generally increases by approximately 0.03 below ∼260 km and decreases by approximately

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Apex-height (top row) variation of the at 00 UT (left) and differences in between Case-2021 and Case-1958 (middle) and between Case-2121 and Case-2021 (right) for different longitudes. Local-time (bottom row) variations are illustrated in the second to fourth rows for apex heights of 240 km, 280 km, and 360 km.
0.04 in the upper ionosphere, corresponding to the increasing (decreasing) F-layer electron density in the lower (upper) ionosphere (Figure 1a). The increased CO$_2$ cooling effect also significantly decreases the neutral temperature in the thermosphere, so the ion-neutral collisional frequency changes. In the simulation, the ion-neutral collisional frequency is calculated as Equations 2a–2d, which is based on the formula of Schunk and Nagy (1980). The temperature change mainly modulates the resonant ion-neutral interaction. As temperature decreases, the ion-neutral collisional rate would also decrease because the derivative of the collisional rate with the temperature (Equations 2a and 2b) is generally positive.

\[
\nu_{O^+}\rightarrow n = 6.82 \times 10^{-16}[N_2] + 6.64 \times 10^{-16}[O_2] \\
+3.67 \times 10^{-17}[O]\sqrt\left\{\frac{T_i + T_e}{2}\right\} \left(1 - 0.064 \log_{10}\frac{T_i + T_e}{2}\right)^2 
\]  

\[
\nu_{O^+}\rightarrow n = 4.13 \times 10^{-16}[N_2] + 2.31 \times 10^{-16}[O] \\
+2.59 \times 10^{-17}[O_2]\sqrt\left\{\frac{T_i + T_e}{2}\right\} \left(1 - 0.073 \log_{10}\frac{T_i + T_e}{2}\right)^2 
\]

\[
\nu_{NO^+}\rightarrow n = 4.34 \times 10^{-16}[N_2] + 4.27 \times 10^{-16}[O_2] + 2.44 \times 10^{-15}[O] 
\]

**Figure 3.** Changes in the Rayleigh-Taylor instability growth rate at different longitudes and local times (top row) caused by CO$_2$ increasing from 417 ppmv to 667 ppmv. Contributions from the gravity term (second row), electric-field term (third row), and neutral wind term (bottom row) are plotted for comparison. Plots from left to right are for apex heights of 240 km, 280 km, and 360 km, respectively.
The net effect of the three terms ($K^r$, $\sum P_r$, and $\nu_{i0}$) manifests as the gravity term increases (decreases) in the lower (upper) ionosphere. In the altitudes in between, complex local-time and longitudinal variation of the change in gravity term is a coupled result. The nightside westward electric field (downward drift velocity) becomes weak at ∼LT20–02. The change in nighttime electric fields should be driven by background thermospheric winds through the F-region dynamo (Maute & Richmond, 2017). The electric-field term becoming less important in the upper ionosphere comes from $V_p$, being almost constant not like the $1/v_{fpr}^2$, which exponentially increases with altitude. The net electric-field term manifests to be a positive contribution to the $\gamma_{RT}$ in LT20–02 and to be negative at other night times. These results reveal that the CO2 effect on the ionospheric Rayleigh-Taylor instability/EPBs occurrence is significant but complicated, including not only the vertical thermal and plasma structure but also the electrodynamics.

However, as a preliminary work on this topic, there are quite a few flaws. For example, gravity waves, which are regarded as an important seeding source for initializing EPBs (e.g., K. Liu et al., 2019; Singh et al., 1997), have not been considered. Limited observations have demonstrated the long-term trend of gravity wave activities (Hoffmann et al., 2011; Jacobi, 2014), but the trend is mainly caused by solar activity changes and is strongly dependent on the location and season. Whether the increase in anthropogenic emissions has a significant impact on gravity wave activity is still unknown. Much more effort could be made to depict the long-term changes in mesoscale atmospheric dynamics and establish a relationship with ionosphere behavior. Kelvin-Helmholtz (K-H) instability induced by the shear flow in the bottomside equatorial F region could also generate EPBs (Hysell & Kudeki, 2004). The time scale of the K-H instability is ∼50 min, which is several times that of the R-T instability. If anthropogenic emissions continue to increase, there would be intriguing questions regarding whether the background shear flow becomes strong or weak and whether it could significantly strengthen the K-H instability in turn. Another controlling factor on EPB occurrence is the solar activity level. Under varied solar activity conditions, anthropogenic climate change in the upper atmosphere also acts differently (Solomon et al., 2019). We set a constant solar minimum condition in this work, but how the EPB occurrence changes with increasing anthropogenic emissions under different solar conditions still needs investigation. In addition, as H. Liu et al. (2021) reported, geomagnetic activity could strengthen or weaken CO2-driven climate change in the upper atmosphere. The ionospheric long-term trend is also influenced by geomagnetic activity (Mikhailov & Marin, 2000; S. R. Zhang & Holt, 2013). An interesting topic is how the EPB occurrence changes under realistic varied geomagnetic conditions. The main geomagnetic fields have also been undergoing long-term variation, which is confirmed to be another important factor affecting the I-T system other than anthropogenic emission increases (e.g., Cnossen, 2014; Yue et al., 2018). It will be worth investigating the magnitude of the EPB occurrence response to long-term geomagnetic field variations. The newly developed EPB high-resolution models, including the SAMI3 (Huba & Joyce, 2010; Huba & Liu, 2020), High-Resolution Bubble model (Yokoyama et al., 2014), a two-dimensional model developed by Li Z. et al. (2021), and a three-dimensional model by Retterer (2010), should be useful tools to investigate how EPBs grow, bifurcate, and break into turbulence. Further investigations on the detailed physical processes of EPB with long-term changes in the background I-T system would also be interesting.

4. Conclusion

Numerical experiments using the GCITEM-IGGCAS model reveal that increased CO2 affects the growth rate of R-T instability ($\gamma_{RT}$), which is closely related to EPB occurrence. As CO2 increases, the EPB occurrence significantly increases in the lower ionosphere (<~260 km) and decreases in the upper ionosphere (>~320 km). In the altitudes in between, which is also around the $\gamma_{RT}$ peaks, $\gamma_{RT}$ increases before midnight but decreases after midnight. The maximum increase rate of $\gamma_{RT}$ enhancement around the peak height (∼280 km) due to increased CO2 is ∼0.1% per ppmv in the South American longitude sector. Obvious longitudinal variability of the $\gamma_{RT}$ change is found above ∼280 km. The primary contribution of the growth rate change is the change in the gravity term, and the change in the electric field term is also important at low altitudes. Changes in the neutral wind term are relatively unimportant. This work suggested that a long-term increase in anthropogenic emissions not only alters the steady state of the I-T system but also has the possibility to change the occurrence of short-term ionospheric irregularity, which in turn will influence the radio communication system and modern technological systems.
Data Availability Statement

The simulated data used in this paper can be downloaded at https://zenodo.org/record/5759337#.Yax8jNBBwQ8.

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