Reply to Reviewer Comments

Referee comments on “Simultaneous OI 630 nm imaging observations of thermospheric gravity waves and associated revival of fossil depletions around midnight near the EIA crest” by Navin Parihar et al. submitted to Annales Geophysicae.

Dear Editor,

The manuscript titled "Simultaneous OI 630 nm imaging observations of thermospheric gravity waves and associated revival of fossil depletions around midnight near the EIA crest" presents a possible interaction between thermospheric gravity waves (GWs) and fossil equatorial plasma bubbles (EPBs) over Ranchi, India, on 16 April 2012. The authors argue that after the interaction, the EPBs return to the growth stage.

The major issues addressed in the previous review were not fixed by the authors. Therefore, we still believe that the paper, 'Simultaneous OI 630 nm imaging observations of thermospheric gravity waves and the associated revival of fossil depletions around midnight near the EIA crest,' requires significant revision and clarification before it can be accepted for publication.

Reply: We sincerely thank the esteemed Reviewer for his tremendous encouragement, suggestions on utilizing GIRO data and critical comments that helped us to enrich our submission. We have tried our level best to address his concerns in this Second Revised Version.

Comments:

1 - Regarding Figures 1, 2, and 3 (Typical time difference in ASAI of OI 630 nm emission) and Movie S1 (Supplementary Material), they exclusively depict the standard development of equatorial plasma bubbles. These images do not reveal any distinct evidence of thermospheric gravity waves (GWs).

Reply: Sincere thanks for this critical comment. We understand the concern of Reviewer and have revised these three Figures so as to enhance features.

Corrections:

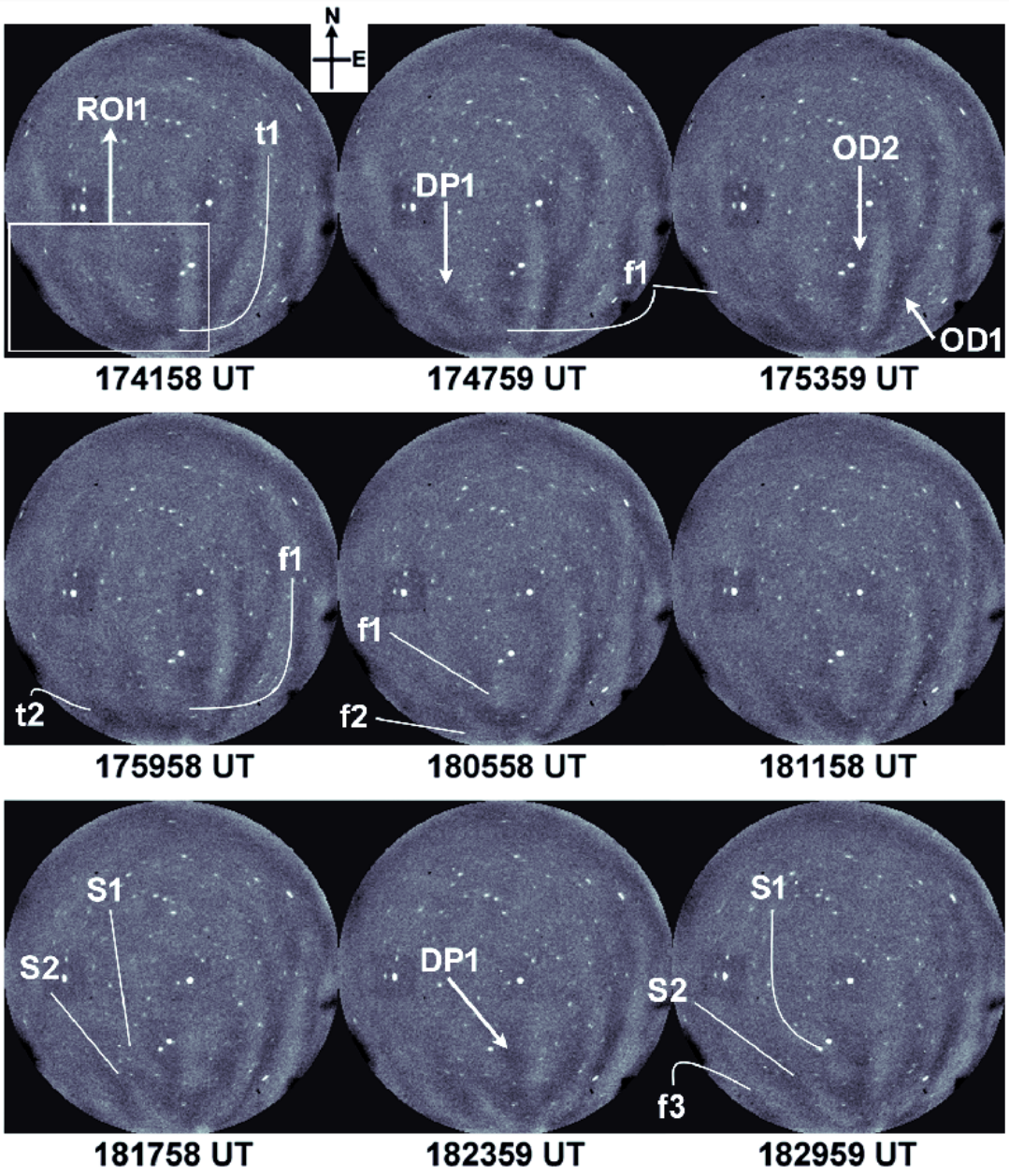

Figure 1. ASAI images during 1742-1830 UT over Ranchi (23.3º N, 85.3º E, mlat. ~19º N) on 16 April 2012. DP1 is the first fossil plasma depletion that showed GWs driven revival. Depletions OD1 and OD2 preceded depletion DP1. ROI1 is the region-of-interest wherein the south-north propagating GW activity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

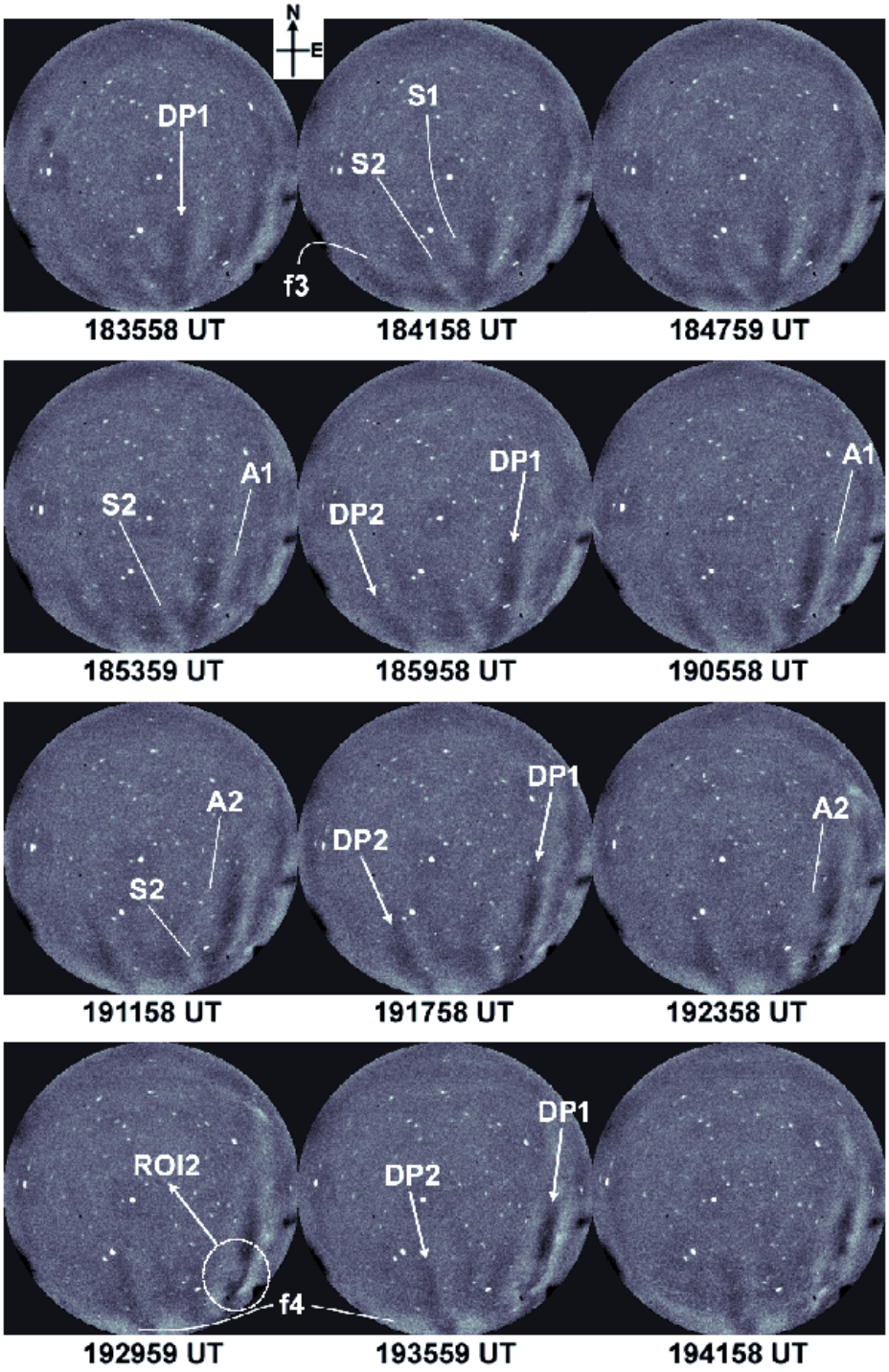

Figure 2. Same as Figure 1 but for 1836-1942 UT. DP2 is the second fossil depletion that showed GWs driven revival. Some noticeable GWs fronts are 'f3' and 'f4'. A1 and A2 are two arc-shaped regions of airglow enhancement near the east and west wall of depletion DP1. ROI2 is the region-of-interest wherein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

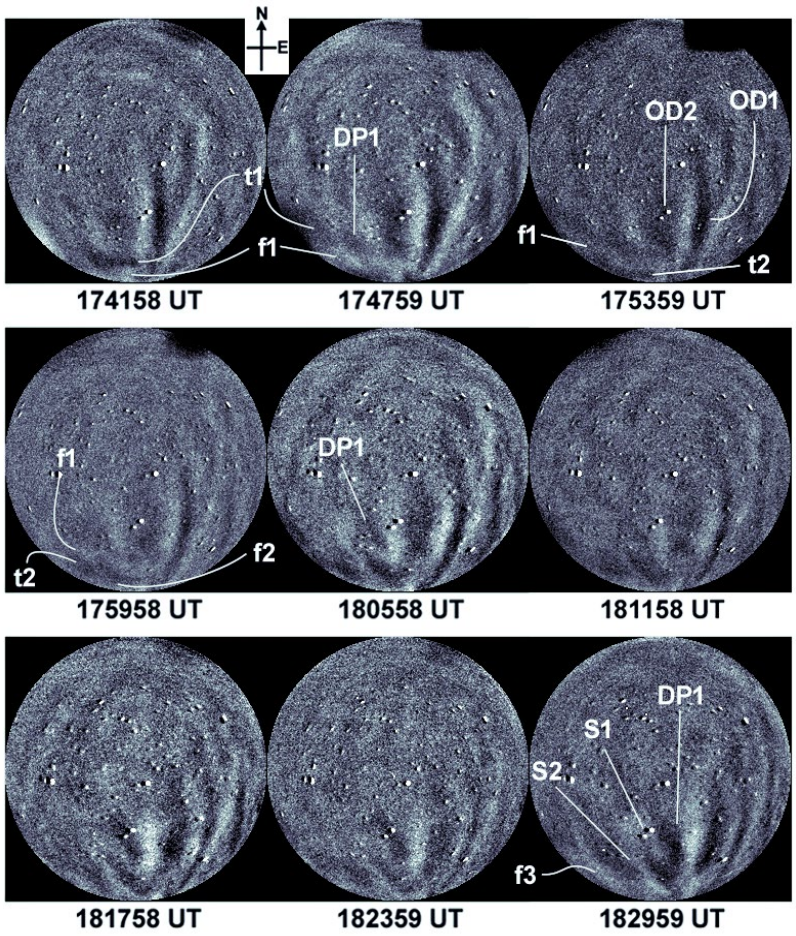

Figure 3. Typical time difference ASAI of OI 630 nm emission over Ranchi showing GW activity during 1742–1830 UT.

The authors should present additional cases that demonstrate a noticeable interaction between GWs and EPBs.

Reply: Sincere thanks for this invaluable suggestion. We noted another such GWs driven revival event on 06 March 2013 and has been included in Discussions. Added content is as under as:

Corrections:

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.

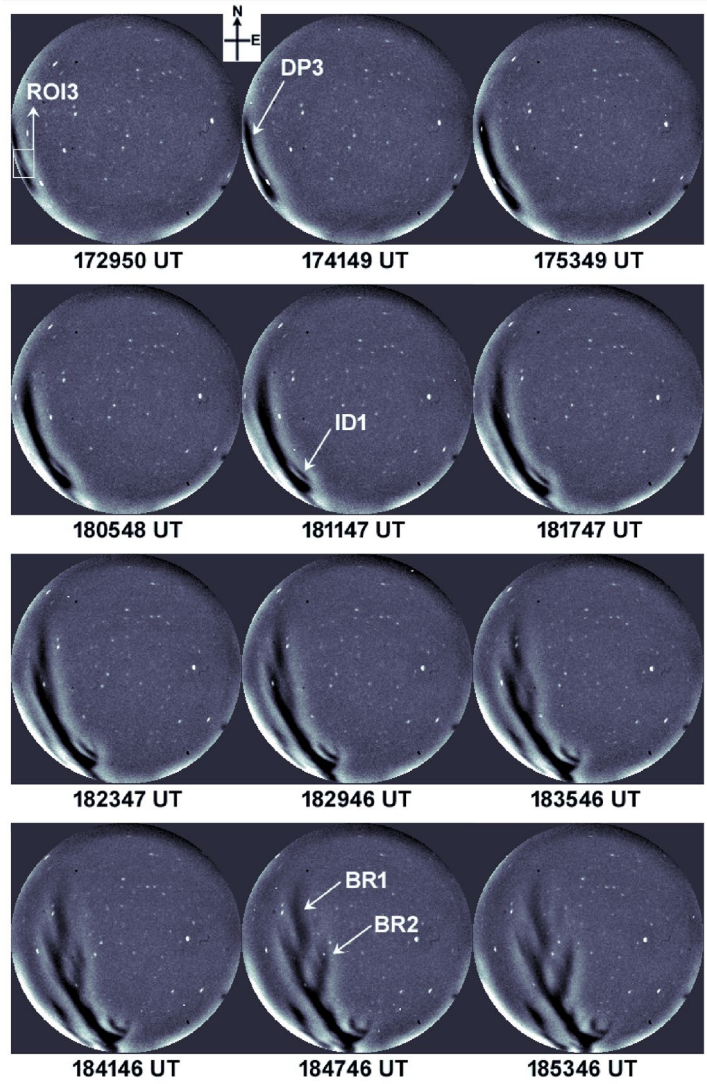

Figure 6. Selected ASAI images showing the revival of fossil depletion **DP3** during 1730-1854 UT on 06 March 2013 over Ranchi. **ROI3** is the region-of-interest wherein depletion **DP3**

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

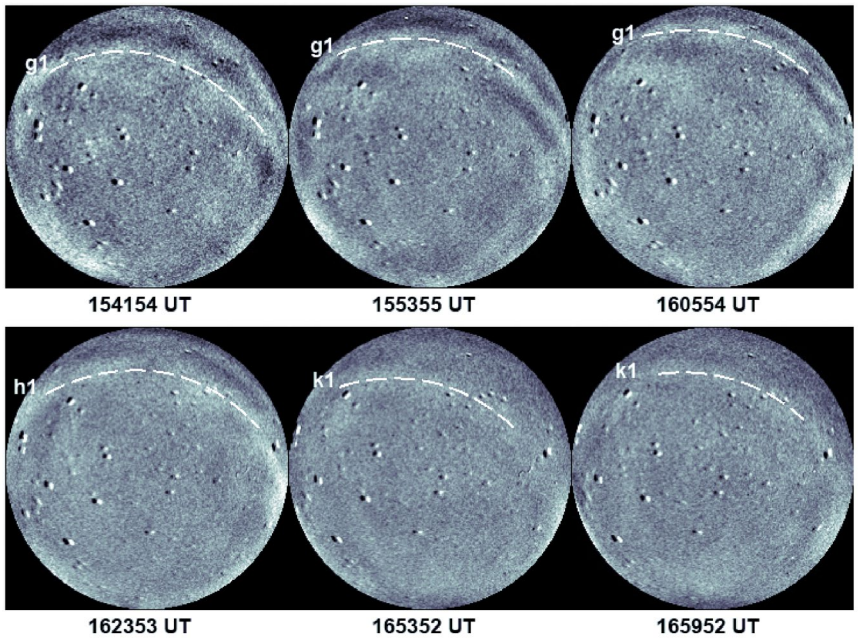

Figure 7. Limited time difference ASAI images showing GW activity during 1530-1700 UT on 06 March 2013. Beginning 1336 UT, GW signatures were seen in airglow images; however, activity intensified during 1530-1736 UT. Some of clear GW fronts are marked as 'g1', 'h1' and 'k1'.

2 - The authors claim that, 'due to a lack of expertise in GNSS data analysis,' they are unable to employ multiple GNSS receivers positioned near the event or use more GNSS satellites, including GPS, GLONASS, Galileo, and BeiDou. However, there is no difficulty in adding a few more GNSS receivers to check if the oscillations shown in Figure 5 are associated with EPBs or a possible GW occurrence.

Reply: Sincere thanks for this invaluable suggestion. We looked into GPS-GLONASS and have generated Figure 05 afresh. Previous version did contain GLONASS measurements but were wrongly term with prefix 'G'. Corrected Figure is as under as:

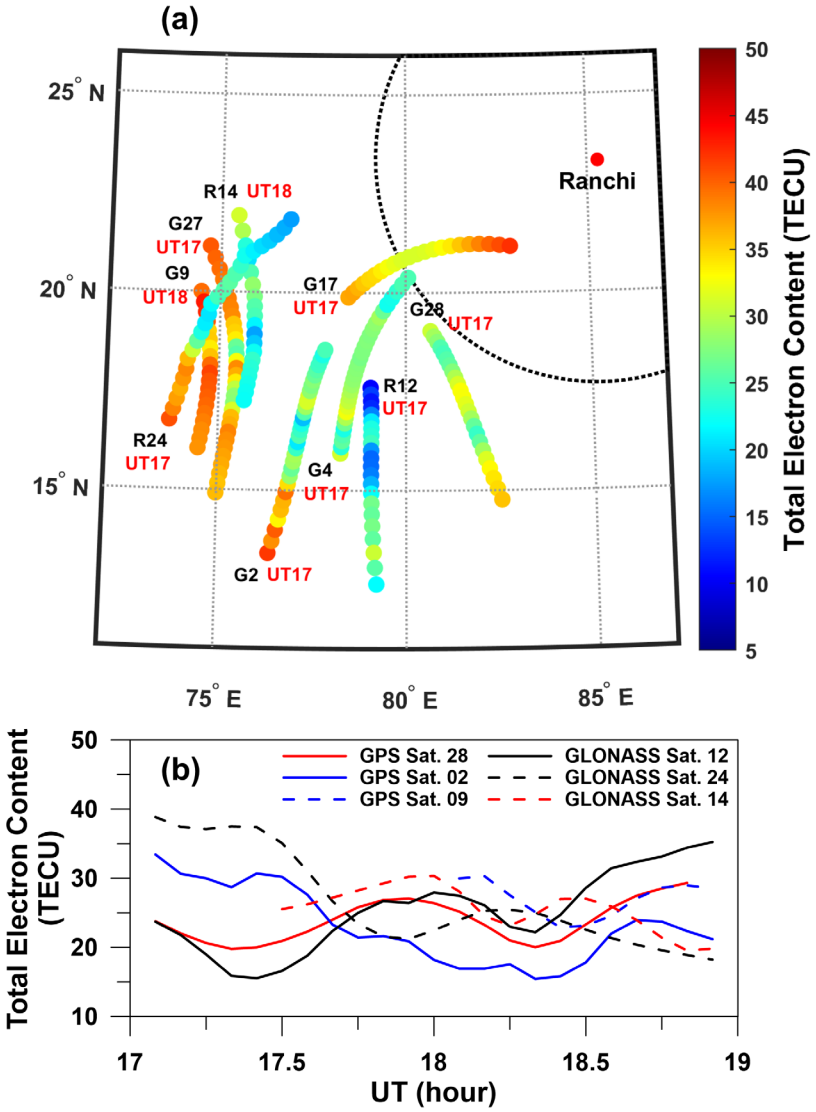

Figure 5. (a) Scatter plot of the TEC along the track of IPPs for a few GPS and GLONASS satellites (prefixed as 'G' and 'R', respectively) in the geographic grid of 5-35° N x 65-95° E during 1630-1930 UT on 16 April 2012. PRN numbers of GPS/GLONASS satellites along with the start time at 1700 UT are 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.

Therefore, a quick validation is necessary. The author should find an IPP track that corresponds to the same location as the OI 630 nm images to check whether the oscillations presented in Figure 5 are associated with EPBs or a possible GW occurrence.

Reply: Many thanks for this suggestion. We were unable to find IPPs tracks within the imager's field-of-view. However, GPS and GLONASS TEC measurement by satellites G28 and R12 [shown in Figure 5(b)] does indicate the presence of similar waves.

Just to remember, the GWs signature in the TEC GPS IPP tracks are associated to a fluctuation of about 1-5% of the TEC level (e.g., Otsuka et al., 2013; Figueiredo et al., 2018; Takahashi et al., 2021/ https://angeo.copernicus.org/articles/31/163/2013/; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JA025021; http://www.eppcgs.org/en/article/doi/10.26464/epp2021047). Figure 5a and 5b present a TEC oscillation of about 10 TECU (see GPS PRN 28). This kind of TEC fluctuations are usually associated to EPBs signature (Barrros et al., 2018/ https://angeo.copernicus.org/articles/36/91/2018/). Same interpretation can be done for Figure 4a and 4b, the north-south keograms clearly show EPBs signatures with their bifurcation.

Reply: Many thanks for these critical suggestions. We agree with References suggested by Reviewer. We cross-checked the same by estimating Rate of TEC Index (ROTI) using G28 and R14 TEC measurements and found it to be less than 0.29 TECU/min during 1700-1800 UT. Usually EPBs are characterized by ROTI > 0.5 TECU/min (Ma and Maruyama, 2006). As such, we think that the observed variations are not due to EPBs. Bifurcations seen here are of preceding depletion **OD1** (See Figure 1) that lay on the eastern sector of the field-of-view of imager. Whereas IPP trajectory of G28 and R14 (as well as other satellites) lay on the west of the field-of-view. Owing of this, we believe that the wavelike features seen in TEC measurements probably represent GWs and not EPBs. At this moment, we are unable to completely address this comment of Reviewer as of now. Probably an extensive study will throw more light on this issue.

3 - In the authors' response, they said that there is no ionosonde near the OI 630 nm event. However, the GIRO (global ionosphere radio observatory - https://giro.uml.edu/didbase/) program provides ionosonde data in Delhi (see the figure below). I understand that it is not near Ranchi (approximately 1,000 km away), but the ionosondes have a 30° zenith angle for oblique reflections, which can diminish the spatial difference.

These data can be useful to check the evolution of the EPBs and to determine if there is a vertical drift of the ionosphere associated with an enhancement of the eastward polarization electric field.

Reply: We are grateful to Reviewer for this invaluable suggestion. We looked into GIRO webpage (https://giro.uml.edu/ionoweb/ & https://giro.uml.edu/didbase/scaled.php) and found three Indian stations listed therein viz. ***Ahmedabad*** (URSI Code: AH223 23.00° N 72.50° E), ***Gadanki*** (URSI Code: GA313 13.46° N 79.17° E) and ***Trivandrum*** (URSI Code: TM308 8.54° N 76.87° E). However, the ionograms for 16 April 2012 or 06 March 2013 were not available. We were unable to find '***Delhi***' in the list. Owing to this, we are unable to address this comment of the esteemed Reviewer.