3-2-3 Large-Scale Zonal Structure of the Equatorial Ionosphere and Equatorial Spread F Occurrence

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Ionospheric height variations associated with the prereversal enhancement (PRE) were compared between two ionosonde stations near the magnetic equator (Chumphon, Thailand (10.7°N, 99.4°E, +3.3° magnetic latitude), Bac Lieu, Vietnam (9.3°N, 105.7°E, +1.6° magnetic latitude)) separated by 6.34° in longitude. Variations of ionospheric virtual height at 2.5 MHz (h'F) and equatorial spread F (ESF) occurrences were analyzed for a period from March to April, 2006. The results show that h'F variations at the two stations were very similar when no ESF was observed. However, h'F variations at the two stations were often very different when ESF was observed. This indicates that the ionospheric height enhancement, and hence the eastward electric field associated with PRE is quite localized when ESF occurs. Ionospheric structures with a zonal scale of several 100 km appear to be play an important role in the ESF occurrence.

Keywords
Plasma bubble, Equatorial spread F, Day-to-day variation of plasma bubble occurrence, Large-scale zonal structure of the ionosphere, SEALION ionosonde network

1 Introduction

Plasma bubbles are low-latitude equatorial magnetic phenomena that appear in ionosonde observations as intense range-type spread F (equatorial spread F or ESF). Sharp changes in TEC and scintillations in satellite radio waves resulting from various scales of ionospheric irregularities associated with plasma bubbles can lead to degraded satellite positioning or communication. The physical mechanism of plasma bubble formation is commonly associated with Rayleigh-Taylor plasma instability, resulting from a significant ionospheric uplift caused by an intense eastward ionospheric electric field around the sunset known as prereversal enhancement (PRE). Yet, the mechanism that governs day-to-day variations of plasma bubble occurrence has yet to be elucidated, and its elucidation should offer immense value to space weather prediction tasks, since this mechanism would aid in forecasting the formation of plasma bubbles that detract from the practical usefulness of satellite positioning and communication.

The iterative formation of ESF or plasma bubbles with a certain degree of periodicity overnight has been known from past observations based on transequatorial HF propagation measurements[1][2], aircraft-mounted airglow imager measurements[3], satellite observations[4], observations using incoherent scatter radars[5], and those based on coherent scatter radars[6]. Table 1 summarizes the space intervals of ESF/plasma bubbles derived from those observations. It has been pointed out that these large-scale quasi-periodic structures may be involved in the formation of ESF and plasma bubbles[5][6].

Tsunoda[5] conducted an observation[7] using ALTAIR incoherent scatter radar at the Kwajalein Atoll, and discovered the existence of a large-scale wave structure (LSWS) having a wavelength of about 400 km when plasma

Table 1 *Documented scales of ionospheric wave structures*

Literature	Ionospheric wave structure scale (km)
Röttger (1973)	380
Weber et al. (1980)	100 – 700 (1 – 6°)
Tsunoda (2005)	400
Lin et al. (2005)	300 – 1000
Fukao et al. (2006)	370 – 1000
Maruyama and Kawamura (2006)	2090

bubbles form. This LSWS is also known to be stationary relative to the ground and appears as a standing wave when observed from the ground. More recently, Tsunoda and Ecklund[8] conducted observations using a VHF coherent scatter radar to demonstrate that the velocity of the upward flow associated with plasma bubbles is superimposed with two components having a PRE-like east-west scale (of 2000 to 3000 km) and a LSWS east-west scale (of several hundred kilometers), respectively. Moreover, Tsunoda[9] found that the formation of ESF was preceded by increased ionosonde echo intensity, resulting in iterations of pronounced multi-reflection between the ionosphere and ground, and interpreted the phenomenon as pointing to a focusing effect resulting from a curved ionospheric isoelectronic density surface caused by LSWS.

Fukao et al.[6] conducted observations using equatorial atmosphere radar installed in Indonesia, and discovered the frequent formation of multiple plasma bubbles, each separated by distance of 370 to 1000 km. They speculated that this formation was a consequence of the ionosphere having been directly or indirectly modulated by atmospheric gravitational waves propagated from the lower atmosphere[6].

Fejer et al.[9] also probed the issue of east-west spatial changes in the ionospheric electric field associated with PRE, and found that the relation of ionospheric vertical drift velocity between two locations in Peru (Jicamarca and Huancayo) separated by an east-west distance of 170 km would vary significantly from day to day. In considering the similarities noted in observations between both locations on average, Fejer et al.[10] believed that such day-to-day variability resulted from differences in the observation methodology used (i.e., an incoherent scatter radar used at Jicamaraca versus an ionosonde at Huancayo).

All these previous studies suggest that a wave structure stretching several hundred kilometers is a key factor in plasma bubble formation. However, the physical mechanism that creates such a wave structure has yet to be identified. One possible reason for the slow pace of progress in understanding the physical mechanism of LSWS creation as revealed by these studies is the small number of observations analyzed by Tsunoda[5] and Fukao et al.[6] Another reason is the inadequate distance between Jicamarca and Huancayo for probing a wave structure stretching on an order of several hundred kilometers. Yet another reason in observations conducted by Fukao et al.[6] is the lack of background ionospheric information.

In this study, the authors observed PRE using two ionosondes installed 700 km apart (east and west) along the magnetic equator in Southeast Asia for the first time ever, in order to scrutinize the effect of a LSWS stretching several hundred kilometers when a plasma bubble forms. The role of this LSWS in the formation of ESF was thus reviewed by using the observation data, the relation between day-to-day variations in the formation of ESF, and the zonal changes in ionospheric height variations.

Although this study was intended to elucidate the physical mechanism of plasma bubble formation, the term “plasma bubble” is not used under observational constraints described later; instead, the term “equatorial spread F (ESF)” is used to describe the existence of irregularities involving plasma bubbles.

This report is based on the work of Saito and Maruyama[11] as published in Geophysical Research Letters in 2007.

2 Observations

In this study, the authors conducted a simultaneous observation program at Chumphon, Thailand (10.7ºN, 99.4ºE, magnetic latitude +3.3º) and Bac Lieu, Vietnam (9.3ºN, 105.7ºE, magnetic latitude +1.6º) that are aligned east and west along the magnetic equator, among the ionosonde stations that comprise the SEALION ionospheric observation network[12][13]. Figure 1 summarizes the information about both locations. Chumphon and Bac Lieu are located at 7.8° latitude (738 km apart east and west at a height of 300 km), with a local time gap of 25.4 minutes.

This observation program employed an observed frequency range of 2 to 30 MHz, with five-minute observation intervals. Table 2 lists the observation parameters used in this study. For more details about the ionosonde observation methodology of the SEALION observation network, refer to another article[14] published in this journal.

The simultaneous observation program began at the two locations on December 5, 2005, and has since been pursued without interruption, except for outages to conduct equipment maintenance.

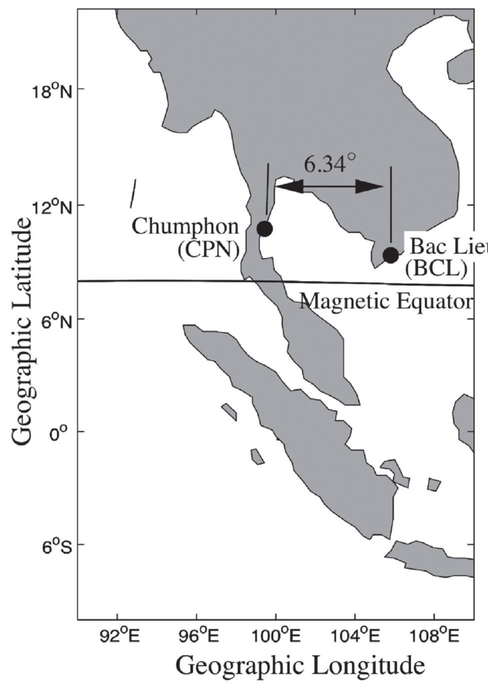

Fig. 1 Locations of ionosonde stations

Table 2 Ionosonde observation parameters

Type	Frequency modulated-continuous wave (FM-CW) (Switched between transmission and reception by pseudo-random code)
Transmitting power (peak)	20 W
Transmitting power (average)	10 W
Frequency sweep range	2–30 MHz
Frequency seep rate	100 kHz s^{-1}
Sweep repetition period	5 min

3 Analytical method

In this study, the virtual height (h'F) manually read at 2.5 MHz (corresponding to electron density of $7.75 \cdot 10^{10}$ m^{-3}) was used as a measure of ionospheric height variations for the reasons based on the work by Bittencourt and Abdu[15]. For a more detailed explanation and notes, refer to the other article[14] published in this journal as mentioned earlier. The occurrence of ionospheric F-region irregularities can be identified by the appearance of equatorial spread F (ESF). In this study, the values of h'F and ESF were scaled from ionograms collected every five minutes. There are three ESF classifications: intense range-type, weak range-type, and multi-trace echo. This study defined intense range-type ESF as an F-region ionogram appearing obscure in the height direction, and losing its characteristic form in the vicinity of critical frequency; weak range-type ESF as an F-region ionogram appearing obscure in the height direction but still retaining its characteristic form in the vicinity of critical frequency; and multi-trace echo as an appearance of multiple clear F-region ionogram traces. Figure 2 shows examples of these three types of ionograms.

When a plasma bubble forms, it appears on an ionosonde as being ESF, but not all types of ESF are plasma bubbles. For example, irregularities that have not grown into a plasma bubble to reach the topside of the peak of the ionospheric F-region, but remain in the bottomside ionosphere in the vicinity of the magnetic equator would be observed as ESF around the magnetic equator. A plasma bubble and bottomside ionospheric irregularities can be distinguished by examining the status of ESF growing along the magnetic meridian plane as reported in another article[14] published in this journal. However, this study had no low magnetic latitude observation station associated with Bac Lieu—one of two locations utilized along the magnetic equator. Consequently, we cannot confirm a plasma bubble here. Accordingly, ESF observed by this study may or may not contain ionospheric irregularities as well as a plasma bubble confined to the vicinity of the magnetic equator. The authors therefore decided to use the term "ESF" to designate ionospheric irregularities detected by their observations. As of 2009, an ionosonde observation station at Phu Thuy, Vietnam (21.0ºN, 106.0ºE, magnetic latitude +15.7º) located on the same latitude as Bac Lieu helps to distinguish between a plasma bubble and bottomside ionospheric irregularities.

4 Analysis results

Because ESFs are known to form frequently during the vernal and autumnal equinox periods in the regions under test[16]-[18], analyses were conducted using the data collected from March 10, 2006, to April 10, 2006.

Figure 3 shows examples of the temporal

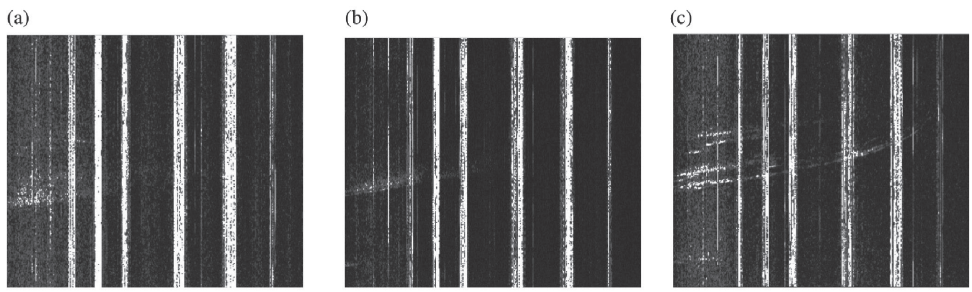

Fig.2 *Examples of (a) Intense spread F, (b) Weak spread F, and (c) Multi-trace echo*
The frequency is taken on the axis of abscissa, with virtual height (h′F) on the axis of ordinate. The marked vertical lines shown in individual frequencies are external interference waves.

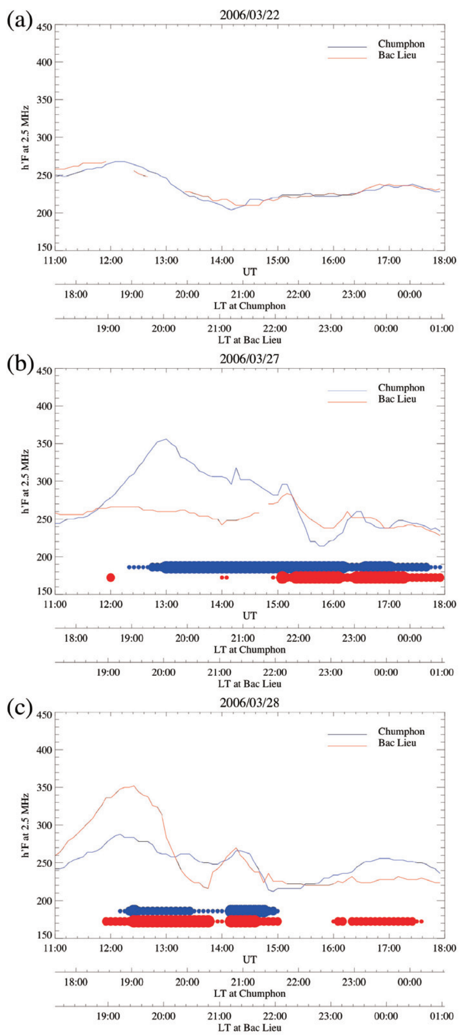

Fig.3 *Examples of typical h'F variations at Chumphon (blue) and Bac Lieu (red)*
(a) No ESF was observed. (b) and (c) ESF was observed. Each circle denotes the formation of an unusual F-region echo trace in ionosonde observation. Large, medium-size and small circles represent intense range-type ESF, weak range-type ESF and multi-trace echo, respectively. The local times at Chumphon and Bac Lieu are UT + 6.62 hours and UT + 7.05 hours, respectively[11].

variations in h'F observed at Chumphon and Bac Lieu, with temporal variations in h'F when no ESF was observed at both locations (on March 22, 2006) as shown in Fig. 3 (a). Note that h'F at Bac Lieu lagged behind h'F at Chumphon by 20 to 30 minutes with very similar variations. The lag of 20 to 30 minutes is associated with the local time gap (of 25.4 minutes) between both locations. However, the values of h'F observed at Chumphon and Bac Lieu on March 27, 2006 as shown in Fig. 3 (b) exhibit surprisingly different courses of behavior. Intense PRE was observed at Chumphon, but with little or no PRE observed at Bac Lieu, and with the difference in h'F between both locations reaching a maximum of 100 km. Intense ESF was observed at Chumphon right after sunset at this time, but not until 1500 hours UT (2200 hours LT) at Bac Lieu. Intense ESF associated with a weak increase in h'F was observed at Bac Lieu at 1500 hours UT. This may be logically considered a consequence of ESF formed over Chumphon drifting eastward at about 100 m s^{-1}. The value of 100 m s^{-1} is typically observed as the plasma bubble drift velocity[6]. In the example of observation on March 28, 2006, as shown in Fig. 3 (c), intense ESF was observed at Bac Lieu immediately after sunset when only weak ESF was observed at Chumphon. Bac Lieu registered more intense PRE, with the difference in maximum h'F between both locations reaching about 70 km. ESF observed at both locations around 1400 hours UT may well have been caused by the h'F maximum observed at the same time. Magnetic activity was so low on that day that the h'F maximum is unlikely to have been caused by a penetrating electric field associated with the magnetic activity. The causes of the h'F maximum and ESF formation in this particular case thus remain unknown.

Figure 4 shows the values of maximum h'F and the formation of ESF from 1900 to 2100 hours LT recorded at Chumphon and Bac Lieu from March 10, 2006, to April 10, 2006. Since ESF observed at 2100 hours LT and later was considered to form in a remote place and then move in, this formation is considered to have no direct bearing on the then prevailing background ionosphere, so that only ESF formed before 2100 hours LT is indicated here. As evident in the diagram, intense ESF is observed when the difference in maximum h'F between Chumphon and Bac

Lieu widens, but not when both values of maximum h'F at the two locations are small. In the latter case, the values of h'F at both locations exhibited extremely similar temporal variations, with the difference in the time of maximum h'F averaging 14 minutes. This time difference approximates the local time difference between both locations. One can also notice that intense ESF may or may not be formed even though both values of maximum h'F at the two locations have expanded to a certain degree. Other factors involved in the formation of intense ESF may well be at work, including transequatorial north-south winds[16][19][20] as described in the article mentioned earlier[14] and changes in solar variability[21]. These additional factors may have suppressed ESF formation even though both values of maximum h'F have somewhat expanded.

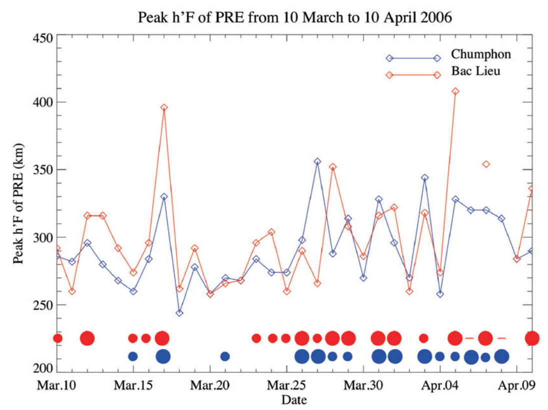

Fig.4 Day-to-day variations in maximum h'F associated with PRE at Chumphon (blue) and Bac Lieu (red)
Each circle denotes ESF formation at 1900 to 2100 hours LT. Large and small circles represent intense range-type ESF and weak range-type ESF, respectively. Values are missing between 1300 and 1500 hours UT (1833 and 2203 hours LT) on April 6, 2006, and at nighttime on April 8, 2006, because no observation data was available during these periods[11].

Even with a wave structure existing at ionospheric height, Chumphon and Bac Lieu may deliver the same maximum h'F value in certain situations, such as when recording maximum h'F. Figure 5 shows the relation between the values of h'F from 1800 to 2200 hours LT at Chumphon and those of h'F recorded at Bac Lieu during the corresponding time period. When ESF was not observed at all (for 10 days), the values of h'F recorded at both locations exhibited a good correlation

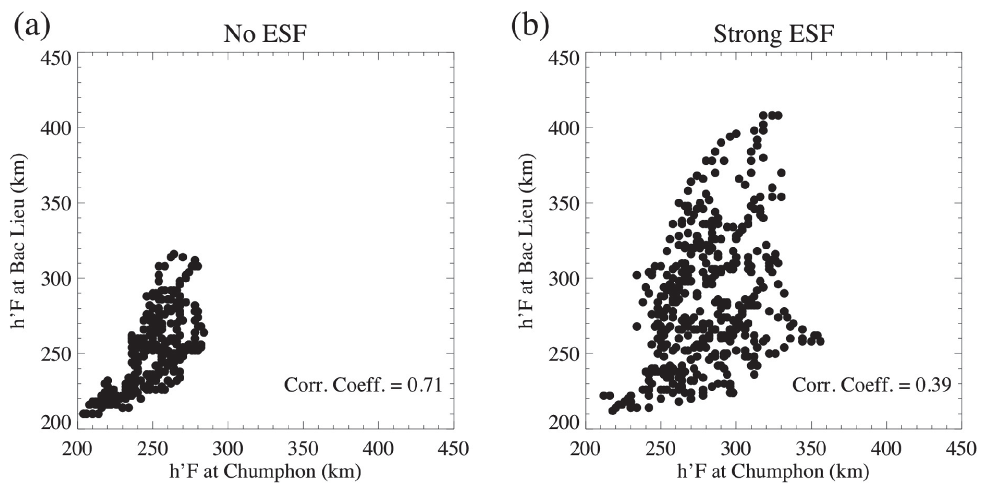

Fig.5 Scatter diagram of h'F observed at Chumphon and Bac Lieu between 1800 and 2200 hours LT at Chumphon
(a) Days on which no ESF was observed (10 days)
(b) Days on which intense ESF was observed (12 days)[11]

(correlation coefficient of 0.71) as shown in Fig. 5 (a), but when intense ESF was observed at either location (on 12 days), the correlation coefficient of h’F values recorded at both locations was as low as 0.39 as shown in Fig. 5 (b). This evidently shows that intense ESF often forms when the values of h’F observed at both locations differ.

5 Discussions and conclusions

This study probed the relation between variations in ionospheric height associated with PRE and ESF based on one-month continuous ionosonde observations conducted between Chumphon and Bac Lieu, which are 738 km apart (east and west) at a height of 300 km along the magnetic equator. When the increases in h’F associated with PRE were weak at both points, similar temporal variations in h’F were observed with a time gap equivalent to the local time gap. In such cases, no intense ESF was observed. Conversely, when intense ESF was observed, the difference in temporal variations in h’F at both locations would often be significant, suggesting that the formation of intense ESF is often accompanied by an ionospheric wave structure that varies largely over a distance of several hundred kilometers. When intense ESF was observed at both locations, similar increases in h’F were observed at the two locations (such as on April 1, 2006). When an ionospheric wave structure stretching several hundred kilometers exists, the two locations can post similar increases in h’F, provided that the wavelength of the ionospheric wave structure is close to the distance between both locations. Nothing further can be drawn since no observation point is available between Chumphon and Bac Lieu. According to theoretical studies[22][23], it had been thought that temporal changes in h’F could be replaced by spatial variations, as long as the magnetic declination and gap between the magnetic equator and geographic equator were about the same. This representation of PRE envisions an observation station passing under the PRE structure by the earth’s rotation as being fixed at local time. Since increases in h’F associated with PRE are often about two hours[24], the wave structure associated with PRE is considered to have a latitude of 30°, covering a distance of about 3000 km. Variations in h’F observed at the two locations where PRE was so weak that no ESF was observed are in precise agreement with this representation of PRE. Major differences in h’F between both locations located about 700 km apart (east and west) in observing intense ESF are unexpectedly remote from this representation. In such a situation, temporal variations at a given location cannot be replaced by spatial variations. This means that even though h’F is observed at a given location, it is no longer representative at another location several hundred kilometers away. As a result, observations made at a single location might be insufficient for forecasting the formation of a plasma bubble on a scale of several hundred kilometers east and west.

Significant day-to-day variations are noted in the relation of h’F values between Chumphon and Bac Lieu. For instance, Chumphon may post a higher value on a given day, while Bac Lieu registers a higher value on another day, and both locations may yield identical values on yet another day. The relation between wavelength and phase for a LSWS stretching several hundred kilometers and believed to be involved in the formation of intense ESF is thus found to vary significantly from day to day. Because only two observation points were available for this study, there is no way of knowing the actual wavelength of the wave structure, or whether it is propagated or stationary. It can be concluded from the findings of this study that, when intense ESF is formed, the ionosphere has a structure in the east-west direction that is smaller than the scale conceivable from a representation of PRE fixed at local time. These findings agree with those obtained by Tsunoda[5].

This study has revealed that the generation of a LSWS stretching on a scale of several hundred kilometers is related to the formation of intense ESF at a day-to-day variation level. This finding supports the proposals made by previous studies[5][6] and can be considered an important discovery. The LSWS stretching several hundred kilometers discovered by Tsunoda[5] had existed prior to the formation of a plasma bubble, and its detection could aid the future forecasting of plasma bubble formation. Yet, the relation between such an ionospheric wave structure and other factors that may be related to the formation of ESF remains unknown. The findings of this study point to an increase in h'F, or a localized eastward electric field that lifts the ionosphere, and its physical mechanism may be a consequence of plasma instability caused by the sheer motion of F-region plasma[25], or the spatial resonance of an electric field associated with atmospheric gravity waves and PRE[26][27], or could even be totally different altogether. Detailed knowledge of the scale, periodicity, propagation and other characteristics of this ionospheric wave structure is necessary to distinguish these mechanisms, but such information has yet to be acquired due to a lack of observations. Deploying a chain of ionosondes in a far-reaching east-west range at shorter intervals than the scale of the wave structure should prove to be of immense value. Its usefulness might be augmented through the combined use of direct observations by such equatorial orbiting satellites as the C/NOFS satellite[28], and TEC wave structure observations aided by satellite beacons[29].

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References

1 Röttger, J., “Wave-like structures of large-scale equatorial spread-F irregularities,” J.Atmos. Terr. Phys., Vol. 35, pp. 1195–1206, 1973.

2 Maruyama, T. and M. Kawamura, “Equatorial ionospheric disturbance observed through a transequatorial HF propagation experiment,” Ann. Geophys., Vol. 24, pp. 1401–1409, 2006.

3 Weber, E. J., J. Buchau, and J. G. Moore, “Airborne studies of Equatorial F layer ionospheric irregularities,” J. Geophys. Res., Vol. 85, pp. 4631–4641, 1980.

4 Lin, C. S., T. J. Immel, H. -C. Yeh, S. B. Mende, and J. L. Burch, “Simultaneous observations of equatorial plasma depletion by IMAGE and ROCSAT-1 satellites,” J. Geophys. Res., Vol. 110, pp. A06304, doi: 10.1029/2004JA010774, 2005.

5 Tsunoda, R. T., “On the enigma of day-to-day variability in equatorial spread F,” Geophys. Res. Lett., Vol. 32, pp. L08103, doi: 10.1029/2005GL022512, 2005.

6 Fukao, S., T. Yokoyama, T. Tayama, M. Yamamoto, T. Maruyama, and S. Saito, “Eastward traverse of equatorial plasma plumes observed with the Equatorial Atmosphere Radar in Indonesia,” Ann. Geophys., Vol. 24, pp. 1411–1418, 2006.

7 Tsunoda, R. T, and B. R. White, “On the generation and growth of equatorial backscatter plumes, 1. Wave structure in the bottomside F layer,” J. Geophys. Res., Vol. 86, pp. 3610–3616, 1981.

8 Tsunoda, R. T. and W. L. Ecklund, “On the post-sunset rise of the equatorial F layer and superposed upwelling and bubbles,” Geophys. Res. Lett., Vol. 34, pp. L04101, doi: 10.1029/2006GL028832, 2007.

9 Tsunoda, R. T., “Multi-reflected echoes: Another ionogram signature of large-scale wave structure,” Geophys. Res. Lett., Vol. 36, pp. L01102, doi: 10.1029/2008GL036221, 2009.

10 Fejer, B. G., E. R. de Paula, L. Scherliess, and I. S. Batista, “Incoherent scatter radar, ionosonde, and satellite measurements of equatorial F region vertical plasma drifts in the evening sector,” Geophys. Res. Lett., Vol. 23, pp. 1733–1736, 1996.

11 Saito, S. and T. Maruyama, “Large-scale longitudinal variation in ionospheric height and equatorial spread F occurrences observed by ionosondes,” Geophys. Res. Lett., Vol. 34, pp. L16109, doi: 10. 1029/2007GL030618, 2007.

12 Maruyama, T., M. Kawamura, S. Saito, K. Nozaki, H. Kato, N. Hemmakorn, T. Boonchuk, T. Komolmis, and C. Ha Duyen, “Low latitude ionospher-thermosphere dynamics studies with ionosondechain in Southeast Asia,” Ann. Geophys., Vol. 25, pp. 1569–1577, 2007.

13 Maruyama, T., S. Saito, M. Kawamura, K. Nozaki, J. Uemoto, T. Tsugawa, H. Jin, M. Ishii, and M. Kubota, “Outline of the SEALION Project and Initial Results,” Special issue of this NICT Journal, 3-2-1, 2009.

14 S. Saito and T. Maruyama, “Effects of Transequatorial Thermospheric Wind on Plasma Bubble Occurrences,” Special issue of this NICT Journal, 3-2-2, 2009.

15 Bittencourt, J. A., and M. A. Abdu, “A theoretical comparison between apparent and real vertical ionization drift velocities in the equatorial F region,” J. Geophys. Res., Vol. 86, pp. 2451–2455, 1981.

16 Maruyama, T. and N. Matuura, “Longitudinal variability of annual changes in activity of equatorial spread F and plasma bubbles,” J. Geophys. Res.. Vol. 89, pp. 10903–10912, 1984.

17 Burke, W. J., C. Y. Huang, L. C. Gentile, and L. Bauer, “Seasonal-longitudinal variability of equatorial plasma bubbles,” Ann. Geophys., Vol. 22, pp. 3089–3098, 2004.

18 Otsuka, Y., K. Shiokawa, and T. Ogawa, “Equatorial ionospheric scintillations and zonal irregularity drifts observed with closely-spaced GPS receivers in Indonesia,” J. Meteor. Soc. Japan, Vol. 84A, pp. 343–351, 2006.

19 Maruyama, T., “A diagnostic model for equatorial spread F1. Model description and application to electric field and neutral wind effects,” J. Geophys. Res.. Vol. 93, pp. 14611–14622, 1988.

20 Saito, S. and T. Maruyama, “Ionospheric height variations observed ionosondes along magnetic meridian and plasma bubble onsets,” Ann. Geophys., Vol. 24, pp. 2991–2996, 2006.

21 Jayachandran, B., N. Balan, P. B. Rao, J. H. Sastri, and G. J. Bailey, “HF Doppler and ionosonde observations on the onset conditions of equatorial spread F,” J. Geophys. Res.. Vol. 98, pp. 13741–13750, 1993.

22 Batista, I. S., M. A. Abdu, and J. A. -Bittencourt, “Equatorial F region vertical plasma drifts- Seasonal and longitudinal asymmetries in the American sector,” J.Geophys. Res., Vol. 91, pp. 12055–12064, 1986.

23 Fejer, B., “The electrodynamics of the low-latitude ionosphere, recent results and future challenges,” J. Atmos. Terr. Phys., Vol. 59, pp. 1465–1482, 1997.

24 Woodman, R. F., “Vertical drift velocities and east-west electric fields at the magnetic equator,” J. Geophys. Res., Vol.75, pp.6249–6259, 1970.

25 Hysell, D. L., M. C. Kelley, and W. E. Swartz, “Seeding and layering of equatorial spread F by gravity Waves,” J. Geophys. Res.. Vol. 95, pp. 17253–17260, 1990.

26 Kelley, M. C., M. F. Larsen, C. LaHoz, and J. P. McClure, “Gravity wave interaction of equatorial spread F, a case study(1981),” J. Geophys. Res.. Vol. 86, pp. 9087–9100, 1981.

27 Hysell, D. L. and E. Kudeki, “Collisional shear instability in the equatorial F region ionosphere,” J. Geophys. Res.. Vol. 109, pp. A11301, doi: 10.1029/2004JA010636, 2004.

28 de La Beaujardière, O. and the C/NOFS Science Definition Team, “C/NOFS: a mission to forecast Scintillations,” J. Atmos. Solar-Terr. Phys., Vol. 66, pp. 1573–1591, 2004.

29 Thampi S. V., M. Yamamoto, R. T. Tsunoda, Y. Otsuka, T. Tsugawa, J. Uemoto, and M. Ishii, "First observations of large-scale wave structure and equatorial spread F using CERTO radio beacon on the C/NOFS satellite," Geophys. Res. Lett., Vol. 36, pp. L18111, doi: 10.1029/2009GL039887, 2009.

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