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New insights on the precursors to the onset of equatorial plasma irregularity generation

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Abstract

This work presents some new findings in terms of the vertical propagation speeds of gravity waves in the daytime as possible precursors to the ESF. These findings have resulted from a new approach of analyzing the radiowave reflections from the ionosphere to obtain the information of gravity waves in the daytime. Also, the typical horizontal gravity wave scale sizes in the daytime that could potentially offer the required perturbation for the ESF generation are also presented.

1. Introduction

The upper atmosphere over the low and equatorial latitudes is a host to several complex, and intricately interwoven/coupled phenomena. The development of plasma irregularities in the nighttime F-region of the equatorial ionosphere, known as the equatorial Spread-F (ESF), is one such phenomenon, which is known to be the result of the electrodynamical coupling between the ionosphere-thermosphere-system in the magnetic equatorial regions. These equatorial plasma irregularities span seven orders of magnitudes in scale-sizes (from a few hundred kilometers to a few centimeters) and adversely affect the trans-ionospheric radio-wave communications. Investigations of this phenomenon using various datasets have received considerable attention over the past decades due to advancements in technology. Results from numerous ground-based, rocket-borne, and satellite-borne instruments have enriched our understanding of the temporal and spatial extents of this magnificent phenomenon.

Although there is a broad understanding on the generation mechanism of ESF and its occurrence morphology, there exists an uncertainty in its day-to-day occurrence. Morphologically, it is known that there are seasons when the ESF is more likely to occur. These are the durations when the solar terminator aligns closely with the magnetic declination angle [Abdu et al., 1981; Tsunoda, 1985]. As the magnetic declination angles are different at different longitudes, this alignment occurs in different months in different longitudes. Such alignment enables simultaneous sunset in both the hemispheres and therefore assists in the sustenance of the F-region electric fields thereby contributing to the growth of the plasma instability, if generated on that night. It is also shown that there are seasons when the ESF is less likely to occur [Maruyama and Matuuraa, 1984]. These are non-equinoctial seasons, when trans-equatorial winds are known to move the plasma to highly conducting E-region in the opposite hemisphere and thereby inhibiting the growth of the plasma irregularities . Both these conditions combinedly give rise to 'ESF seasons' for a given longitude when, statistically, the occurrence has been recorded to be more during northern winters in Atlantic longitudes, northern summers in Pacific longitudes and during equinoxes at Indian and South American longitudes. Even in this so-called 'ESF season' during which the ionospheric conditions on different days are nearly identical, the occurrence of ESF cannot be predicted.

Even though, it is now known that varied combinations of background electron density gradients, eastward electric fields, vertical winds, eastward winds in presence of westward gradients, and meridional winds play important roles in the day-to-day variability of the ESF, it has remained a challenge to predict its occurrence. At the same time, it is extremely important to be able to predict its occurrence, since it affects the radio-wave communications and navigation systems in a wide range of frequencies. In fact, the day-to-day variability in the occurrence of ESF irregularities is one of the key missing links in our understanding of the upper atmosphere. This work presents some new findings in terms of the vertical propagation speeds of gravity waves in the daytime as possible precursors to the ESF. These findings have resulted from a new approach of analyzing the radiowave reflections from the ionosphere to obtain the information of gravity waves in the daytime. This methodology to derive gravity waves will also be discussed. Also, the typical horizontal gravity wave scale sizes that could offer the required perturbation for the ESF generation are also presented.

2. Relation between the daytime and nighttime upper atmospheric phenomena

The eastward electric field in the daytime gives rise to the vertical drift of plasma over the magnetic equator, which deposit plasma away from the magnetic equator on either side to form ionization crests, which is referred to as the Equatorial ionization anomaly (EIA) [Anderson, 1981; Raghavarao et al., 1988]. These crests in ionization form the sources for neutral temperature and wind anomaly (ETWA) with substantial vertically upward winds over the crests and downward winds over the trough at the magnetic equator [Raghavarao et al., 1991, 1993]. All these phenomena occur in the daytime. It has been observed by different experiments that the strong development of EIA precedes the occurrence of the ESF irregularities [Raghavarao et al., 1988, Sridharan et al., 1994, Mendillo et al., 2001; Valladares et al., 2001], which is a major Space-Weather event that occurs even during geomagnetic quiet days.

Several works focused on the background ionospheric conditions just before the ESF onset time. These include the variation in the base height of ionospheric F-layer on the days with and without the presence of ESF. It was shown that assistance of meridional winds was required in some cases. There were works which showed that if the F-region height was greater than 300 km, then ESF occurred irrespective of the directions of meridional winds [Devasia et al., 2002]. There have also been studies which parameterized the values of h'F for ESF occurrence for different solar flux levels [Tulasi Ram et al. 2007].

3. Experiments on daytime Gravity waves and their relation with ESF

The Range time intensity maps from Jicamarca Incoherent scatter radar showed a wavelike feature, suggesting that the gravity waves could possibly provide the initial trigger for the instability to grow [Kelley et al., 1981]. In that regard several works focusing on the gravity waves in the daytime have been initiated using optical measurements at multiple wavelengths including one on-board high-altitude balloon [Laskar et al., 2013; 2015; Pallamraju et al., 2004, 2010, 2013, 2014, 2016; Kumar et al., 2022] and significant understanding has been gained in terms of the two- and three-dimensional characterization of gravity waves in the daytime. Bi-directional mode experiments using large field-of-view optical measurement from an off-equatorial location, Hyderabad, revealed the presence of zonal scale sizes of around 200 km in the daytime and so have a great potential in relating their effect on the nighttime ESF generation.

In a recent study [Saha et al., 2022], by carrying out wave number analyses for around 1300 all-sky images with nearly equal number of with and without the occurrence of equatorial plasma bubbles, it was found that, typically, the zonal scale sizes are in the range of 150-200 km and 250-300 km (with a greater strength in the latter scale-size) on geomagnetic quiet nights without the presence of any plasma bubbles. The scale sizes of gravity waves smaller than 250 km have been observed on almost all the times whenever the plasma bubbles were present, which correspond to the inter-bubble separation distance. As the bubble depletions over the magnetic equator most likely occur at the crest location of the gravity waves, the zonal distances between the bubbles, as seen in a location close to the magnetic equator can be assumed to represent the zonal scale sizes of gravity waves over the equator [Das et al., 2020]. Therefore, it is proposed that the gravity wave scale sizes smaller than 250 km in the zonal direction, if present, in the evening could potentially act as the triggers for the generation of plasma bubbles.

4. A new approach of deriving gravity wave characteristics using radiowave technique

As the optical measurements are hindered by the presence of clouds and during overcast skies during monsoon, a new approach using radiowave reflections from the ionosphere to derive gravity wave characteristics has been arrived at [Mandal et al., 2019]. It involves monitoring of variations in the heights of densities at a given frequency (isoelectron) as a function of time, and measuring their phase shifts, if any, to derive vertical propagation speeds of the gravity waves. In this method, it is important to ensure that isoelectron density contours at different frequencies show the same gravity wave time period, and that there exists a downward phase shift in these fluctuations. The product of the vertical phase speeds and gravity wave time period yields information on the vertical scale size of the gravity waves. This new approach has revealed several new and insightful results in terms of seasonal, solar flux, and geomagnetic dependent behavior of gravity waves [Mandal and Pallamraju, 2020; Mandal et al., 2020].

In the present work, the vertical propagation of gravity waves in daytime thermosphere has been systematically investigated using the digisonde data over the magnetic equator with a specific aim of exploring their behavior before the occurrence of ESF. It was noted that the otherwise not so regular vertical propagation of gravity waves (they were shown to be existing only around 40% of occasions), seem to be existing on 85 % occasions on ESF days compared with only 50% of occasions for non-ESF days. On the ESF days, the time periods, amplitudes, and vertical phase speeds of these daytime gravity waves range from 0.86 to 2.89 hr, 1 to 3.5 km, and 21.74 to 151.22 ms^{-1}, respectively. These values for the non-ESF days are 1.5–2.97 hr, 1–4 km, and 22.69–82.78 ms^{-1}, respectively. It can be noted that the time periods and amplitudes of these daytime gravity waves are not so different on these days, but the vertical propagation speeds appear to be higher on the ESF days compared to the non-ESF days. As the interest is in finding indicators of the occurrence of plasma irregularities much before their actual onset, we have selected the average of the vertical phase speed values of these gravity waves between 10 and 14 LT ($<C_z>_{10\text{-}14LT}$). It has been seen that for all the non-ESF days, the values of

$\langle C_Z \rangle_{10\text{-}14LT}$ are less than 80 ms^{-1}, whereas, they are higher than 80 ms^{-1} for 8 out of 17 ESF days in which vertical propagation is seen. It needs to be ascertained if the gravity waves seen in the neutral atmosphere do get communicated to the ionospheric F-region to form the triggers to ESF. To investigate this aspect, we have carried out time-series analyses of variations in the base height of the F-region (h'F) and multiplied their amplitude with the gravity wave vertical phase propagation speeds. This quantity can be considered to represent the energy per unit mass integrated over one second (m^{2}s^{-1}) transferred by these upward propagating gravity waves to the ionosphere [Mandal et al., 2022]. This quantity is much larger on the ESF days as compared to the non-ESF days.

5. Conclusion

This work reports on novel approach of obtaining the information on neutral gravity waves through radiowave technique. By using this technique, it is revealed that on the days with ESF occurrence, the gravity wave phase speeds were larger (> 80 ms^{-1}) well before (at around 12-14 LT) the sunset time. Whereas, on the non-ESF days, the presence of vertical propagation was infrequent, and when present, the speeds were smaller. Further, the product of the amplitude of the F-region oscillation and the vertical propagation speed of gravity wave was larger on the ESF days in comparison to the non-ESF days, which indicated a greater vertical displacement in energy. The gravity wave scale size smaller than 250 km has been found to be another indicator at the sunset time to be critical for the ESF onset. These factors that are present in the daytime could potentially form the precursors to the ESF occurrence in the nighttime.

6. Reference

1. Abdu, M. A., J. A. Bittencourt, and 1. S. Batista, "Magnetic declination control of the equatorial F-region dynamo electric field development and spread-F", J. Geophys. Res., 85, December 1981, pp. 11443-11446, doi: 10.1029/JA086iA13p11443.

2. Anderson, D. N., "Modelling the ambient low latitude F region ionosphere – A review", Journal of Atmospheric and Solar-Terrestrial Physics, 43, August 1981, pp. 753-762, doi: 10.1016/0021-9169(81)90051-9.

3. Das, S.K., Patra, A.K., Kherani, E.A., Chaitanya, P.P., Niranjan, K., "Relationship between post sunset wave structures and interbubble spacing: the seeding perspective of equatorial plasma bubble", Journal of Geophysical Research: Space Physics, 125(8), July 2020, 2020JA028122, doi: 10.1029/2020JA028122.

4. Devasia, C., Jyoti, N., Subbarao, K., Viswanathan, K., Tiwari, D., and Sridharan, R., "On the plausible linkage of thermospheric meridional winds with the equatorial spread F", Journal of Atmospheric and Solar-Terrestrial Physics, 64, January 2002, pp. 1–12, doi: 10.1016/s1364-6826(01)00089-x

5. Kelley, M. C., M. F. Larsen, C. A. LaHoz, and J. P. McClure, "Gravity wave initiation of equatorial spread A case study", Journal of Geophysical Research, 86, October 1981, pp. 9087-9100, doi: 10.1029/JA086iA11p09087.

6. Kumar, S., D. Pallamraju, P. Suryawanshi, T. Vijayalakshmi, and G. K. Seemala, "On the latitudinal variation in oi 630.0 nm dayglow emissions in response to the equatorial electrodynamic processes and neutral winds", Advances in Space Research, 69, January 2022, pp. 926–938, doi: 10.1016/j.asr.2021.10.034.

7. Laskar, F. I., Pallamraju, D., Lakshmi, T. V., Reddy, M. A., Pathan, B.M., and Chakrabarti, S., "Investigations on vertical coupling of atmospheric regions using combined multiwavelength optical dayglow, magnetic, and radio measurements", Journal of Geophysical Research, Space Physics, 118 (7), July 2013, pp. 4618–4627, doi: 10.1002/jgra.50426.

8. Laskar, F. I., Pallamraju, D., Veenadhari, B., Vijaya Lakshmi, T., Anji Reddy, M., and Chakrabarti, S., "Gravity waves in the thermosphere: Solar activity dependence", Advances in Space Research, 55, January 2015, pp. 1651–1659, doi: 10.1016/j.asr.2014.12.040.

9. Mandal, S., Pallamraju, D., Karan, D. K., Phadke, K. A., Singh, R. P., and Suryawanshi, P., "On deriving gravity wave characteristics in the daytime upper atmosphere using radio technique", Journal of Geophysical Research: Space Physics, 124, August 2019, pp. 6985–6997, doi: 10.1029/ 2019JA026723.

10. Mandal, S., and Pallamraju, D., "Thermospheric gravity wave characteristics in the daytime over low-latitudes during geomagnetic quiet and disturbed conditions", Journal of Atmospheric and Solar-Terrestrial Physics, 211(105), December 2020, 470, doi: 10.1016/j.jastp.2020.105470

11. Mandal, S., Pallamraju, D., & Suryawanshi, P., "Changes in the daytime thermospheric gravity wave propagation characteristics over low-latitudes in response to the variation in solar flux", Journal of Atmospheric and Solar-Terrestrial Physics, 209, August 2020, pp. 105414, doi: 10.1016/j.jastp.2020.105414.

12. Mandal, S., Pallamraju, D., and Pant, T. K., "Vertical propagation speeds of gravity waves in the daytime as a precursor to the onset of the equatorial spread-F", Journal of Geophysical Research: Space Physics, 127, July 2022, e2022JA030401, doi: 10.1029/2022JA030401.

13. Maruyama, T., and Matuura, N., "Longitudinal Variability of Annual Changes in Activity of Equatorial Spread-F and Plasma Bubbles", Journal of Geophysical

Research, 89, December 1984, pp. 10903-10912, doi: 10.1029/JA089iA12p10903.

14. Mendillo, M., Meriwether, J., and Biondi, M., "Testing the thermospheric neutral wind suppression mechanism for day-to-day variability of equatorial spread F", Journal of Geophysical Research, 106, March 2001, pp. 3655–3663, doi: 10.1029/2000ja000148.

15. Pallamraju, D., Chakrabarti, S., and Valladares, C. E., "Magnetic storm-induced enhancement in neutral composition at low latitudes as inferred by O(1D) dayglow measurements from Chile", Annales de Geophysique, 22, September 2004, pp. 3241–3250, doi: 10.5194/angeo-22-3241-2004.

16. Pallamraju, D., Das, U., and Chakrabarti, S., "Short- and long-timescale thermospheric variability as observed from OI 630.0 nm dayglow emissions from low latitudes", Journal of Geophysical Research, 115, June 2010, A06312, doi: 10.1029/2009JA015042.

17. Pallamraju, D., Laskar, F. I., Singh, R. P., Baumgardner, J., and Chakrabarti, S., "MISE: A multiwavelength imaging spectrograph using echelle grating for daytime optical aeronomy investigations", Journal of Atmospheric and Solar-Terrestrial Physics, 103, October 2013, pp. 176–183, doi: 10.1016/j.jastp.2012.12.003.

18. Pallamraju, D., Baumgardner, J., Singh, R. P., Laskar, F. I., Mendillo, C., Cook, T., et al., "Daytime wave characteristics in the mesosphere lower thermosphere region: Results from the Balloon-borne Investigations of Regional-atmospheric Dynamics experiment", Journal of Geophysical Research, 119, February 2014, pp. 2229-2242, doi: 10.1002/2013JA019368.

19. Pallamraju, D., Karan, D. K., and Phadke, K. A., "First three dimensional wave characteristics in the daytime upper atmosphere derived from ground-based multiwavelength oxygen dayglow emission measurements", Geophysical Research Letters, 43, June 2016, pp. 5545–5553, doi: 10.1002/2016GL069074.

20. Raghavarao, R., Nageswararao, M., Sastri, J.H., Vyas, G.D., and Sriramarao, M., "Role of equatorial ionization anomaly in the initiation of equatorial spread F", Journal of Geophysical Research, 93, A6, June 1988, pp. 5959-5964, doi: 10.1029/JA093iA06p05959.

21. Raghavarao, R., L. E. Wharton, N. W. Spencer, H. G. Mayr, and L. H. Brace, "An equatorial temperature and wind anomaly (ETWA)", Geophysical research letters, 18, July 1991, pp. 1193–1196, doi: 10.1029/91GL01561.

22. Raghavarao, R., Hoegy, W.R., Spencer, N.W., and Wharton, L.E., "Neutral temperature anomaly in the equatorial thermosphere-A source of vertical winds", Geophysical research letters, 20(11), June 1993, pp. 1023-1026. doi: 10.1029/93GL01253.

23. Saha, S., D. Pallamraju and R. N. Ghodpage, "Investigations of equatorial plasma bubbles as observed in the OI 630 nm nightglow emissions over off-equatorial and low-latitudinal locations over Indian longitudes", Advances in Space Research, 2022, doi: 10.1016/j.asr.2022.08.023.

24. Sridharan, R., Pallamraju, D., Raghavarao, R., and Ramarao, P.V.S., "Precursor to equatorial spread-F in OI 630.0 nm dayglow", Geophysical Research Letters, 21, December 1994, pp. 2797–2800, doi: 10.1029/94GL02732.

25. Tsunoda, R. T., "Control of the seasonal and longitudinal occurrence of equatorial scintillations by longitudinal gradient in integrated E-region Pedersen Conductivity", Journal of Geophysical Research, 90, January 1985, pp. 447-456, doi: 10.1029/JA090iA01p00447.

26. Tulasi Ram, S., Rama Rao, P., Prasad, D., Niranjan, K., Raja Babu, A., Sridharan, R., et al., "The combined effects of electrojet strength and the geomagnetic activity (kp-index) on the post sunset height rise of the f-layer and its role in the generation of ESF during high and low solar activity periods", Annales Geophysicae, 25, October 2007, pp. 2007–2017, doi: 10.5194/angeo-25-2007-2007.

27. Valladares, C. E., Basu, S., Groves, K., Hagan, M. P., Hysell, D., Mazzella Jr., A. J., and Sheehan, R. E., "Measurement of the latitudinal distributions of total electron content during equatorial spread-F events", Journal of Geophysical Research, 106, December 2001, pp. 29133-29152, doi: 10.1029/2000JA000426.