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Effects of pre-reversal enhancement of $E \times B$ drift on the latitudinal extension of plasma bubble in Southeast Asia

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Abstract

We investigated the effects of the F region bottomside altitude ($h'F$), maximum upward $E \times B$ drift velocity, duration of pre-reversal enhancement and the integral of upward $E \times B$ drift on the latitudinal extension of equatorial plasma bubbles in the Southeast Asian sector using the observations recorded by three GPS receivers and two ionosondes. The GPS receivers are installed at Kototabang (0.2°S, 100.3°E; 9.9°S magnetic latitude), Pontianak (0.02°S, 109.3°E; 9.8°S magnetic latitude) and Bandung (6.9°S, 107.6°E; 16.7°S magnetic latitude) in Indonesia. The ionosondes are installed at magnetically equatorial stations, Chumphon (10.7°N, 99.4°E; 0.86°N magnetic latitude) in Thailand and Bac Lieu (9.3°N, 105.7°E; 0.62°N magnetic latitude) in Vietnam. We analysed those observations acquired in the equinoctial months (March, April, September and October) in 2010–2012, when the solar activity index $F_{10.7}$ was in the range from 75 to 150. Assuming that plasma bubbles are the major source of scintillations, the latitudinal extension of the bubbles was determined according to the S4 index. We have found that the peak of $h'F$, maximum upward $E \times B$ drift and the integral of upward $E \times B$ drift during the pre-reversal enhancement period are positively correlated with the maximum latitude extension of plasma bubbles, but that duration of pre-reversal enhancement does not show correlation. The plasma bubbles reached magnetic latitudes of 10°–20° in the following conditions: (1) the peak value of $h'F$ is greater than 250–450 km, (2) the maximum upward $E \times B$ drift is greater than 10–70 m/s and (3) the integral of upward $E \times B$ drift is greater than 50–250 m/s. These results suggest that the latitudinal extension of plasma bubbles is controlled mainly by the magnitude of pre-reversal enhancement and the peak value of $h'F$ at the initial phase of development of plasma bubbles (or equatorial spread F) rather than by the duration of pre-reversal enhancement.

Keywords: Equatorial ionosphere; Plasma bubble; Pre-reversal enhancement; Scintillation

Background

Plasma bubble refers to depletion of plasma density at the nighttime equatorial and low-latitude region and is generated through the Rayleigh-Taylor instability (RTI) mechanism (Sultan 1996; Fejer et al. 1999). Even though plasma bubble generation may need a seed perturbation to trigger the instability (Tsunoda 2010; Narayanan et al. 2014), one of the most important factor for the plasma bubble growth is zonal electric field. At the sunset terminator, the eastward electric field is enhanced before the electric field become westward during nighttime.

This phenomenon is called pre-reversal enhancement (PRE). PRE causes an enhanced upward $E \times B$ drift in the post-sunset sector and thus affects the plasma bubble generation significantly by lifting the ionosphere to higher altitudes, where the growth rate of the RTI is large because of the small ion-neutral collision. The magnitude of the PRE depends on season, solar cycle and longitude (Fejer et al. 1999). The thresholds of PRE strength under different solar and magnetic activities have been inferred for plasma bubble onset (Farley et al. 1970; Jayachandran et al. 1993; Fejer et al. 1999).

Previous studies have investigated relation between the strength of PRE (as indicated by the peak of $h'F$, peak vertical drift velocity and magnitude and latitudinal extension of EIA crest) and latitudinal/altitudinal extension of plasma bubble in some longitudinal sectors (see, for

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example Valladares et al. 2004; Beniguel et al. 2009; Dabas et al. 1998; Bagiya et al. 2013). Plasma density irregularities within plasma bubble cause scintillation, which is the fluctuation of amplitude and/or phase of the radio wave propagating from satellites to ground-based receiver through the ionosphere. Since the irregularities exist within the plasma bubbles, the scintillation region coincided with the plasma bubbles. Therefore, by the GPS scintillation measurement, latitudinal extension of the plasma bubbles can be observed. By analysing the GPS data in the American sector in September 2001–June 2002 (solar maximum period), Valladares et al. (2004) have found that TEC depletion/GPS scintillation can reach more than 8° from magnetic equator when the peak of $h'F$ at the magnetic equator is above 500 km. In the Indian sector during September–October 1989 when $F_{10.7}$ was 100–300, scintillation at 4 GHz occurred over the equatorial region when $h'F$ at the magnetic equator exceeded 400 km and that scintillation occurred at low latitudes when $h'F$ at the magnetic equator exceeded 500 km with vertical drift velocity 30 m/s or more (Dabas et al. 1998). These results indicate that uplift of F layer to higher altitude

is responsible for higher latitudinal extension of plasma bubble. Recently, Bagiya et al. (2013) have reported that $h'F$ at 19:30 LT in the Indian equatorial region is well correlated with the altitudinal extension of spread F , which corresponds to the latitudinal extension of plasma bubbles.

In this study, we aim to disclose the relation between PRE and the latitudinal extension of plasma bubbles in the Southeast Asian region. We use $h'F$ and vertical drift velocity, obtained from ionosondes in the magnetic equator, to investigate effect of the PRE on latitudinal extension of plasma bubble. The latitudinal extension of plasma bubble is observed by GPS receivers installed at three sites in Indonesia.

Methods

Frequency-modulated continuous wave (FMCW) ionosondes are operated at Chumphon (10.7°N, 99.4°E; 0.86°N magnetic latitude) in Thailand and at Bac Lieu (9.3°N, 105.7°E; 0.62°N magnetic latitude) in Vietnam as a part of the SEALION (Southeast Asia low-latitude ionospheric network) project (for details, see Maruyama et al. 2007). The locations of the ionosondes are shown in Fig. 1. We

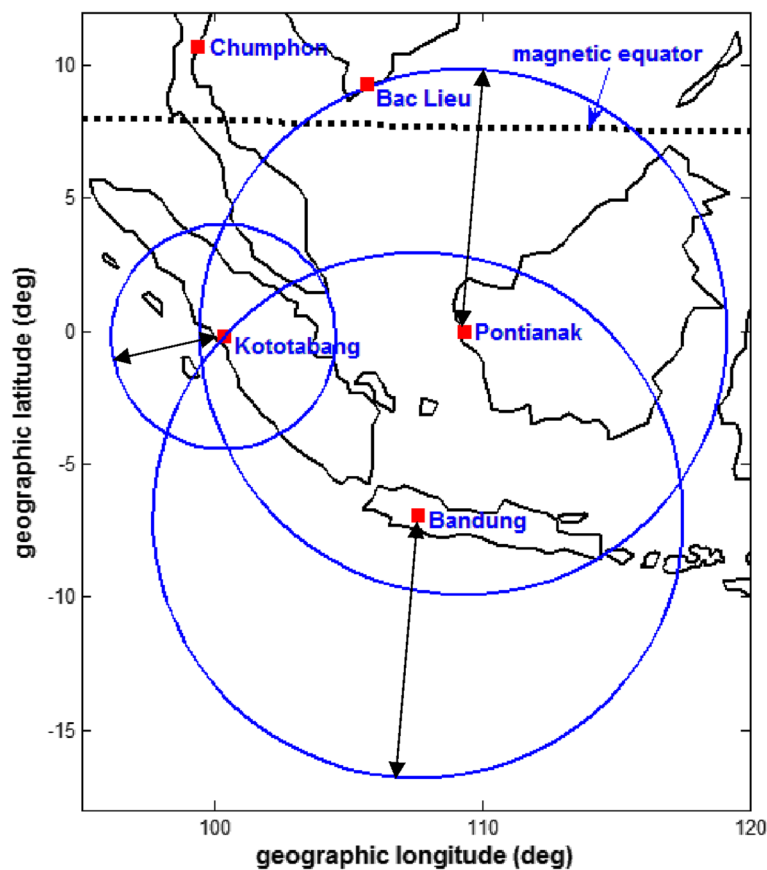


Fig. 1 Geometry of study observations. Two FMCW ionosondes are installed at Chumphon and Bac Lieu. Three GPS receivers for monitoring GPS L1 scintillation are installed at Kototabang, Pontianak and Bandung. Circles indicate the field-of-view of the GPS scintillation measurements assuming that the ionospheric pierce points of GPS radio path exists at an altitude of 300 km

manually scaled the virtual height ($h'F$) at 2.5–3 MHz from the ionograms at time intervals of 10 min between 18:00 and 24:00 LT (LT = UT + 7 h) for equinoctial months (March, April, September and October) in 2010, 2011 and 2012. The solar activity index $F_{10.7}$ in this period ranged from 75 to 150.

The $h'F$ at 2.5–3 MHz is a good indicator for altitude of the F layer bottomside in the post-sunset period. The value of $h'F$ at 2.5–3 MHz with higher altitude after sunset provides information about the dynamic process in the F layer, particularly vertical motion due to $E \times B$ drift after sunset (Maruyama et al. 2007). We considered that the vertical drift derived from $dh'F/dt$ with $h'F$ exceeding 300 km can be a good indicator for true vertical motion during nighttime.

Three GPS receivers installed in the western part of Indonesia are used to observe ionospheric scintillation activity at night in the equinoctial months of 2010, 2011 and 2012. Two of the three GPS receivers which have been operated at Bandung (6.9°S, 107.6°E; 16.7°S magnetic latitude) and Pontianak (0.02°S, 109.3°E; 9.8°S magnetic latitude) are Novatel GSV4004B units. The GSV4004B provides the S4 index, which represents magnitude of the amplitude scintillations. S4 is defined as the ratio of standard deviation of the received signal intensity to the average. In this study, we use the S4 index taken from satellite elevation angles greater than 10°. Scintillation due to multipath frequently occurs at elevation angles less than 30°. We have excluded scintillation due to multipath, by applying the method of Abadi et al. (2014), who have successfully excluded multipath-affected scintillation using the standard deviation of code-carrier divergence (sigma-CCDiv) measure. The other GPS receiver was installed at Kototabang (0.2°S, 100.3°E; 9.9°S magnetic latitude). This receiver measures signal intensity of the GPS radio waves of the L1 frequency at a sampling rate of 20 Hz. We calculated the S4 index from the measured signal intensity. However, the multipath effects were not excluded from the scintillation data obtained from this receiver because this receiver does not provide code-carrier divergence data. Consequently, in order to minimise the multipath effects, we used only the S4 indices taken with elevation angle higher than 30°.

Figure 1 shows the geometry of the observations. Two ionosondes are located near the magnetic equator. From the rate of increase in $h'F$ at the magnetic equator, we estimated vertical drift caused by eastward electric fields during the PRE period. The field-of-view of all GPS receivers covers an area from near the magnetic equator up to 15°S in geographic latitude. The geometry of the observations therefore allows us to study the relation between the upward $E \times B$ drift and the latitudinal extension of plasma bubble at the low latitudes in the Southeast Asian sector.

Analysis methods

Figure 2 shows local time variations of $h'F$ at 3 MHz and vertical drift derived from the rate of change of $h'F$ (i.e., $dh'F/dt$), as obtained by the ionograms at Chumphon on 26 October 2012. The value of $h'F$ increased between 17:10 and 19:20 LT, reached a maximum at 19:20 LT and decreased afterward. The increase of $h'F$ could be caused by an enhancement of the eastward electric field (E) at the evening terminator, so-called PRE. Bittencourt and Abdu (1981) showed that $dh'F/dt$ closely represents the upward $E \times B$ drift when $h'F$ exceeds about 300 km. According to their result, we calculate the upward $E \times B$ drift (hereafter denoted as V_u) from $dh'F/dt$ when $h'F$ exceeds about 300 km and use the obtained value as a proxy for the eastward E . In this study, we consider that the maximum V_u is one of the important parameters for latitudinal extension of plasma bubble. In Fig. 2, the maximum $dh'F/dt$ during a period between 17:10 and 19:20 LT is defined as maximum V_u .

There are two major causes of uncertainties in $h'F$. When $h'F$ is low, recombination of the plasma density is dominant. For this case, $h'F$ variation does not represent actual movement of the F layer altitude, so that eastward electric field cannot be estimated from the $h'F$ variation. When $h'F$ is less than 300 km, it is probably affected by the recombination process (Bittencourt and Abdu 1981; Maruyama et al. 2007). Therefore, in the present study, we do not use the data when $h'F$ is less than 300 km. Another source of uncertainty is spread F . We exclude $h'F$ and $dh'F/dt$ during the period of spread F occurrence because accuracy for scaling $h'F$ is degraded during the spread F event due to spread of the F layer trace in the ionogram. In Fig. 2, the occurrence of spread F (19:30–22:00 LT) is shown by a red solid rectangle. The spread F occurred after $h'F$ reached a peak. Since spread F occurs after a peak of $h'F$, V_u can be obtained in the above-mentioned procedure.

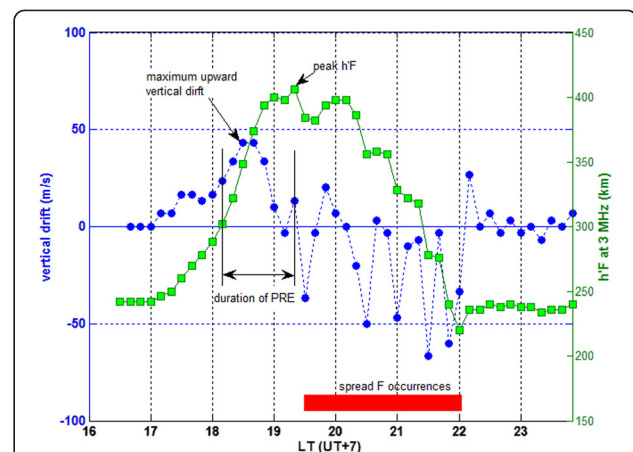


Fig. 2 Local time variations of height of the F layer and vertical drift, as derived from Chumphon ionograms with 26 October 2012 data

In addition to the peak $h'F$ and maximum V_u , we also consider the duration of PRE as a parameter affecting the latitudinal extension of plasma bubble. Krall et al. (2010) have numerically investigated why plasma bubble stops rising and concluded that plasma bubble stops rising when eastward E at the upper edge of the bubble is equal to zero. This result suggests that the duration of PRE at plasma bubble generation could affect the latitudinal extension of plasma bubble. We define the duration of PRE as a period from the start of positive $dh'F/dt$ until the time of the peak $h'F$. To reduce the uncertainty of $h'F$, we exclude $h'F$ lower than an altitude of 300 km. In Fig. 2, shown as an example, $dh'F/dt$ starts increasing at 17:10 LT. However, $h'F$ between 17:10 and 18:00 LT does not exceed an altitude of 300 km. For this case, start of V_u is determined to be 18:10 LT. The end of V_u is determined to be 19:20 LT, when $h'F$ reaches a peak.

The last parameter we also consider in this study is the integral of V_u during the PRE period. We calculate sum of $dh'F/dt$ during a period of duration of PRE

defined in the above procedure. We also use it as the integral of V_u .

In this study, to investigate the effects of PRE on the maximum latitudinal extension of plasma bubbles, we have used two datasets. The first (group 1) is used for comparison of peak $h'F$, maximum V_u , duration of PRE and integral of V_u obtained from the Chumphon ionosonde with the maximum latitude of scintillation observed by the GPS receivers at Kototabang and Bandung between 18:00 and 22:00 LT. We assumed that the ionospheric altitude of the pierce point for the GPS scintillation measurements is at an altitude of 300 km. The other (group 2) is the same comparison but using the Bac Lieu ionosonde and the GPS receivers at Pontianak and Bandung.

Results

Figure 3a–d shows the latitude of scintillation furthest away from the magnetic equator (the maximum latitude of scintillation) during 18:00–22:00 LT as a function of the peak $h'F$, maximum V_u , duration of PRE and integral

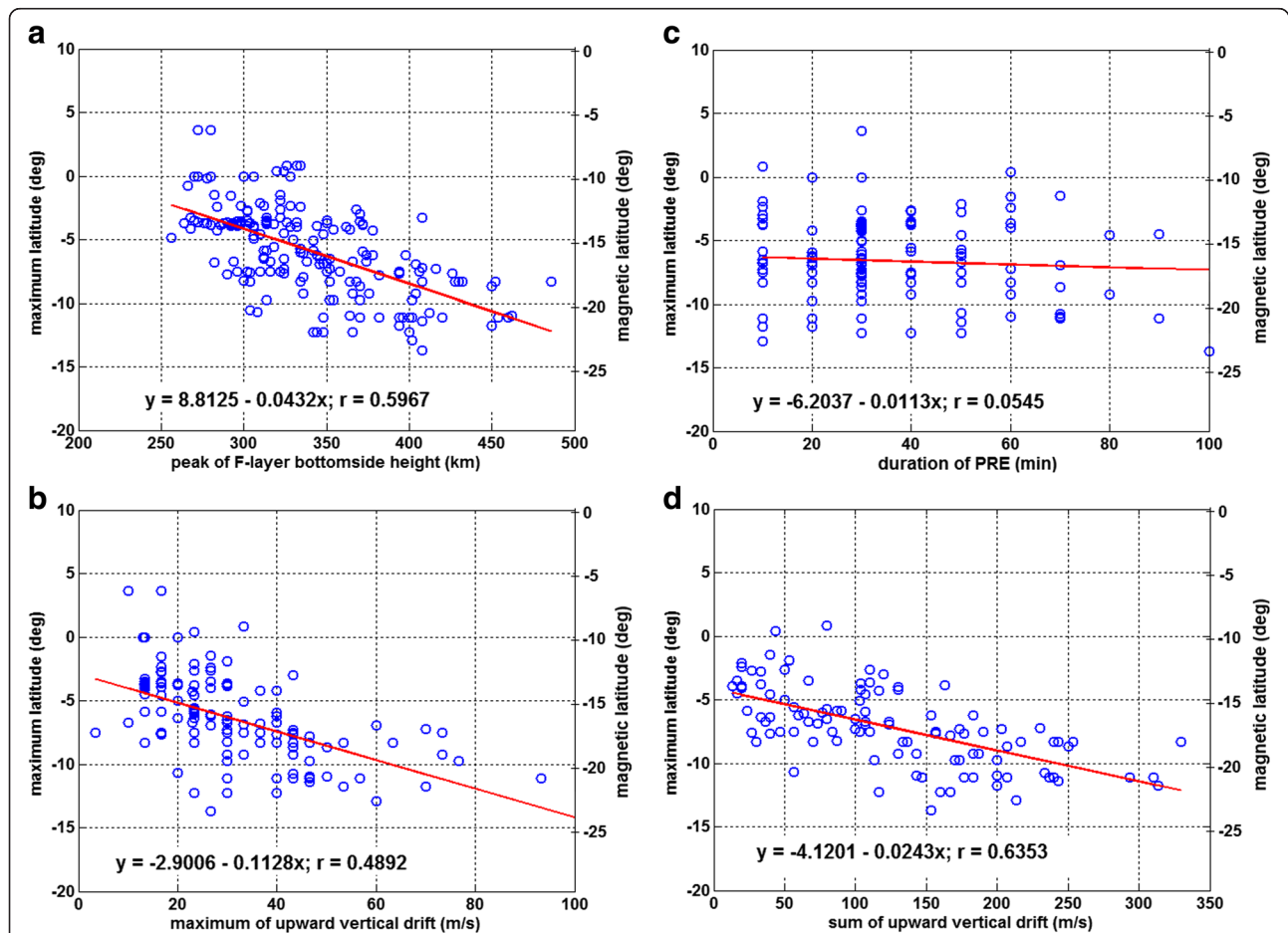


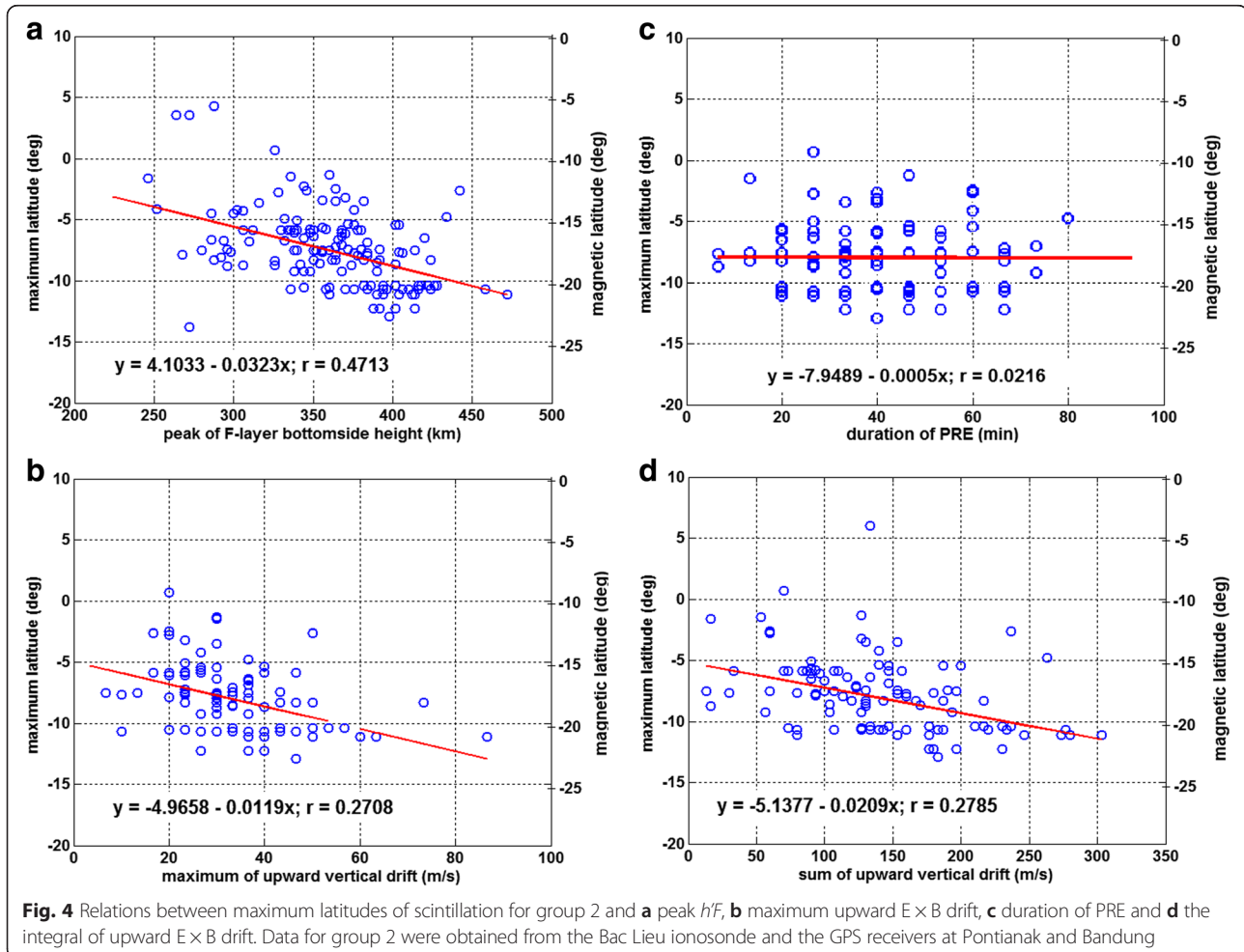
Fig. 3 Relations between maximum latitudes of scintillation for group 1 and **a** peak $h'F$, **b** maximum upward $E \times B$ drift, **c** duration of PRE and **d** the integral of upward $E \times B$ drift. Data for group 1 were obtained from the Chumphon ionosonde and the GPS receivers at Kototabang and Bandung. The y-axis in the right side in each panel indicates magnetic latitude at geographic longitude 99.4°E. Red lines indicate the linear relation between the two parameters in each panel

of V_u , respectively, obtained from group 1 (ionosonde at Chumphon and GPS scintillation at Bandung and Pontianak). From the figure, most of the maximum latitudes of the scintillation during the observation period are found to distribute from 0°S to 10°S corresponding to 10°S–20°S magnetic latitudes in the Southeast Asian longitudinal sector. The peak $h'F$ ranges from 250 to 450 km, maximum V_u from 10 to 70 m/s and integral of V_u from 50 to 250 m/s. A red line in each panel in Fig. 3 represents the linear relation (as obtained by linear regression) between the two corresponding parameters, and the cross-correlation coefficient is noted. The cross-correlation coefficients for the relations of the maximum latitudes of scintillation to the peak $h'F$, maximum V_u , duration of PRE and integral of V_u are 0.6, 0.5, 0.05 and 0.5, respectively. Thus, we can reasonably assert that the maximum latitudes of scintillation are positively correlated with the peak $h'F$, maximum V_u and integral of V_u , and that there is no correlation between the maximum latitude of scintillation and the duration of PRE.

Figure 4a–d is same as Fig. 3a–d but for group 2 data. The maximum latitude of scintillation observed at

Pontianak and Bandung stations is plotted as a function of the peak $h'F$, maximum V_u , duration of PRE and integral of V_u measured at Bac Lieu. Red straight lines represent linear relations, and the cross-correlation coefficient between the two parameters is noted in each panel. Most of the maximum latitudes of scintillation occur in the range between 0°S–10°S, with the peak $h'F$ varying with 250–450 km, maximum V_u varying with 10–60 m/s and integral of V_u varying with 50–250 m/s. Cross-correlation coefficients for the relations of the maximum latitudes of scintillation to the peak $h'F$, maximum V_u , duration of PRE and integral of V_u for group 2 are 0.4, 0.3, 0.02 and 0.3, respectively. These results are consistent with those for group 1 although the data for group 2 are scattered widely compared to the data for group 1. On the basis of the above results for groups 1 and 2, we find that the peak $h'F$, maximum V_u and integral of V_u at the equatorial region are well positively correlated with the maximum latitudinal extension of plasma bubble.

Here, we discuss a possible reason why the data are scattered. Plasma bubbles are generated during the PRE at the evening terminator and move eastward with the



same velocity as ambient plasma. In this study, we use the GPS scintillation data to measure the maximum latitudinal extension of the plasma bubble. The field-of-view of the GPS covers approximately 20° of longitude, as shown in Fig. 1. Although the local time is limited to 4 h between 18:00 and 22:00 LT, plasma bubble observed after the PRE could be generated at the west of the observed location. In this case, the longitude of the observed $h'F$ and V_u is different from the longitude where the plasma bubble occurs. The difference in longitude is 19° at the most, assuming that the plasma bubble moves at a velocity of 150 m/s. The longitudinal difference between the PRE and observed plasma bubble may be responsible for the scatter of the relation between the PRE and maximum latitudinal extension of plasma bubbles.

Discussion

Since the region of scintillation coincides with the plasma bubble, we can investigate the location where plasma bubble exists by using GPS-scintillation monitoring. Abdu et al. (1983) have confirmed that plasma bubble in the post-sunset sector at low-latitude regions could arise from latitudinal extension of plasma bubble generated primarily over the magnetic equator. We can consider that plasma bubbles are extended from the magnetic equator to the location at which the scintillation is observed.

Statistically, our finding of good correlation of the maximum latitude of scintillation versus the peak $h'F$ and magnitude of PRE reaffirms that the altitude of the F layer and V_u at the initial growth of plasma bubble is important in deciding how far plasma bubbles will extend. We have found that peak $h'F$ ranges from 250 to 450 km, maximum V_u from 10 to 70 m/s and integral of V_u from 50 to 250 m/s when the maximum latitudinal extension of plasma bubble varies from 0°S to 10°S (10°S – 20°S magnetic latitude). In the present study, we used the data during a period of $F_{10.7}$ varying from 75 to 150. It is well known that the strength of PRE depends on solar activity. Jayachandran et al. (1993) have reported that the threshold of the F layer altitude determined at 5.5 MHz for plasma bubble generation are 350 and 450 km when the mean of $F_{10.7}$ are 70 and 120, respectively. Fejer et al. (1999) have also shown that the upward drifts larger than about 5–10 m/s and about 40–45 m/s play a dominant role in plasma bubble generation at solar minimum and maximum, respectively. Our results of the peak $h'F$ and the magnitude of PRE for plasma bubble generation are consistent with these previous studies. V_u at the equatorial region lifts the F layer to higher altitudes, where the frequency of ion-neutral collisions is low. Considering the linear growth rate of the RTI (Sultan 1996), it is reasonable that the low ion-neutral collision frequency makes the growth rate large, so that such condition allows the plasma bubble to reach higher altitudes. Thus, in this

study, statistical study of our observation imply that the post-sunset magnitude of PRE and the F layer altitude play an important role in determining the altitudinal and latitudinal extension of the plasma bubbles.

Figure 5 displays amplitude scintillation index (S_4) at maximum latitude for each scintillation event obtained from the Kototabang–Bandung (group 1) and Pontianak–Bandung (group 2) GPS receivers. We have found that strong scintillation (S_4 index >0.5) occurs between 5°S and 10°S (15°S – 20°S in magnetic latitude). These latitudinal ranges in the Southeast Asia longitudinal sector correspond to the EIA crest region. Beniguel et al. (2009) and Abadi et al. (2014) have reported that strong scintillations were concentrated in EIA crest region. Since intensity of the amplitude scintillation is proportional to amplitude of the plasma density, the strong scintillations occur at the EIA crest region, where the plasma density is high. On the other hand, in Fig. 5, we can see that weak scintillations are distributed not only at latitudes of the EIA crest region but also at outside of the EIA crest region. Actually, Valladares et al. (2004) have reported that the maximum latitudes of scintillation are mostly located at lower latitudes than the boundary of the EIA crest at the American longitudinal sector. By detecting weak scintillation, we can investigate latitudinal extension of plasma bubble.

Regarding relation between the latitudinal extension of plasma bubble and the duration of PRE, we have supposed that if vertical drift persists for a long time, plasma bubble may grow for a longer period and thus reach higher altitudes and latitudes; consequently, latitudinal extension of plasma bubble might be higher when the vertical drift persists a longer period. As shown in Figs. 3c and 4c, however, there is no correlation between the duration of PRE and the maximum latitudinal extension of scintillations.

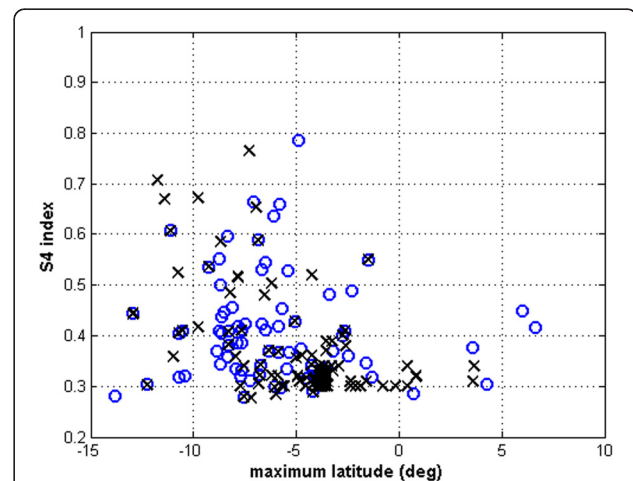


Fig. 5 Distribution of scintillation index, S_4 as a function of maximum latitudes scintillation observed for each day by GPS receivers (blue circle) at Kototabang and Bandung (group 1) and (black cross) at Pontianak and Bandung (group 2)

This result indicates that duration of PRE may not play an important role in the altitudinal and latitudinal extension of plasma bubble. Consequently, our findings in this paper indicate that the altitudinal and latitudinal extension of plasma bubbles largely depend on the magnitude of PRE, rather than on the duration of PRE.

Conclusions

We investigated the effects of the peak $h'F$ and magnitude and duration of PRE on the latitudinal extension of plasma bubble in the Southeast Asian region, under the assumption that region of scintillation coincides with plasma bubble or plasma depletion. We have found that plasma bubble reaches 10° – 20° magnetic latitudes empirically in the following conditions: (1) the peak $h'F$ is greater than 250–450 km, (2) the maximum V_u is greater than 10–70 m/s and (3) the integral of V_u is greater than 50–250 m/s. We have also found that the maximum latitudinal extension of plasma bubble is well positively correlated with the peak $h'F$, maximum V_u and the integral of V_u , but that it is not correlated with the duration of PRE. These results indicate that the altitude of the F layer, the maximum V_u and the integral of V_u at the initial phase of plasma bubble generation strongly control the altitudinal and latitudinal extension of plasma bubble. The duration of PRE may not play an important role in extension of plasma bubble. These results can be interpreted as follows.

The large eastward electric field lifts up the F layer to a higher altitude through $E \times B$ drift. At higher altitude, where the frequency of neutral-ion collisions is lower, the growth rate of plasma bubble becomes larger. This helps the bubble to grow and reach higher altitude. In short, our finding indicates that the key factor of plasma bubble extension is the altitude of bottomside F layer and the magnitude of PRE, not the duration of PRE.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

PA carried out the major part of data analysis and wrote the manuscript. YO was involved in interpretation of data analysis and organization of the paper. TT participated in reviewing the paper and is responsible person for SEALION project. All authors read and approved the final manuscript.

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