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

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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.

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; Figueiredo et al., 2018; 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 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)

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. Lately, Wrasse et al. (2021) presented an interesting event wherein a fossil EPB merged with other ones after interacting with an electrified MSTID and turned into an active bubble.

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 described this ASAI system in detail. OI 630 nm emission was monitored using a 2.2 nm half-power bandwidth optical filter having transmittance of ~77%. Our imager's field-of-view roughly covered about 7-8° latitude/longitude region at 250 km over Ranchi. Airglow images were flat-fielded to reduce the inhomogeneous contribution at lower elevations due to van Rhijn effect and non-uniform sensitivity of CCD detector at different pixels. Next, following the technique described by Wrasse et al. (2021), we detrended the individual images to enhance the contrast of airglow features using an hour running average image. Using known astral positions and assuming OI 630 nm emission peak at 250 km, the geographic coordinates of each pixel was determined following the technique of Garcia et al. (1997). Using this information, all-sky images were unwarped. We follow the technique discussed by Pimenta et al. (2003) to determine the drift velocity of depletions. First, for a given latitude, two intensity profiles along east-west direction as a function of distance was generated using two successive unwarped images. Next, the east-west displacement of depletion was estimated using these two profiles from which drift speed was determined (see Pimenta et al., 2003 for details of this technique). Similarly, the propagation characteristics of GW fronts were estimated by tracking faint crest and trough along the propagation direction in the consecutive images. As GW fronts were unclear in images, we used contrast-enhanced images. We, also, generated NS keograms to visualize GW traces and determine their speed. A keogram is a time-versus-latitude plot generated by extracting a NS column from individual images and stacking them horizontally. Next, GWs speed was, also, estimated from the slope of wave traces seen in these keograms (Makela et al., 2006). We looked into the total electron content (TEC) measurements from an *International GNSS Service* station Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N, located nearby and south of Ranchi) to ascertain GW activity seen in the ASAI observations (Source: https://t-ict4d.ictp.it/nequick2/gnss-tec-calibration, Ciraolo et al., 2007). Quiet geomagnetic conditions prevailed on this night with $Kp < 2$, $Ap = 4$, and $-4 < Dst < 10\ nT$.

3. Observations

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. Figures 1 and 2 present airglow images that depict this event seen over Ranchi during 1742-1942 UT on 16 April 2012. As the faint airglow features were getting lost in the unwarping process, warped all-sky images are presented. Supplementary material S1 shows the movie created from these images that feature this event. 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 perceivable fronts of GWs and fossil depletions coexisted initially.

3.1 Signatures of GW activity in the F-region

We first observed faint signatures of GW activity near the southern edge of the field-of-view (FOV) during ~1715-1724 UT. Successive images showed unclear signatures of GWs activity. Starting ~1730 UT, their presence became more evident and continued until 1906 UT or so. GWs fronts were not clearly seen because of their interaction with co-existing depletions. Some weakly perceivable bright fronts are marked as 'f1', 'f2', 'f3'and 'f4' in Figure 1 and 2. Similarly, dark trough that precede fronts 'f1' and 'f2' are marked as 't1' and 't2', respectively. Often GWs in OI 630 nm imaging are faint and unclear. Under similar situations, Makela et al. (2011) found that time difference (TD) images have proven ability to reflect such GWs faint fronts. In their work, initial analysis of raw images did not show any GWs activity linked with tsunami; however, TD images indeed reflected associated GWs. We generated such TD images and are shown in Figure 3 which clearly show dark troughs 't1' and 't2' and GW fronts 'f1' and 'f2'. North-south (NS) keograms [shown in Figure 4 (a) and (b)] showed a few clear alternating bright and dark intensity striations over the north, and their slope indicates that GWs propagated towards the north. We estimated GWs propagation characteristics using the slope of wave traces (marked by black arrow 'b1', 'b2', 'b3', 'b4') 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.

We further looked into the TEC measurements from IGS station Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N), India to confirm this on-going GWs activity. Figure 5 shows the TEC measurements depicting GW activity in and around Hyderabad during 1700-2000 UT on this night. Figure 5 (a) shows the scatter plots of the TEC along the trajectory of ionospheric pierce points (IPPs) for different GPS satellites during 1700-1930 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 5 (b). Mean TEC and its change index i.e. ROTI is shown in Figure 5 (c). Of our interest is G28's TEC measurement as its IPPs trajectory lay close to the imager's ROI1 during 1700-1800 UT which showed a strong signature of GWs. By performing the periodogram analysis of the temporal and spatial variation of its TEC, we estimated the propagation characteristics of GW to be 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. Further, the propagation direction of GWs seen in airglow imaging 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 to be either northward or northeast around midnight during April-May (Mukherjee et al., 2010). A comprehensive study of 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. Later, such intrusion 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 (see 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 (Kelley et al., 1981; Hysell et al., 1990; Huba and Liu, 2020). 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 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 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.

Similar event of GWs associated revival of a fossil depletion occurred around midnight on 06 March 2013 as well and is shown in Figure 6. On this night, GW activity persisted during 1530-1745 UT and concerned fossil depletion **DP3** revived during 1730-1854 UT. Typical ASAI images showing the signs of GW activity are presented in Figure 7. During 1636-1736 UT, GWs had λ ~196 ± 4 km, υ ~160 ± 4 m/s and τ ~0.34 ± 0.02 h, propagated from SW-NE, and their fronts were ~74º aligned with the geomagnetic field line. First, the southern fraction of depletion **DP3** drifted into the western edge of the FOV at 1706-1712 UT. Later, this depletion was seen as an isolated linear depletion during 1730-1736 UT confined within the ~20.1-23.2° N latitude regime with NS extension of ~480 ± 18 km. On course of its eastward drift, depletion **DP3** gradually intensified and developed both poleward and equatorward. During 1706-1800 UT, its base swiftly surged equatorward approximately from 20.2º to 17.7º N. Comparatively, its poleward growth was slower. When well-developed at 1900 UT, its NS extension was in 17-26º N latitudes (i.e. greater than 980 ± 22 km). Simultaneously, two structuring **BR1** and **BR2** developed on its east wall and an isolated depletion (**ID1**) lay on its east at ~20.5° N latitude. We found its drift speed to be in the 81-109 m/s range.

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.

We know that the electric field perturbations associated with MSTIDs can influence the growth of irregularities. Otsuka et al. (2012) and Shiokawa et al. (2015) 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. Studies by Miller et al. (2009), Taori et al. (2015) and Takahashi et al. (2020) suggest that MSTIDs can directly seed EPBs. Simulation studies by Krall et al. (2011), further, indicates that the electric field associated with electrified MSTIDs can enhance the growth of EPBs. Lately, Wrasse et al. (2021) presented an interesting observations of the interaction of a fossil EPB with an electrified MSTID over 13.3° S. After interaction with the MSTID, concerned fossil EPB merged with other four EPBs, developed poleward and bifurcated. Using detrended TEC data, Takahashi et al. (2021) studied the LSWS over Latin America and found them to be effective in seeding EPBs.

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:

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.

Video supplement. Movie created from all-sky 630 nm nightglow images showing the gravity wave activity and the evolution of depletion DP1 and DP2 is available from https://doi.org/10.5281/zenodo.10851669.

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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 weakly noticeable GWs fronts are 'f1', 'f2' and 'f3' (in succession). 't1' and 't2' are trough that precede fronts 'f1' and 'f2', respectively. Upon interaction with depletions present in ROI1, EW-aligned GW fronts 'f1' and 'f2' fragmented and formed structures 'S1' and 'S2' that, subsequently, got linked to the west wall of depletion DP1 and started moving in unison.

Figure 2. Airglow images showing the subsequent evolution of depletion DP1 during 1836-1942 UT. On course of their eastward motion, structures 'S1' and 'S2' significantly tilted to east, aligned with the west wall of depletion DP1 and contributed to its revival. DP2 is another 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. Typical time difference ASAI of OI 630 nm emission over Ranchi showing GW activity during 1742–1830 UT. Noticeable trough and crest of few GW fronts (as shown in Figure 1) are marked as 't1' and 't2' and 'f1', 'f2' and 'f3'. 'S1' and 'S2' are fragmented structures as described in Figure 1.

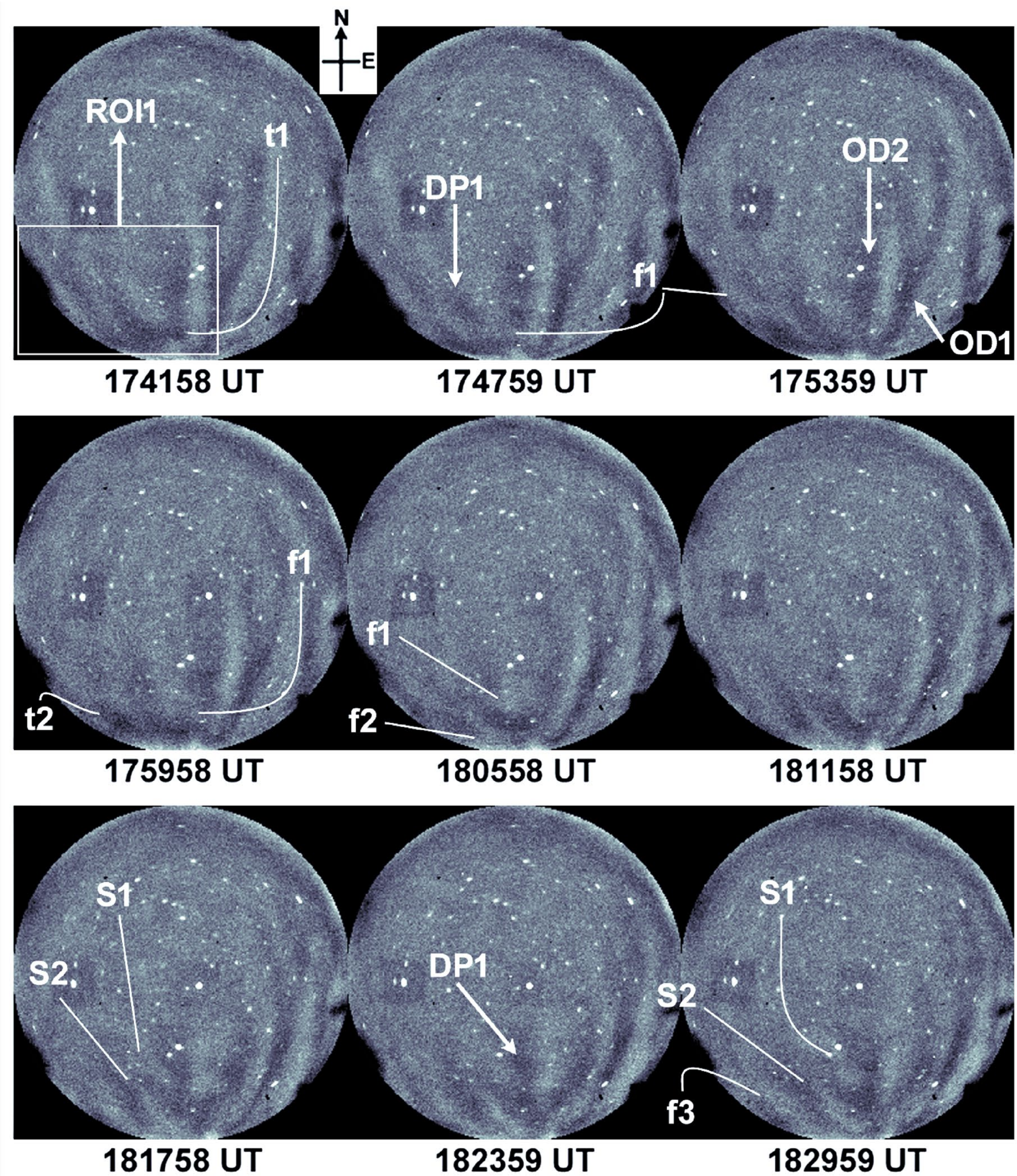
Figure 4. (a)-(b) North-south (NS) keogram along 84.4° E and 85.3° E longitude generated from OI 630 nm images during 1730-1930 UT. Alternating bright and dark intensity striations (i.e. wave traces) can be seen over North. Probably depletions masked GWs features over South, and hence, these wave traces were not seen. Slope of these striations indicates towards the south-north movement of GW fronts. A few clear wave traces that were used to estimate speed of GWs are marked by black arrow as 'b1', 'b2', 'b3' and 'b4'.

Figure 5. (a) Scatter plot of the TEC along the track of IPPs for a few GPS and GLONASS satellites (prefixed as 'G' and 'R', respectively) in the geographic grid of 5-35° N x 65-95° E during 1630-1930 UT on 16 April 2012. PRN numbers of GPS/GLONASS 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. Imager's field-of-view is shown by dashed quarter circle with its centre at Ranchi. (b) TEC variations of a few GPS/GLONASS satellites showing the presence of GWs activity. (c) Mean TEC and ROTI variation over Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N, located equatorward of Ranchi).

Figure 6. Selected ASAI images showing the revival of fossil depletion **DP3** during 1730-1854 UT on 06 March 2013 over Ranchi. **ROI3** is the region-of-interest wherein depletion **DP3** appeared sliced by an unclear thin streak of slightly enhanced airglow. **BR1** and **BR2** are two structuring that developed on its east wall.

Figure 7. Limited time difference ASAI images showing GW activity during 1530-1700 UT on 06 March 2013. Beginning 1336 UT, GW signatures were seen in airglow images; however, activity intensified during 1530-1736 UT. Some of clear GW fronts are marked as 'g1', 'h1' and 'k1'.



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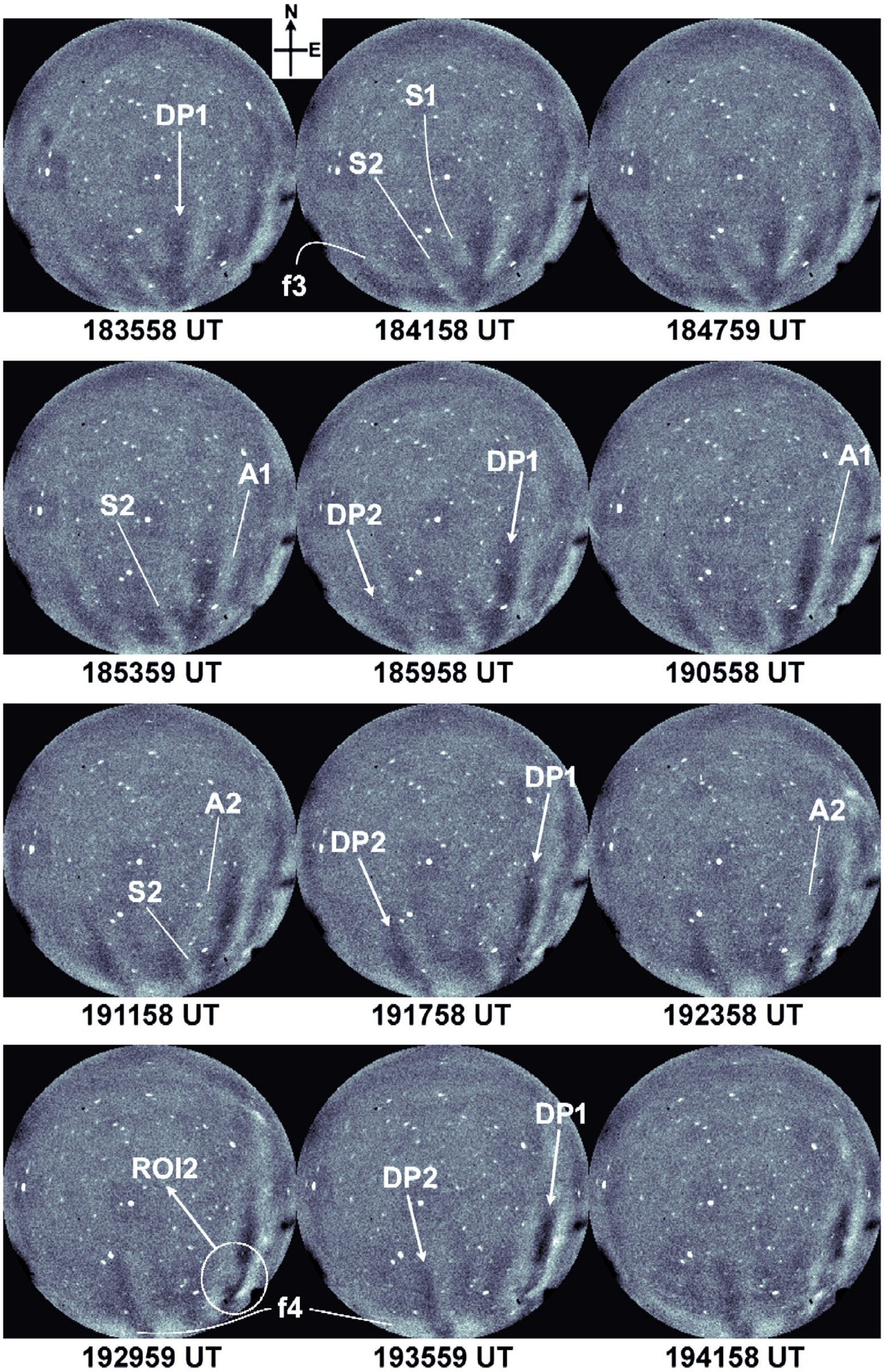

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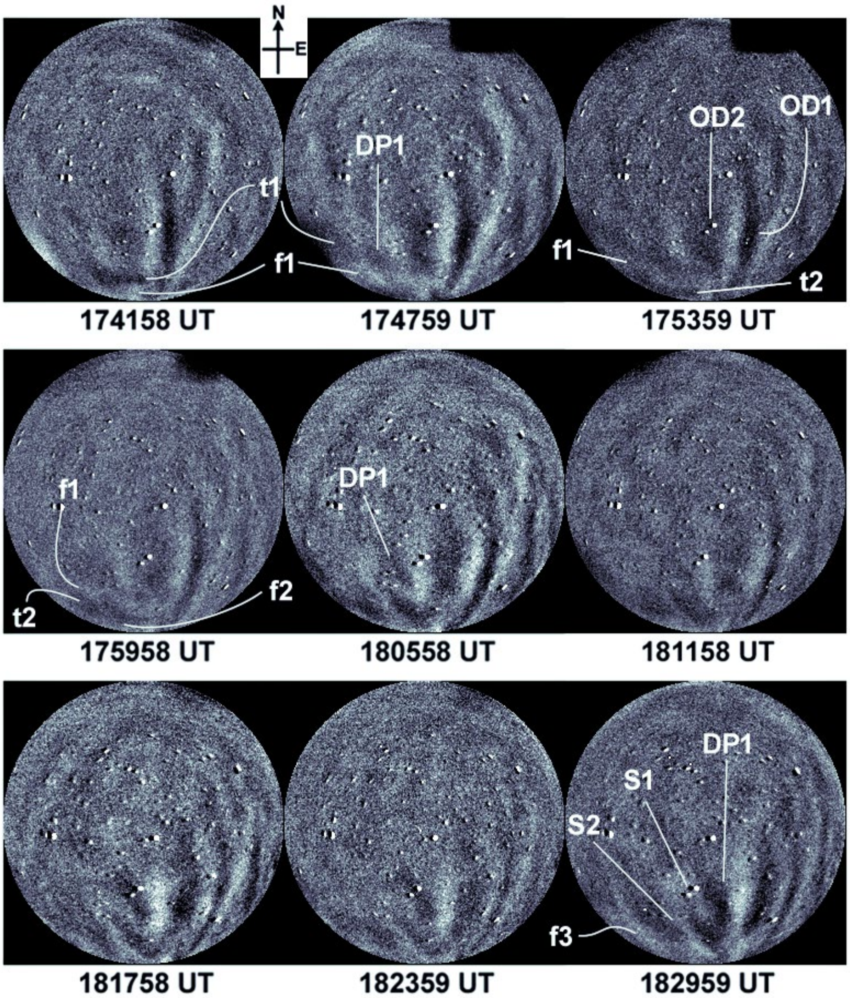

Figure 3. Typical time difference ASAI of OI 630 nm emission over Ranchi showing GW activity during 1742–1830 UT. Noticeable trough and crest of few GW fronts (as shown in Figure 1) are marked as ‘t1’ and ‘t2’ and ‘f1’, ‘f2’ and ‘f3’. ‘S1’ and ‘S2’ are fragmented structures as described in Figure 1.

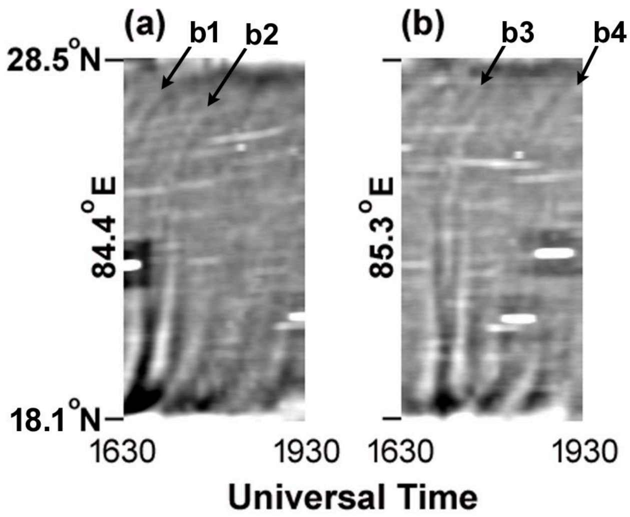

Figure 4. (a)-(b) North-south (NS) keogram along 84.4° E and 85.3° E longitude generated from OI 630 nm images during 1730-1930 UT. Alternating bright and dark intensity striations (i.e. wave traces) can be seen over North. Probably depletions masked GWs features over South, and hence, these wave traces were not seen. Slope of these striations indicates towards the south-north movement of GW fronts. A few clear wave traces that were used to estimate speed of GWs are marked by black arrow as ‘b1’, ‘b2’, ‘b3’ and ‘b4’.

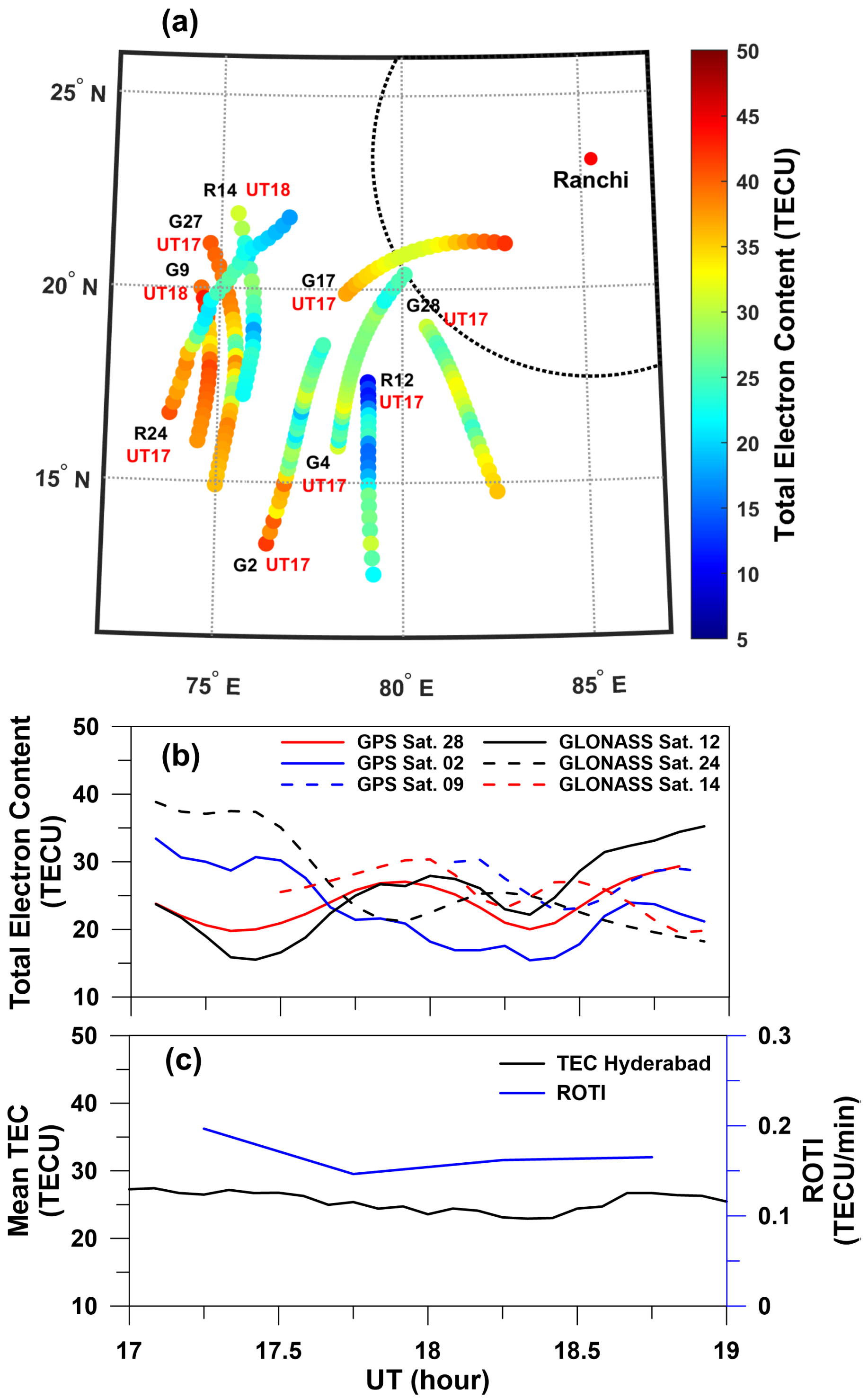

Figure 5. (a) Scatter plot of the TEC along the track of IPPs for a few GPS and GLONASS satellites (prefixed as 'G' and 'R', respectively) in the geographic grid of 5-35° N x 65-95° E during 1630-1930 UT on 16 April 2012. PRN numbers of GPS/GLONASS satellites along with the start time at 1700 UT are marked adjacent to the corresponding IPPs trajectory. G28's trajectory lay close to the south-west sector of the ASAI. Imager's field-of-view is shown by dashed quarter circle with its centre at Ranchi. (b) TEC variations of a few

GPS/GLONASS satellites showing the presence of GWs activity. (c) Mean TEC and ROTI variation over Hyderabad (17.3° N, 78.6° E, mlat. ~12.0° N, located equatorward of Ranchi).

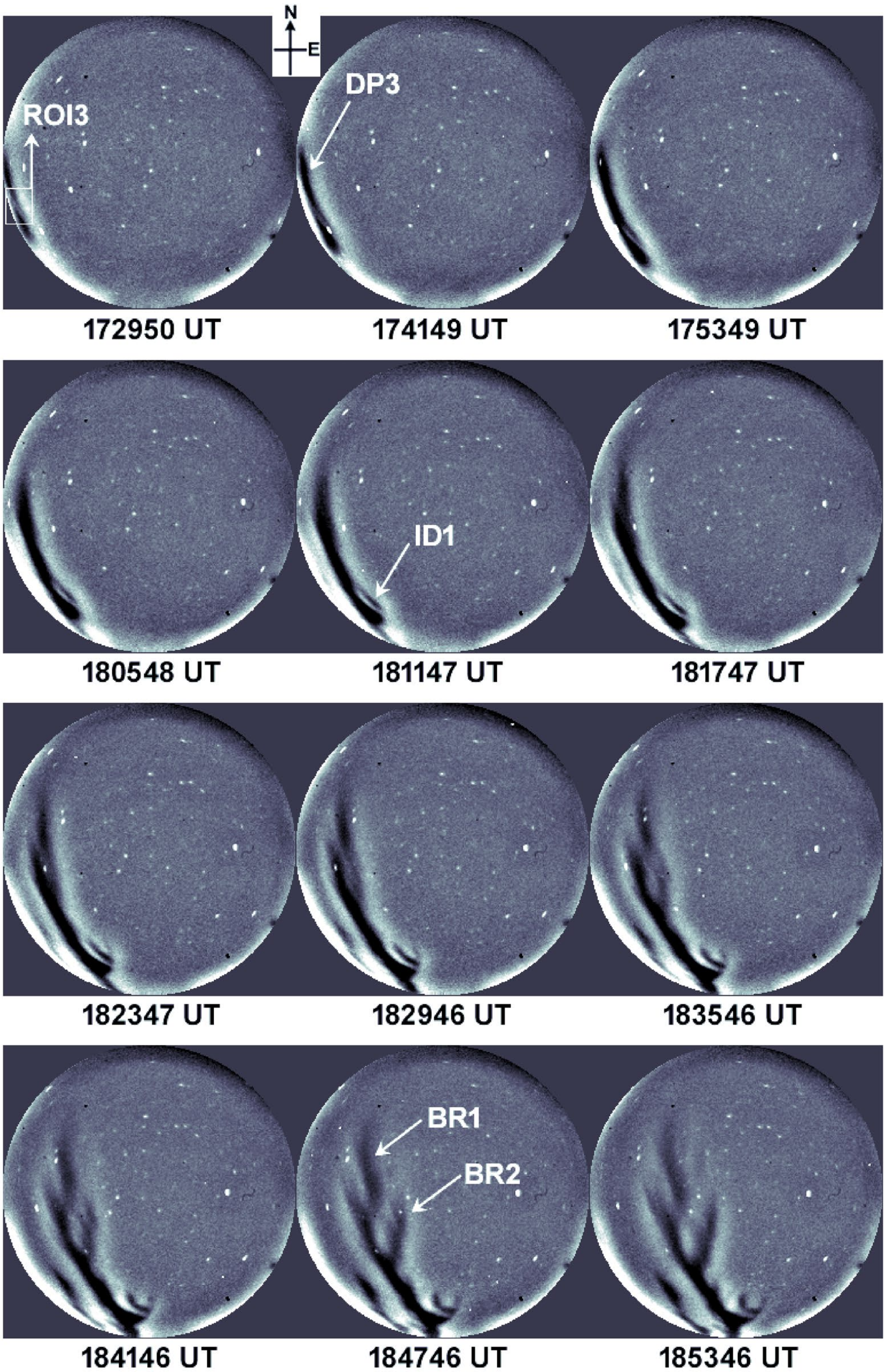

Figure 6. Selected ASAI images showing the revival of fossil depletion **DP3** during 1730-1854 UT on 06 March 2013 over Ranchi. **ROI3** is the region-of-interest wherein depletion

DP3 appeared sliced by an unclear thin streak of slightly enhanced airglow. **BR1** and **BR2** are two structuring that developed on its east wall.

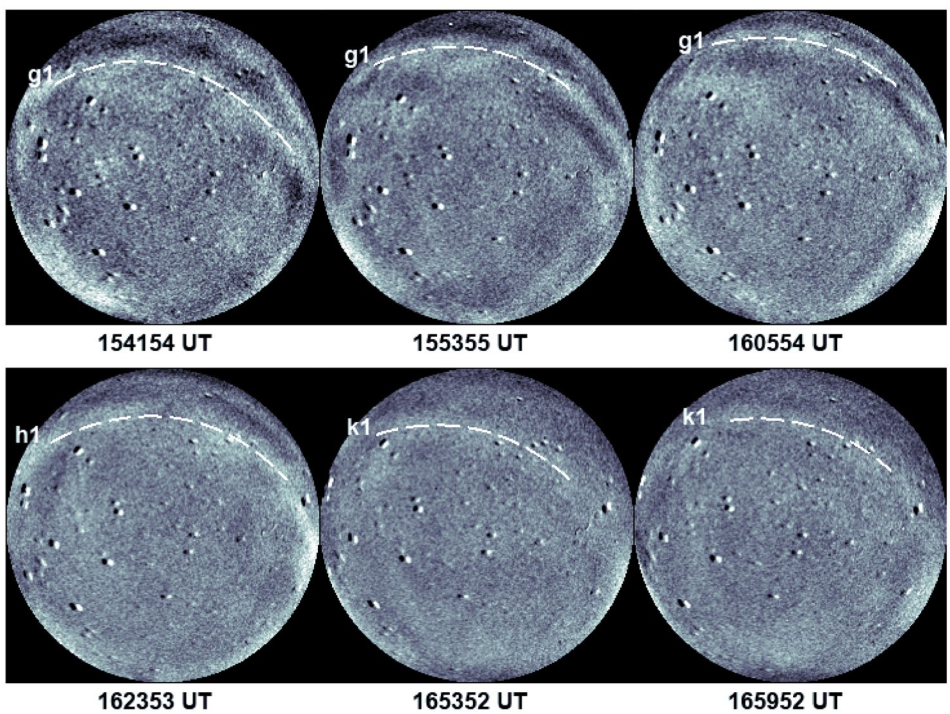

Figure 7. Limited time difference ASAI images showing GW activity during 1530-1700 UT on 06 March 2013. Beginning 1336 UT, GW signatures were seen in airglow images; however, activity intensified during 1530-1736 UT. Some of clear GW fronts are marked as ‘g1’, ‘h1’ and ‘k1’.

Supplementary Material

Supplementary Material S1: Movie created from all-sky 630 nm nightglow images showing the gravity wave activity and the evolution of depletion DP1 and DP2 (available from https://doi.org/10.5281/zenodo.10829073).