https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae Discussions
Open Access

Simultaneous OI 630 nm imaging observations of thermospheric gravity waves and associated revival of fossil depletions around midnight near the EIA crest

Authors:

1. **Navin Parihar**
   Indian Institute of Geomagnetism, Navi Mumbai, India
   e-mail: navindeparihar@gmail.com

2. **Saranya Padincharapad**
   (a) Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Tirunelveli, India
   (b) Manonmaniam Sundaranar University, Tirunelveli, India
   e-mail: anuja8494@gmail.com

3. **Anand Kumar Singh**
   National Centre for Polar and Ocean Research, Goa, India
   e-mail: singhaaks@gmail.com

Corresponding Author:

Navin Parihar, Indian Institute of Geomagnetism, Navi Mumbai, India
e-mail: navindeparihar@gmail.com

Key Words:

Airglow imaging; Midnight Irregularities/Depletions; Gravity wave seeding; Low-latitude ionosphere.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Abstract

We report the F-region airglow imaging of fossil plasma depletions around midnight that revived afresh under the persisting thermospheric gravity wave (GW) activity. An all-sky imager recorded these events in OI 630 nm imaging over Ranchi (23.3º N, 85.3º E, mlat. ~19º N), India, on 16 April 2012. Northward propagating and east-west aligned GWs (λ ~210 km, υ ~64 m/s, and τ ~0.91 h) were seen around midnight. Persisting for ~2 hours, this GW activity revived two co-existing and eastward drifting fossil depletions, DP1 and DP2. GWs-driven revival was prominently seen in depletion DP1, wherein its apex height grew from ~600 km to >800 km, and the level of intensity depletion increased from ~17% to 50%. Present study is novel in the sense that simultaneous observations of thermospheric GWs activity and associated evolution of depletion in OI 630 nm airglow imaging, and that too around local midnight, have not been reported earlier. Current understanding is that GW phase fronts aligned parallel to the geomagnetic field lines and eastward propagating are more effective in seeding Rayleigh-Taylor (RT) instability. Here, GW fronts were east-west aligned (i.e. perpendicular to the geomagnetic field lines) and propagated northward, yet they revived fossil depletions.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

1. Introduction

Gravity waves (GWs) are well-known to influence the mesosphere-lower thermosphere-ionosphere (MLTI) region. GWs significantly contribute to the momentum and energy budget of the MLT region via the wave-dissipation processes (Fritts and Alexander, 2003; Holton, 1983). Apart from the dominant solar and geomagnetic inputs, GWs are the key element in some of the electrodynamical processes in the ionosphere e.g. irregularities, atmosphere-ionosphere (AI) coupling, traveling ionospheric disturbances, etc.. In the equatorial F-region, GWs modulate the ionospheric plasma into wave-like ionization structures. Under favourable conditions, these structures act as a seed to Generalized Rayleigh-Taylor (GRT) instability that generates the irregularities (Fritts et al., 2009; Huba and Joyce, 2007, 2010; Huba and Liu, 2020; Hysell et al., 1990; Kelley, 2009; Woodman, 2009). GWs are also important in the AI coupling during deep convection activity, thunderstorms, lightning, cyclones, tornadoes, transient luminous events (TLEs)/sprites initiation, tsunami, etc. (Azeem and Barlage, 2018; Maurya et al., 2022; Huba et al., 2015). GWs can also generate medium-scale traveling ionospheric disturbances (MSTIDs) (Fukushima et al., 2012; Heale et al., 2022, and references cited therein). On the course of their propagation, GWs can also induce periodic fluctuations in the ionospheric parameters e.g. the electron density or total electron content (TEC), the F-region height, temperatures and winds, etc. (Ford et al., 2006, 2008; Klausner et al., 2009; Parihar et al., 2018; Vadas and Azeem, 2021) or airglow emission (Huba et al., 2015; Makela et al., 2011).

The crucial role of GWs in seeding the post-sunset equatorial spread-F (ESF) or plasma bubbles (EPBs) is fairly well understood (Abdu et al., 2009; Fritts et al., 2009; Huba and Joyce, 2007, 2010; Hysell et al., 1990; Kelley, 2009; Singh et al., 1997; Tsunoda, 2010; Tulasi Ram et al., 2014; Woodman, 2009). However, their role in the seeding of the midnight/post-midnight irregularities remains poorly understood, especially when the important criteria for the triggering of the GRT instability are absent (e.g., the favorable alignment of the solar terminator with the geomagnetic field lines and the pre-reversal enhancement, PRE, of the zonal electric field). Lately, Huba and Liu (2020) reported the global simulations of the ESF using the SAMI3/WACCM-X coupled model. SAMI3 is the abbreviation for '*Sami3 is Another Model of Ionosphere*' (Huba et al., 2008), and WACCM-X stands for the '*Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension*' (Liu et al., 2010). For the first time, Huba and Liu's (2020) simulations demonstrated that GWs are the dominant seed mechanism and can spontaneously generate

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

the ESF, and that the EPBs develop self-consistently in the postsunset ionosphere. Studies by Nishioka et al. (2012) show that the GRT instability can occur near midnight under the influence of enhanced GW activity and then can lead to the growth of irregularities. MSTIDs are an important generation mechanism of post-midnight irregularities wherein the electric field perturbations associated with them acts as the seed (Miller et al., 2009; Taori et al., 2015). Otsuka (2018) have presented an elaborative review of these mechanisms. All-sky airglow imaging (ASAI) along with the radar, ionosonde, and GPS measurements have significantly contributed to our understanding of the crucial role of GWs in seeding the EPBs (Mendillo and Baumgardner, 1982; Mendillo et al., 1997; Taori et al., 2010; Yadav et al., 2017). *Spread-F Experiment (SpreadFEx)* carried out in Brazil during September-November 2005 is one such example (Fritts et al., 2009). In the Indian subcontinent, Sreeja et al. (2009) reported the GWs in OI 630 nm dayglow intensity variations that acted as a seed to the ESF irregularities.

GWs that give rise to the EPBs have usually been reported in the MLT region airglow imaging (e.g. Fritts et al., 2009; Paulino et al., 2011; Takahashi et al., 2009; Taori et al., 2013). Reports featuring them in the F-region airglow imaging are rare and limited to that of Makela et al. (2011), Paulino et al. (2016, 2018), Sau et al. (2018), and Smith et al. (2015). Makela et al. (2011) and Smith et al. (2015) reported the thermospheric imaging observations of GWs associated with tsunami and earthquake, respectively. Paulino et al. (2016, 2018) and Sau et al. (2018) presented their observations in OI 630 nm imaging from Brazil and India, respectively. However, these authors did not report any occurrence of depletions during the undergoing GW activity. We report, for the first time, simultaneous observations GWs and depletions in the F-region airglow imaging.

On the course of temporary campaign-based ASAI observations of OI 630 nm emission under ***Climate And Weather of Sun-Earth System (CAWSES) India Phase II Programme*** at Ranchi (23.3º N, 85.3º E, mlat. ~19º N), GW activity and "fossil depletions" were seen together on 16 April 2012 with the former reviving the latter. Fossil depletions are the remnants of airglow depletion or EPBs that have ceased growing upward or poleward; however, they continue to persist and move with ambient plasma drift. Under *Maui Middle Atmosphere and Lower Thermosphere (Maui-MALT)* initiative, Makela et al. (2004) reported their extensive observations in OI 630 nm imaging from Haleakala Volcano (20.7° N, 203.7° E; mlat. 21.3° N), Hawaii during the solar maximum of 2002-2003. Chapagain et al. (2011)

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae Discussions

presented their limited observations from Christmas Island (2.1° N, 157.4° W, mlat. 2.8° N) during September 1995. In India, Sekar et al. (2007) presented their case study from Gadanki (13.5° N, 79.2° E, mlat. 6.3° N). However, these investigations did not discuss any resurgence of fossil depletions associated with the GW activity. Novelty of this study is that the "fossil depletions" revived into "active depletions" after the emission layer witnessed the GW activity.

2. Instrumentation and data

Under the ***CAWSES India Phase II Programme***, an ASAI was installed for limited nightglow observations at Ranchi (23.3º N, 85.3º E, mlat. ~19º N), located near the crest of equatorial ionization anomaly (EIA) in India during April 2012. Parihar et al. (2017) and Parihar (2019) have presented an elaborative account of this ASAI system, the filter characteristics of OI 630 nm emission imaging, the image processing technique, and the limitations associated with the intensity calibration. Such GWs-driven revival of "fossil depletions" was recorded in airglow images during 1700-2000 UT on 16 April 2012. Here, Indian Standard Time (IST) = Universal Time (UT) + 0530 and Local Time (LT) ≈ IST. As such, 1700-2000 UT corresponds to ~1.5 h duration before and after the local midnight. On this night, the geomagnetic conditions were quiet with $Kp < 2$, $Ap = 4$, and $-4 < Dst < 10$ nT. We looked into the total electron content (TEC) measurements from an IGS station Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N, located nearby and south of Ranchi) to support the ASAI observations of GWs (Source: https://t-ict4d.ictp.it/nequick2/gnss-tec-calibration, Ciraolo et al., 2007). Assuming that OI 630.0 nm emission peaks at 250 km and using known astral positions, spatial displacement of depletions and GWs were determined from (i) the intensity profiling along a desired direction in two successive images and (ii) the keogram analysis. Pimenta et al. (2003) and Makela et al. (2006) have discussed these techniques, respectively.

3. Observations

Figures 1 and 2 present airglow images that depict this event seen over Ranchi during 1742-1942 UT on 16 April 2012. All-sky image's timestamp information is in *hhmmss* format. Fossil depletions of our interest that showed the GWs-driven revival are marked as **DP1** and **DP2** in Figure 1 and 2. Here, **ROI1** is the region-of-interest wherein a few weakly

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

perceivable fronts of GWs and fossil depletions coexisted initially. Figure 3 shows the TEC measurements depicting GW activity in and around Hyderabad during 1700-2000 UT on this night.

3.1 Signatures of GW activity in the F-region

Faint signatures of GW activity were first seen near the southern edge of the field-of-view (FOV) during ~1715-1724 UT. Starting ~1730 UT, their presence became more evident and continued until 1906 UT or so. Some visible ones are marked as ‘f1’, ‘f2’, ‘f3’and ‘f4’ in Figure 1 and 2. North-south (NS) keograms [shown in Figure 3 (a) and (b)] showed alternating bright and dark intensity striations over the north, and their slope indicates that GWs propagated towards the north. Often GWs in OI 630 nm imaging are faint and unclear. Under similar situations, time differenced images have proven ability to reflect them (Makela et al., 2011). Presented in Figure 3 (c)-(d), time difference images show two GW fronts, ‘f1’ and ‘f2’, separated by a dark trough during 1754-1806 UT. Being faint in nature, GWs signatures in ASAI images were getting lost in the geographic unwarping process. We estimated GWs propagation characteristics using the slope of striations in keograms and cross-verified them with the intensity profiling technique. We found that these GWs propagated from the south to north with the phase speed (υ) of ~64 ± 2 m/s and had the horizontal wavelength (λ) and period (τ) of ~210 ± 6 km and ~0.91 ± 0.06 h, respectively.

Figure 3 (e) shows the scatter plots of the TEC along the trajectory of ionospheric pierce points (IPPs) for different GPS satellites during 1700-2000 UT on this night. PRN numbers of GPS satellites, along with the start time at 1700 UT, are indicated next to the corresponding IPPs trajectory. TEC variations along the NS-aligned IPPs tracks (e.g. G27 and G28) clearly show the wavelike fluctuations in the 15-20° N latitude range. The temporal evolution of the TEC for a few satellites is shown in Figure 3 (f). Of our interest is G28’s TEC measurement as its IPPs trajectory lay close to the imager’s ROI1 during 1700-1800 UT. It showed a strong signature of GWs having τ ~0.95 ± 0.03 h, λ ~229 ± 12 km, and υ ~67 ± 5 m/s, and is in good agreement with the ASAI observations. The propagation direction of GWs seen here is in good agreement with these previous reports. Studies on the GW activity at the MLT heights over a farther low-latitude station Prayagraj (25.5° N, formerly Allahabad) in India showed their propagation either northward or northeast around midnight during April-May (Mukherjee et al., 2010). A comprehensive study of

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

thermospheric GWs in the ASAI observations over Tirunelveli (8.7° N) in India during 2013-2015 indicated their propagation toward the north-northwest during the equinoxes (Sau et al., 2018).

3.2 GWs-driven revival of fossil depletions

During 1730-1748 UT, faint signatures of depletion DP1 that revived were seen in the ROI1. Depletion DP1 lacked any poleward growth during 1730-1806 UT. Using the equation given in Kelley (2009) and by tracking the poleward tip of depletion, we estimated the apex height of the associated geomagnetic flux tubes (A_H) and found it to be steady at ~600 km. Within it, the level of intensity reduction with respect to that of the ambient region (i.e., $\Delta I/I_{ambient\ region}$) was ~17 %. However, depletion DP1 drifted gradually to the east with a speed of 59-70 m/s. Beginning 1812-1818 UT, this depletion started to intensify steadily, gain contrast against the background and become noticeable. Southern end of depletion DP1 was fused with that of a preceding depletion OD2. A few faint NS-aligned depletions were also present in the ROI1. Along with depletion DP1, they intersected the EW-aligned fronts 'f1' and 'f2' of GWs, and fragmented them into few isolated structures. Later on, these structures got attached to the west wall of depletion DP1 and started moving in unison. Clear signs of two such fragments (marked as S1 and S2 in Figure 1 and 2) can be seen at ~1830 UT and ~1806-1812 UT, respectively. Starting 1824-1830 UT, we noted airglow enhancement to occur near its east wall that then started to become distinct. As a result, an *inverted arrowhead*-shaped depletion with an unusually wide southern fraction was evident during 1836-1854 UT. As two attached structures S1 and S2 drifted along with depletion DP1, they tilted considerably to the east by ~60-75° (see the ASAI images beginning 1830 UT in Figures 1 and 2). At ~1900 UT, the structure S1 was almost aligned and merged with the west wall of depletion DP1, which led to a fairly distinct west wall (seen as weak airglow enhancement). Airglow enhancement near both the east and west wall (marked as A1 and A2, respectively, in Figure 2) continued, and a linear NS-aligned depletion DP1 (having A_H > 800 km and $\Delta I/I_{ambient\ region}$ ~50 %) was seen at 1906-1912 UT. Within the next 6-12 min, the apex of structure S2 merged with airglow enhancement A2 near the west wall.

Next, some airglow enhancement occurred in the inner edge of the west wall of depletion DP1 at 1924 UT (see the region-of-interest, ROI2 in Figure 2). We interpret this as a consequence of some ambient plasma intrusion across its west wall. Otsuka et al. (2012) and

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Shiokawa et al. (2015) earlier reported the disappearance of an EPB upon interaction with MSTIDs and large-scale traveling ionospheric disturbances (LSTIDs), respectively. Authors suggested that the electric field associated with MSTIDs/LSTIDs can move ambient plasma into the bubble across the geomagnetic field line through **E x B** drift which will result in the filling and subsequent disappearance of the depletion. We found that such intrusion, later, led to the disappearance of its southern fraction and the formation of an isolated depletion at 1942 UT. Possibly these disappearances occurred due to the filling of the EIA plasma into depletion across its western wall via the mechanism suggested by Otsuka et al. (2012). Similarly, fossil depletion DP2 also revived; however, its evolution was much simpler than that of depletion DP1.

4 Discussions

We present rare simultaneous observations of GWs activity and associated revival of fossil depletions in the F-region airglow imaging around midnight over an off-equatorial station Ranchi (located near the EIA crest) in India. Post-sunset ionospheric irregularities, in the equatorial region, are generated by the GRT instability that sets off under the suitable combination of (i) favourable alignment of solar terminator with geomagnetic field lines; (ii) rapid height rise of the F-layer; (iii) absence of strong transequatorial wind and (iv) necessary seed perturbation (Fejer and Kelley, 1980; Kelley, 2009; Makela and Otsuka, 2012; Woodman, 2009). Stronger the height rise of the F-layer and an initial seed perturbation is, the faster the growth rate of GRT instability, which ultimately leads to the rapid evolution of the irregularities (Huba and Joyce, 2007; Huang et al., 1993; Hysell et al., 2014; Kelley et al., 1981; Krall et al., 2013; Tsunoda, 2010; Zalesak and Ossakow, 1980). GWs are well known to deform the bottom side plasma of the F-region into the wavelike ionization structures that then act as a seed to GRT instability, which, in turn, generates irregularities. While their role in the generation of the post-sunset irregularities is well known, our understanding is limited in the context of midnight/post-midnight irregularities. Present study features midnight fossil airglow depletions that revived due to undergoing GW activity and turned into an active depletion.

Northward propagating GWs having λ ~210 km, υ ~64 m/s, and τ ~0.91 h were recorded in 630 nm nightglow images during 1715-1906 UT. Supporting airglow observations, TEC measurements, too, showed the presence of similar GWs. Simultaneously, an eastward

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

drifting fossil depletion DP1 (A_H ~600 km and $\Delta I/I_{ambient\ region}$, ~17 %) co-existed during 1730-1748 UT. Next, depletion DP1 and other co-existing depletions intercepted EW-aligned GW fronts and fragmented them during 1806-1824 UT. Subsequently, two such fragments viz. S1 and S2 that lay close to depletion DP1 got attached to its west wall, started drifting eastward in unison, tilted significantly to the east, and almost got aligned with the west wall. Next, depletion DP1 gradually intensified, surged polewards, and became a well-developed linear depletion (A_H > 800 km and $\Delta I/I_{ambient\ region}$ ~50 %) during 1906-1912 UT. Meanwhile, airglow enhancement continued to develop near both its walls and an uneven broadening was seen in its southern half. Next, some ambient plasma diffusion occurred near this uneven region leading to airglow enhancement in the inner edge of its west wall at 1924 UT. Such intrusion continued, its southern fraction gradually disappeared, and an isolated depletion was formed at 1942 UT. Present observations clearly indicate that "fossil depletion" DP1 revived and became an "active depletion" under the influence of co-existing GWs activity. Another succeeding depletion, DP2, too, showed a similar revival.

An important consideration in the GWs seeding of the GRT instability is the alignment of their wavefronts with the geomagnetic field lines. The current understanding is that the strength of the polarization electric field generated by the GWs greatly depends on the angle between them, and the maximum polarization occurs when their wavefront is aligned with the geomagnetic field (Huba et al., 2015; Hysell et al., 2014; Krall et al., 2013; Tulasi Ram et al., 2014; Tsunoda, 2010). Numerical simulations by Hysell et al. (2014) suggest that the GWs-induced modulations were the most severe when their fronts were aligned with the magnetic meridian. Using Communications/Navigation Outrage Forecasting System (C/NOFS) mission TEC measurements, Tulasi Ram et al. (2014) studied the characteristics of large-scale wave structure (LSWS) at the base of the F-region and their association with the EPBs occurrences in Southeast Asia and Africa. Authors found that the EPBs frequently occurred when the amplitudes of LSWS were adequately increased, and their phase fronts were geomagnetic field-aligned.

In the present study, the GWs fronts were east-west aligned (i.e., transverse to the geomagnetic field lines) and propagated northward. Yet, fossil depletions DP1 and DP2 revived and is intriguing. Meridional wind perturbations associated with GWs are known to be ineffective in the initiation and development of depletions. Present observations are in

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

contrast with this notion and point towards another excitation mechanism rather than GRT instability, which we conjecture, is the spatial resonance mechanism for these reasons. Good matching was seen between the GWs phase speed (υ ~64-67 m/s) and the eastward drift of depletion DP1 (υ ~59-70 m/s). Horizontal Wind Model 2007 estimates also indicated the zonal thermospheric wind speed of 51-61 m/s (Drob et al., 2008). We estimated the speed at which the apex of DP1 progressed poleward and found it to be in the range of 46-56 m/s. Spatial resonance theory of GWs seeding of irregularities states that the effects of GWs perturbations are the strongest when its phase speed and the plasma drift velocity are nearly equal (Kelley et al., 1981). Under such conditions, the ionospheric plasma exerts the GW-associated forcing for a longer duration; thereby, accelerating the formation of ionization structures. As such, we conjecture that this GWs-driven revival of fossil depletions occurred via the spatial resonance mechanism. Numerical simulations by Huang and Kelley (1996) suggest that this mechanism can accelerate the formation of depletions. Possibly continuously undergoing GWs activity for 2 hours in the F-region sufficiently intensified the magnitude of associated ionization modulations, which in turn triggered and sustained the revival of fossil depletions via the spatially resonant mechanism.

Meridional wind can influence the growth rate of GRT instability by altering the field-line integrated Pederson conductivity. Maruyama (1988) and Abdu et al. (2006) found that strong meridional winds could reduce the growth rate of RTI and suppress irregularities. Huba and Krall (2013) have reported both stabilizing and destabilizing effects of the meridional winds on RT instability. Devasia et al. (2002) found that a suitable combination of the meridional wind and F-region base height favours ESF development. In the present study, the meridional wind measurements using a Fabry-Perot interferometer, etc. were not available; hence, their possible role in the evolution of these fossil depletions could not be investigated.

5 Summary

We present, here, airglow imaging observations of fossil plasma depletions that revived afresh under the action of prolonged GW activity and became active depletions. Such simultaneous imaging of thermospheric GWs and depletions was recorded in the ASAI of OI 630 nm emission over Ranchi (mlat. ~19º N), India, on 16 April 2012. Salient features of the present study are as under:

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

1. First, airglow images showed EW-aligned and SN-propagating GWs (λ ~210 km, υ ~64 m/s, and τ ~0.91 h) over Ranchi during 1715-1906 UT. Similar GWs were, also, seen in TEC measurements over a lower latitude station Hyderabad.
2. A co-existing and prominent fossil depletion DP1 revived under this GW activity wherein its apex raised from 600 km to >800 km, and the level of intensity depletion increased from 17 % to 50 %. Another fossil depletion DP2, too, revived. Interestingly, GWs phase fronts were transverse to the geomagnetic field lines, yet two fossil depletions revived under their influence and became active depletions.
3. As GWs phase speed (υ ~64-67 m/s) nearly matched the eastward drift of depletion DP1 (υ ~59-70 m/s), we conjecture that the GWs-driven revival of these fossil depletions possibly occurred via the spatial resonance mechanism.
4. An uneven region of increased thickness existed on the southern half of the revived depletion DP1, wherein some airglow enhancement was seen later in the inner edge of its west wall. Possibly the gradual disappearance of its southern fraction occurred because of the intrusion of ambient plasma across the west wall.

Contrary to the current understanding, this study shows that the GWs fronts aligned perpendicular to the geomagnetic field lines can effectively grow irregularities. Present observations of the GWs-driven revival of fossil airglow depletions further contribute to our understanding of their generation mechanism around midnight.

Data Availability. Airglow data used in the present study are available through the institutional data repository (http://www.iigm.res.in/) or https://doi.org/10.5281/zenodo.8143215. Calibrated TEC data is available from https://t-ict4d.ictp.it/nequick2/gnss-tec-calibration.

Author contributions. NP conceptualized the research problem and prepared the first draft. All authors contributed to the interpretation of results, discussion, and subsequent drafting of the manuscript.

Acknowledgements: Funds for Airglow Research at ***Indian Institute of Geomagnetism*** are being provided by ***Department of Science and Technology (DST), Govt. of India, New Delhi***. GNSS TEC Calibrated data were downloaded from https://t-ict4d.ictp.it/nequick2/gnss-tec-calibration and ***Telecommunications/ICT for Development (T/ICT4D) Laboratory of the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy*** is gratefully acknowledged. ***SP*** is grateful to ***Director, Indian Institute of Geomagnetism, Navi Mumbai*** for the award of Research Scholarship.

References:

Abdu, M., Iyer, K. N., de Medeiros, R., Batista, I. S. and Sobral, J. H.: Thermospheric meridional wind control of equatorial spread F and evening prereversal electric field, Geophys. Res. Lett. 33 (7). http://dx.doi.org/10.1029/2005GL024835, 2006.

Abdu, M. A., Kherani, E. A., Batista, I. S., de Paula, E. R., Fritts, D. C., and Sobral, J. H.: Gravity wave initiation of equatorial spread F/plasma bubble irregularities based on observational data from the SpreadFEx campaign, Ann. Geophys., 27, 2607-2622. https://doi.org/10.5194/angeo-27-2607-2009, 2009.

Azeem, I., and Barlage, M.: Atmosphere-ionosphere coupling from convectively generated gravity waves. Adv. Space Res., 61(7), 1931-1941. https://doi.org/10.1016/j.asr.2017.09.029, 2018.

Ciraolo, L., Azpilicueta, F., Brunini, C., Meza, A. and Radicella, S. M.: Calibration errors on experimental slant total electron content (TEC) determined with GPS. J. Geod., 81, 111–120, https://doi.org/10.1007/s00190-006-0093-1, 2007.

Chapagain, N. P., Taylor, M. J., and Eccles, J. V.: Airglow observations and modeling of F region depletion zonal velocities over Christmas Island, J. Geophys. Res., 116, A02301, https://doi.org/10.1029/2010JA015958, 2011.

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, J. Atmos. Sol.-Terrest. Phys. 64 (1), 1–12, http://dx.doi.org/10.1016/S1364-6826(01)00089-X, 2002.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Drob, D. P., Emmert, J. T., Crowley, G., Picone, J. M., Shepherd, G. G., Skinner, W., et al.: An empirical model of the Earth's horizontal wind fields: HWM07. J. Geophys. Res., 113, A12304, https://doi.org/10.1029/2008JA013668, 2008.

Fejer, B. G., and Kelley, M. C.: Ionospheric irregularities. Rev. Geophys., 18(2), 401-454, https://doi.org/10.1029/RG018i002p00401, 1980.

Ford, E. A. K., Aruliah, A. L., Griffin, E. M., and McWhirter, I.: Thermospheric gravity waves in Fabry-Perot Interferometer measurements of the 630.0nm OI line, Ann. Geophys., 24, 555–566, https://doi.org/10.5194/angeo-24-555-2006, 2006.

Ford, E. A. K., Aruliah, A. L., Griffin, E. M., and McWhirter, I.: Statistical analysis of thermospheric gravity waves from Fabry-Perot Interferometer measurements of atomic oxygen, Ann. Geophys., 26, 29–45, https://doi.org/10.5194/angeo-26-29-2008, 2008.

Fritts, D. C., and Alexander, M. J.: Gravity wave dynamics and effects in the middle atmosphere, Rev. Geophys., 41, 1003, https://doi.org/10.1029/2001RG000106,1, 2003.

Fritts, D. C., Abdu, M. A., Batista, B. R., Batista, I. S., Batista, P. P., Buriti, R., Clemesha, B. R., Dautermann, T., de Paula, E. R., Fechine, B. J., Fejer, B. G., Gobbi, D., Haase, J., Kamalabadi, F., Kherani, E. A., Laughman, B., Lima, P. P., Liu, H.-L., Medeiros, A., Pautet, P.-D., Riggin, D. M., Rodrigues, F. S., São Sabbas, F., Sobral, J. H. A., Stamus, P., Takahashi, H., Taylor, M. J., Vadas, S. L., Vargas, F., and Wrasse, C. M.: Overview and summary of the Spread F Experiment (SpreadFEx), Ann. Geophys., 27, 2141–2155, https://doi.org/10.5194/angeo-27-2141-2009, 2009.

Fukushima, D., Shiokawa, K., Otsuka, Y., and Ogawa, T.: Observation of equatorial nighttime medium-scale traveling ionospheric disturbances in 630-nm airglow images over 7 years. J. Geophys. Res., 117, A10324. https://doi.org/10.1029/2012JA017758, 2012.

Heale, C. J., Inchin, P. A., and Snively, J. B.: Primary versus secondary gravity wave responses at F-region heights generated by a convective source, J. Geophys. Res. Space Physics, 127, e2021JA029947, https://doi.org/10.1029/2021JA029947, 2022.

Huang, C.-S., Kelley, M. C., and Hysell, D. L.: Nonlinear Rayleigh-Taylor instabilities, atmospheric gravity waves and equatorial spread F, J. Geophys. Res., 98(A9), 15631-15642, https://doi.org/10.1029/93JA00762, 1993.

Huang, C.-S., and Kelley, M. C.: Nonlinear evolution of equatorial spread F: 1. On the role of plasma instabilities and spatial resonance associated with gravity wave seeding, J. Geophys. Res., 101(A1), 283-292, https://doi.org/10.1029/95JA02211, 1996.

Huba, J. D., and Joyce, G.: Equatorial spread F modeling: Multiple bifurcated structures, secondary instabilities, large density 'bite-outs' and supersonic flows. Geophys. Res. Lett., 34, L07105. https://doi.org/10.1029/2006GL028519, 2007.

Huba, J. D., Joyce, G., and Krall, J.: Three-dimensional equatorial spread F modeling, Geophys. Res. Lett., 35, L10102. https://doi.org/10.1029/2008GL033509, 2008.

Huba, J. D., and Joyce, G.: Global modeling of equatorial plasma bubbles, Geophys. Res. Lett., 37, L17104, https://doi.org/10.1029/2010GL044281, 2010.

Huba, J. D., and Krall, J.: Impact of meridional winds on equatorial spread F: Revisited, Geophys. Res. Lett., 40, 1268– 1272, doi:10.1002/grl.50292, 2013.

Huba, J. D., Drob, D. P., Wu, T.-W., and Makela, J. J.: Modeling the ionospheric impact of tsunami-driven gravity waves with SAMI3: Conjugate effects. Geophys. Res. Lett., 42, 5719–5726. https://doi.org/10.1002/2015GL064871, 2015.

Huba, J. D., and Liu, H.-L.: Global modeling of equatorial spread F with SAMI3/WACCM-X. Geophys. Res. Lett., 47, e2020GL088258. https://doi.org/10.1029/2020GL088258, 2020.

Hysell, D. L., Kelley, M. C., Swartz, W. E., and Woodman, R. F.: Seeding and layering of equatorial spread F by gravity waves. J. Geophys. Res., 95(A10), 17,253-17,260. https://doi.org/10.1029/JA095iA10p17253, 1990.

Hysell, D. L., Jafari, R., Fritts, D. C., and Laughman, B.: Gravity wave effects on postsunset equatorial F region stability, J. Geophys. Res. Space Physics, 119, 5847– 5860, doi:10.1002/2014JA019990, 2014.

Kelley, M. C., Larsen, M. F., LaHoz, C., and McClure, J. P.: Gravity wave initiation of equatorial spread F: A case study, J. Geophys. Res., 86 (A11), 9087-9100, https://doi.org/10.1029/JA086iA11p09087, 1981.

Kelley, M. C.: The Earth's ionosphere: Plasma physics and electrodynamics (2nd ed.). Burlington, MA: Elsevier, 2009.

Klausner, V., Fagundes, P. R., Sahai, Y., Wrasse, C. M., Pillat, V. G., and Becker-Guedes, F.: Observations of GW/TID oscillations in the F2 layer at low latitude during high and low solar activity, geomagnetic quiet and disturbed periods, J. Geophys. Res., 114, A02313, https://doi.org/10.1029/2008JA013448, 2009.

Krall, J., Huba, J. D., and Fritts, D. C.: On the seeding of equatorial spread F by gravity waves, Geophys. Res. Lett., 40, 661-664, https://doi.org/10.1002/grl.50144, 2013.

Makela, J. J., Ledvina, B. M., Kelley, M. C. and. Kintner, P. M: Analysis of the seasonal variations of equatorial plasma bubble occurrence observed from Haleakala, Hawaii, Ann. Geophys., 22, 3109-3121, https://doi.org/10.5194/angeo-22-3109-2004, 2004.

Makela, J. J., Kelley, M. C., and Nicolls, M. J.: Optical observations of the development of secondary instabilities on the eastern wall of an equatorial plasma bubble. J. Geophys. Res., 111, A09311, https://doi.org/10.1029/2006JA011646, 2006.

Makela, J. J., Lognonne, P., Hebert, H., Gehrels, T., Rolland, L., Allgeyer, S., et al.: Imaging and modeling the ionospheric airglow response over Hawaii to the tsunami generated by the Tohoku earthquake of 11 March 2011. Geophys. Res. Lett., 38, L00G02. https://doi.org/10.1029/2011GL047860, 2011.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae Discussions

Makela, J. J., and Otsuka, Y.: Overview of nighttime ionospheric instabilities at low- and mid-latitudes: Coupling aspects resulting in structuring at the mesoscale. Space Sci. Rev., 168(1-4), 419-440. https://doi.org/10.1007/s11214-011-9816-6, 2012.

Maruyama, T.: A diagnostic model for equatorial spread F: 1. Model description and application to electric field and neutral wind effects, J. Geophys. Res., 93 (A12), 14611–14622. http://dx.doi.org/10.1029/JA093iA12p14611, 1988.

Maurya, A. K., Parihar, N., Dube, A., Singh, R., Kumar, S., Chanrion, O., Tomicic, M., and Neubert, T.: Rare observations of sprites and gravity waves supporting D, E, F-regions ionospheric coupling, Sci. Rep., 12, 581. https://doi.org/10.1038/s41598-021-03808-5, 2022.

Mendillo, M., and Baumgardner, J.: Airglow characteristics of equatorial plasma depletions. J. Geophys. Res., 87, 7641-7652, https://doi.org/10.1029/JA087iA09p07641, 1982.

Mendillo, M., Baumgardner, J., Colerico, M., and Nottingham, D.: Imaging science contributions to equatorial aeronomy: initial results from the MISETA program, J. Atmos. Terr. Phys., 59, 1587-1599, https://doi.org/10.1016/S1364-6826(96)00158-7, 1997.

Miller, E. S., Makela, J. J., and Kelley, M. C.: Seeding of equatorial plasma depletions by polarization electric fields from middle latitudes: Experimental evidence, Geophys. Res. Lett., 36, L18105, https://doi.org/10.1029/2009GL039695, 2009.

Mukherjee, G. K., Pragati Shikha, R., Parihar, N., Ghodpage, R. and Patil, P. T.: Studies of the wind filtering effect of gravity waves observed at Allahabad (25.45° N, 81.85° E). Earth Planets Space 62, 309-318, https://doi.org/10.5047/eps.2009.11.008, 2010.

Nishioka, M., Otsuka, Y., Shiokawa, K., Tsugawa, T., Effendy, , Supnithi, P., Nagatsuma, T., and Murata, K. T.: On post-midnight field-aligned irregularities observed with a 30.8-MHz radar at a low latitude: Comparison with F-layer altitude near the geomagnetic equator, J. Geophys. Res., 117, A08337, https://doi.org/10.1029/2012JA017692, 2012.

Otsuka, Y., Shiokawa, K. and Ogawa, T.: Disappearance of equatorial plasma bubble after interaction with mid-latitude medium-scale traveling ionospheric disturbance, Geophysical Research Letters, 39, L14105, https://doi.org/10.1029/2012GL052286, 2012.

Otsuka, Y.: Review of the generation mechanisms of post-midnight irregularities in the equatorial and low-latitude ionosphere. Prog.. Earth Planet. Sci. 5, 57. https://doi.org/10.1186/s40645-018-0212-7, 2018.

Parihar, N., Singh, D., and Gurubaran, S.: A comparison of ground-based hydroxyl airglow temperatures with SABER/TIMED measurements over 23° N, India, Ann. Geophys., 35, 353–363, https://doi.org/10.5194/angeo-35-353-2017, 2017.

Parihar, N., Radicella, S. M., Nava, B., Migoya-Orue, Y. O., Tiwari, P., and Singh, R.: An investigation of the ionospheric F region near the EIA crest in India using OI 777.4 and 630.0 nm nightglow observations. Ann. Geophys., 36(3), 809-823. https://doi.org/10.5194/angeo-36-809-2018, 2018.

Parihar, N.: Rare occurrence of off-equatorial edge initiating and equatorward surging plasma depletions observed in OI 630-nm imaging. J. Geophys. Res. Space Physics, 124, 2887-2896. https://doi.org/10.1029/2018JA026155, 2019.

Paulino, I., Takahashi, H., Medeiros, A. F., Wrasse, C. M., Buriti, R. A., Sobral, J. H. A., and Gobbi, D.: Mesospheric gravity waves and ionospheric plasma bubbles observed during the COPEX campaign. J. Atmos. Sol.-Terr. Phys., 73(11-12), 1575-1580. https://doi.org/10.1016/j.jastp.2010.12.004, 2011.

Paulino, I., Medeiros, A. F., Vadas, S. L., Wrasse, C. M., Takahashi, H., Buriti, R. A., Leite, D., Filgueira, S., Bageston, J. V., Sobral, J. H. A., and Gobbi, D.: Periodic waves in the lower thermosphere observed by OI630 nm airglow images, Ann. Geophys., 34, 293-301, https://doi.org/10.5194/angeo-34-293-2016, 2016.

Paulino, I., Moraes, J. F., Maranhão, G. L., Wrasse, C. M., Buriti, R. A., Medeiros, A. F., Paulino, A. R., Takahashi, H., Makela, J. J., Meriwether, J. W., and Campos, J. A. V.: Intrinsic parameters of periodic waves observed in the OI6300 airglow layer over the

Brazilian equatorial region, Ann. Geophys., 36, 265–273, https://doi.org/10.5194/angeo-36-265-2018, 2018.

Pimenta, A. A., Fagundes, P. R., Sahai, Y., Bittencourt, J. A., and Abalde, J. R.: Equatorial F-region plasma depletion drifts: latitudinal and seasonal variations. Ann. Geophys., 21, 2315-2322, https://doi.org/10.5194/angeo-21-2315-2003, 2003.

Sau, S., Narayanan, V. L., Gurubaran, S., and Emperumal, K.: Study of wave signatures observed in thermospheric airglow imaging over the dip equatorial region. Adv. Space Res., 62(7), 1762–1774, https://doi.org/10.1016/j.asr.2018.06.039, 2018.

Sekar, R., Chakrabarty, D., Sarkhel, S., Patra, A. K., Devasia, C. V., and Kelley, M. C.: Identification of active fossil bubbles based on coordinated VHF radar and airglow measurements, Ann. Geophys., 25, 2099-2102, https://doi.org/10.5194/angeo-25-2099-2007, 2007.

Shiokawa, K., Otsuka, Y., Lynn, K. J., Wilkinson, P., and Tsugawa, T.: Airglow-imaging observation of plasma bubble disappearance at geomagnetically conjugate points. Earth Planets and Space, 67(1), 43, https://doi.org/10.1186/s40623-015-0202-6, 2015.

Singh, S., Johnson, F. S., and Power, R. A.: Gravity wave seeding of equatorial plasma bubbles. J. Geophys. Res., 102(A4), 7399– 7410, https://doi.org/10.1029/96JA03998, 1997.

Smith, S. M., Martinis, C. R., Baumgardner, J., and Mendillo, M.: All-sky imaging of transglobal thermospheric gravity waves generated by the March 2011 Tohoku Earthquake, J. Geophys. Res. Space Physics, 120, 10,992-10,999, https://doi.org/10.1002/2015JA021638, 2015.

Sreeja, V., Vineeth, C., Pant, T. K., Ravindran, S. and Sridharan, R.: Role of gravity wavelike seed perturbations on the triggering of ESF-First results from unique dayglow observations, Ann. Geophys., 27, 313-318, https://doi.org/10.5194/angeo-27-313-2009, 2009.

Takahashi, H., Taylor, M. J., Pautet, P.-D., Medeiros, A. F., Gobbi, D., Wrasse, C. M., Fechine, J., Abdu, M. A., Batista, I. S., Paula, E., Sobral, J. H. A., Arruda, D., Vadas, S. L.,

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Sabbas, F. S., and Fritts, D. C.: Simultaneous observation of ionospheric plasma bubbles and mesospheric gravity waves during the SpreadFEx Campaign, Ann. Geophys., 27, 1477-1487, https://doi.org/10.5194/angeo-27-1477-2009, 2009.

Taori, A., Makela, J. J., and Taylor, M. J.: Mesospheric wave signatures and equatorial plasma bubbles: A case study, J. Geophys. Res., 115, A6, A06302, https://doi.org/10.1029/2009JA015088, 2010.

Taori, A., Jayaraman, A., and Kamalakar, V.: Imaging of mesosphereñthermosphere airglow emissions over Gadanki (13.5° N, 79.2° E): First results. J. Atmos. Sol.-Terr. Phys., 93, 21-28. https://doi.org/10.1016/j.jastp.2012.11.007, 2013.

Taori, A., Parihar, N., Ghodpage, R., Dashora, N., Sripathi, S., Kherani, E. A., and Patil, P. T. (2015). Probing the possible trigger mechanisms of an equatorial plasma bubble event based on multistation optical data. J. Geophys. Res. Space Physics, 120, 8835-8847. https://doi.org/10.1002/2015JA021541.

Tsunoda, R. T.: On seeding equatorial spread F: Circular gravity waves, Geophys. Res. Lett., 37, L10104, https://doi.org/10.1029/2010GL043422, 2010.

Tulasi Ram, S., Yamamoto, M., Tsunoda, R. T., Chau, H. D., Hoang, T. L., Damtie, B., Wassaie, M., Yatini, C. Y., Manik, T., and Tsugawa, T.: Characteristics of large-scale wave structure observed from African and Southeast Asian longitudinal sectors, J. Geophys. Res. Space Physics, 119, 2288-2297, https://doi.org/10.1002/2013JA019712, 2014.

Vadas, S. L., and Azeem, I.: Concentric secondary gravity waves in the thermosphere and ionosphere over the continental United States on 25-26 march 2015 from deep convection. J. Geophys. Res. Space Physics, 126, e2020JA028275. https://doi.org/10.1029/2020JA028275, 2021.

Woodman, R. F.: Spread F: An old equatorial aeronomy problem finally resolved? Ann. Geophys., 27(5), 1915-1934. https://doi.org/10.5194/angeo-27-1915-2009, 2009.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Yadav, S., Sridharan, R., Sunda, S. and Pant, T. K.: Further refinements to the spatiotemporal forecast model for L-band scintillation based on comparison with C/NOFS observations, J. Geophys. Res. Space Physics, 122, 5643-5652, https://doi.org/10.1002/2017JA023869, 2017.

Zalesak, S., and Ossakow, S.: Nonlinear equatorial spread F: Spatially large bubbles resulting from large horizontal scale initial perturbations. J. Geophys. Res., 85(A5), 2131-2142. https://doi.org/10.1029/JA085iA05p02131, 1980.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae Discussions

Figure Captions

Figure 1. ASAI images during 1742-1830 UT over Ranchi (23.3º N, 85.3º E, mlat. ~19º N) on 16 April 2012. DP1 is the first fossil plasma depletion that showed GWs driven revival. Depletions OD1 and OD2 preceded depletion DP1. ROI1 is the region-of-interest wherein the south-north propagating GW activity and faint signatures of eastward drifting depletion DP1 were seen initially. Some noticeable GWs fronts are 'f1', 'f2' and 'f3' (in succession). 'S1' and 'S2' are the fractions of fronts 'f1' and 'f2', respectively, that subsequently got linked to the west wall of depletion DP1.

Figure 2. Same as Figure 1 but for 1836-1942 UT. DP2 is the second fossil depletion that showed GWs driven revival. Some noticeable GWs fronts are 'f3' and 'f4'. A1 and A2 are two arc-shaped regions of airglow enhancement near the east and west wall of depletion DP1. ROI2 is the region-of-interest wherein ambient plasma diffusion occurred across the west wall of depletions DP1.

Figure 3. (a)-(b) North-south (NS) keogram along 84.4° E and 85.3° E longitude generated from OI 630 nm images during 1730-1930 UT. Alternating bright and dark intensity striations can be seen over North. Slope of these striations indicates towards the south-north movement of GW fronts. (c)-(d) Sample time difference images created from successive images. GW bright fronts 'f1' and 'f2' can clearly be seen separated by a dark trough during 1754-1806 UT. (e) Scatter plot of the TEC along the track of IPPs for different GPS satellites over Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N) during 1700-2000 UT on 16 April 2012. PRN numbers of GPS satellites along with the start time at 1700 UT are marked adjacent to the corresponding IPPs trajectory. G28's trajectory lay close to the south-west sector of the ASAI. (f) TEC variations of a few satellites showing the presence of GWs activity.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae Discussions
Open Access

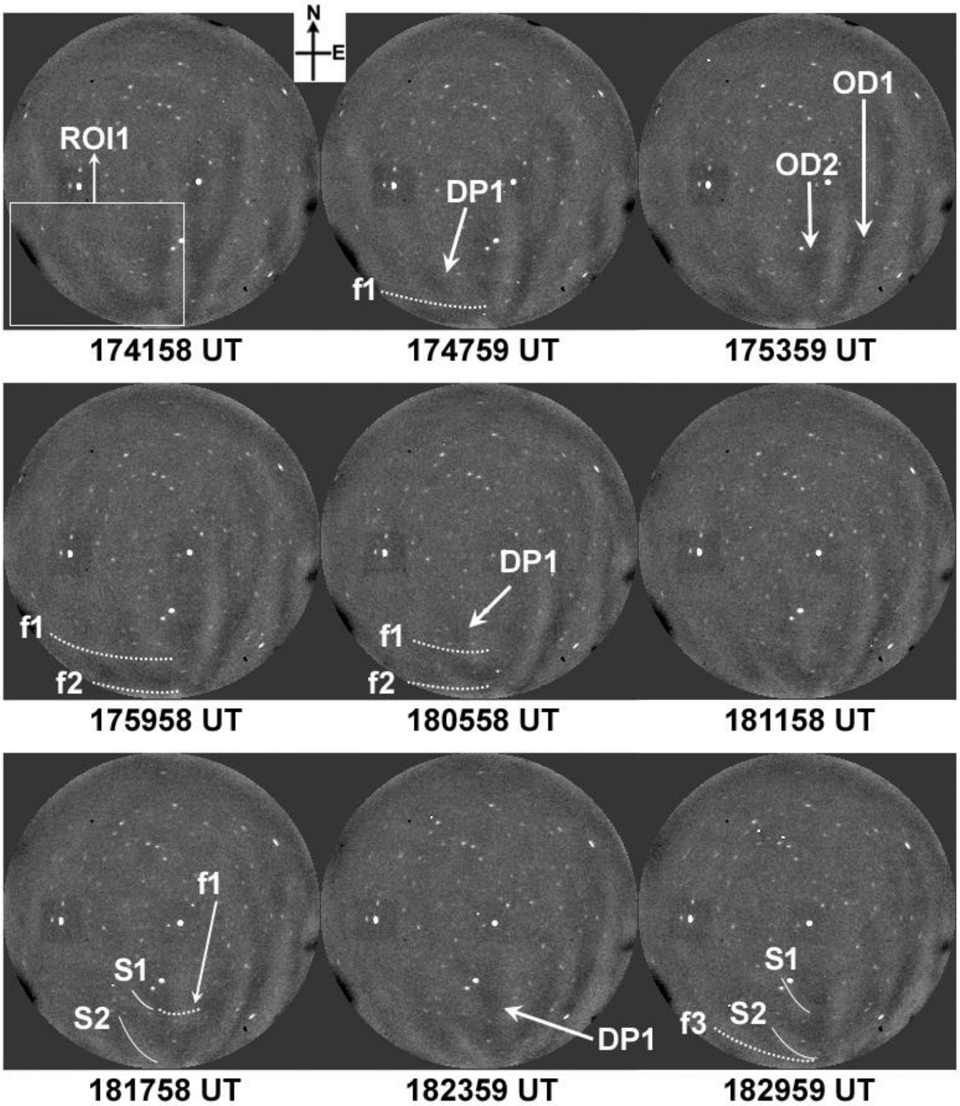

Figure 1. ASAI images during 1742-1830 UT over Ranchi (23.3º N, 85.3º E, mlat. ~19º N) on 16 April 2012. DP1 is the first fossil plasma depletion that showed GWs driven revival. Depletions OD1 and OD2 preceded depletion DP1. ROI1 is the region-of-interest wherein the south-north propagating GW activity and faint signatures of eastward drifting depletion DP1 were seen initially. Some noticeable GWs fronts are 'f1', 'f2' and 'f3' (in succession). 'S1' and 'S2' are the fractions of fronts 'f1' and 'f2', respectively, that subsequently got linked to the west wall of depletion DP1.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae
Discussions
Open Access

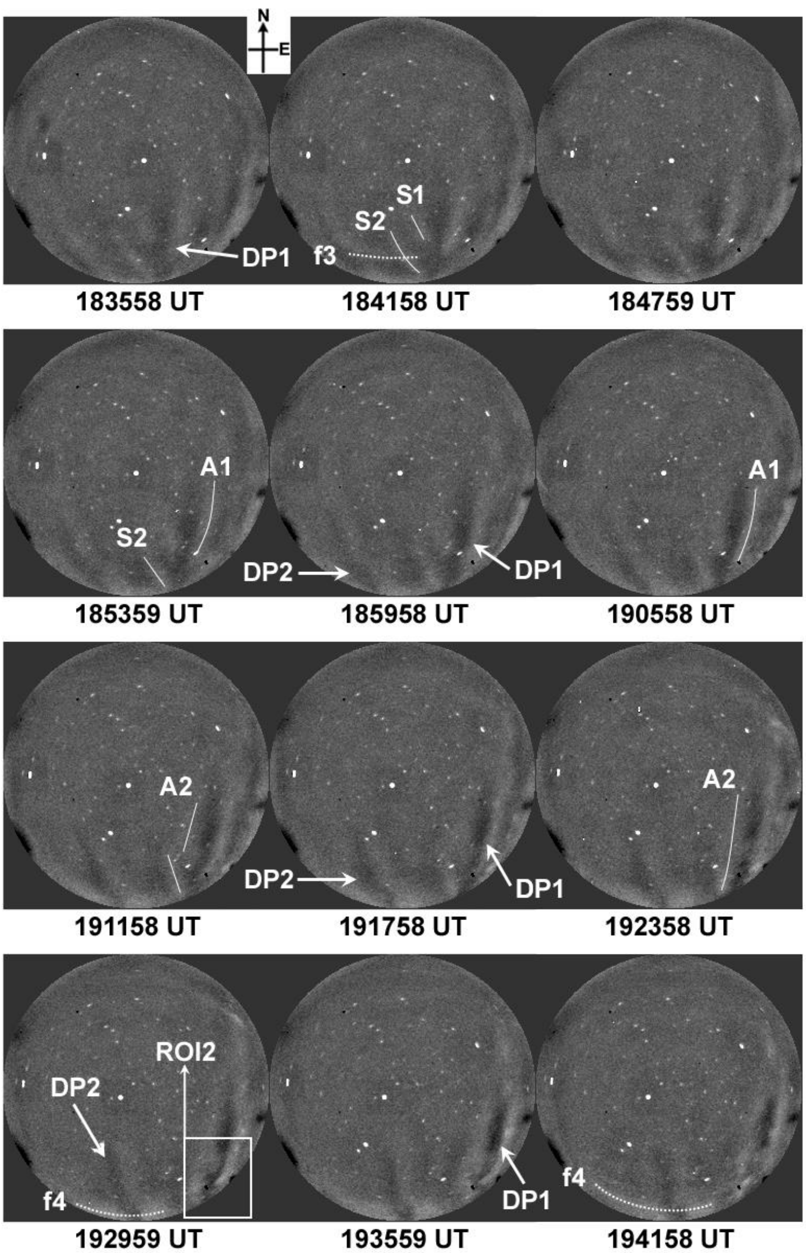

Figure 2. Same as Figure 1 but for 1836-1942 UT. DP2 is the second fossil depletion that showed GWs driven revival. Some noticeable GWs fronts are 'f3' and 'f4'. A1 and A2 are two arc-shaped regions of airglow enhancement near the east and west wall of depletion DP1. ROI2 is the region-of-interest wherein ambient plasma diffusion occurred across the west wall of depletions DP1.

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

Annales Geophysicae Discussions

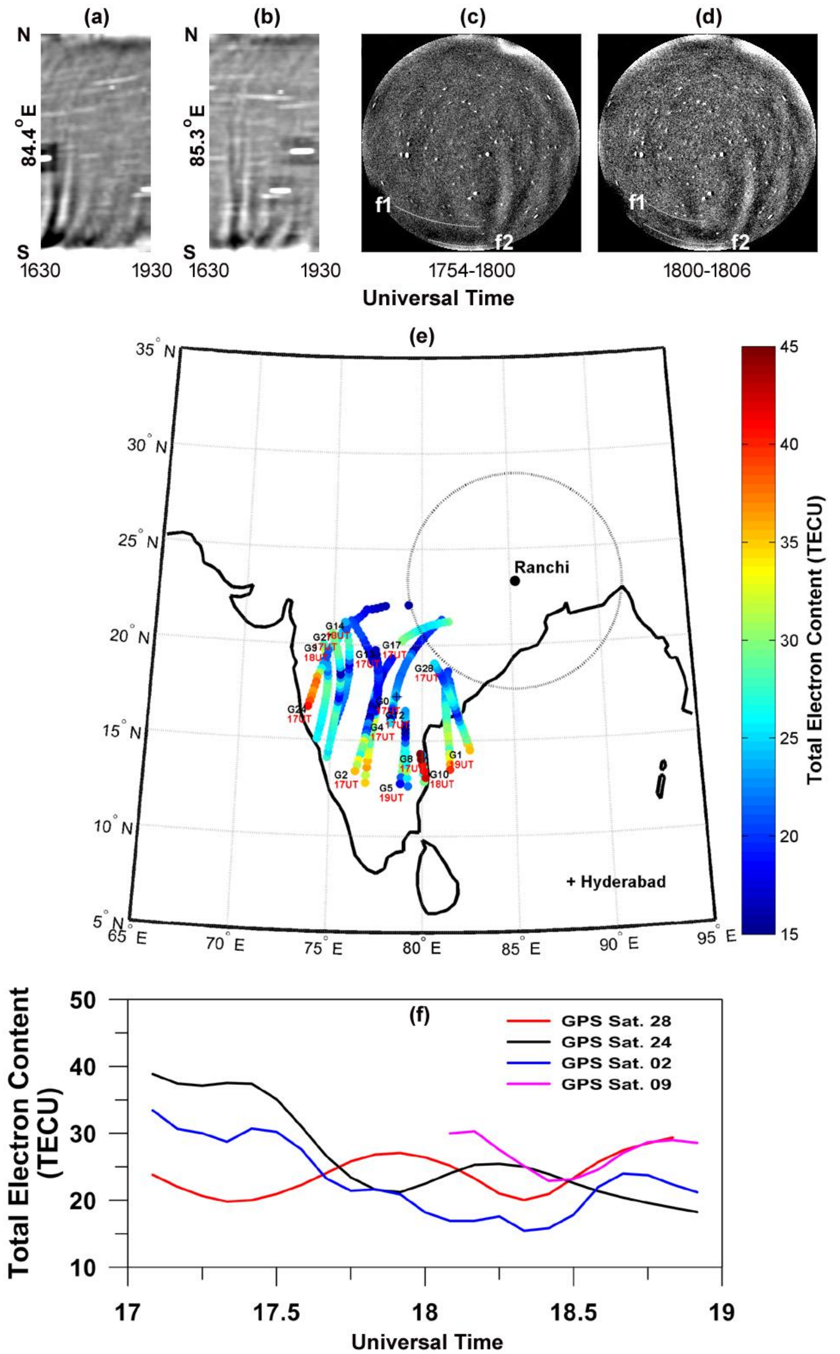

Figure 3. (a)-(b) North-south (NS) keogram along 84.4° E and 85.3° E longitude generated from OI 630 nm images during 1730-1930 UT. Alternating bright and dark intensity striations can be seen over North. Slope of these striations indicates towards the south-north

https://doi.org/10.5194/angeo-2023-26
Preprint. Discussion started: 27 July 2023

movement of GW fronts. (c)-(d) Sample time difference images created from successive images. GW bright fronts 'f1' and 'f2' can clearly be seen separated by a dark trough during 1754-1806 UT. (e) Scatter plot of the TEC along the track of IPPs for different GPS satellites over Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N) during 1700-2000 UT on 16 April 2012. PRN numbers of GPS satellites along with the start time at 1700 UT are marked adjacent to the corresponding IPPs trajectory. G28's trajectory lay close to the south-west sector of the ASAI. (f) TEC variations of a few satellites showing the presence of GWs activity.