Forcing From Lower Thermosphere and Quiet Time Scintillation Longitudinal Dependence

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Abstract The quiet time ionospheric plasma bubbles that occur almost every day become a significant threat for radio frequency (RF) signal degradation that affects communication and navigation systems. We have analyzed multi-instrument observations to determine the driving mechanism for quiet time bubbles and to answer the longstanding problem, what controls the longitudinal and seasonal dependence of ionospheric irregularity occurrence rate? While VHF scintillation and GNSS ROTI are used to characterize irregularity occurrence, the vertical drifts from JRO and IVM onboard C/NOFS, as well as gravity waves (GWs) amplitudes, extracted SABER temperature profiles, are utilized to identify the potential driving mechanism for the generation of small-scale plasma density irregularities. We demonstrated that the postsunset vertical drift enhancement may not always be a requirement for the generation of equatorial plasma bubbles. The tropospheric GWs with a vertical wavelength (4 km < λv < 30 km) can also penetrate to higher altitudes and provide enough seeding to the bottom side ionosphere and elicit density irregularity. This paper, using a one-to-one comparison between GWs amplitudes and irregularity occurrence distributions, also demonstrated that the GWs seeding plays a critical role in modulating the longitudinal dependence of equatorial density irregularities. Thus, it is becoming increasingly clear that understanding the forcing from a lower thermosphere is critically essential for the modeling community to predict and forecast the day-to-day and longitudinal variabilities of ionospheric irregularities and scintillations.

1. Introduction

The equatorial F region irregularity pattern is far too complex to be explained by the dominant paradigm which is the changes in Rayleigh-Taylor (RT) instability due to a simple change in the postsunset F region altitude associated to the dusk sector E and F region conductivity change and enhancement of vertical plasma drift—the prereversal enhancement (PRE). The conventional plasma physics hypotheses, such as RT instability enhancement at the location where the terminator and field lines aligned (e.g., Tsunoda, 1985) can explain the irregularity maxima near-equinox at some longitudes but not at other seasons, especially the June solstice maxima often observed at certain longitudes. This makes the physics of the longitudinal dependence of irregularity distribution incomplete, and it remains as a major problem to the space weather community. The question is, do other mechanisms, such as the forcing from a lower thermosphere (e.g., the gravity wave [GW] seeding), play a role in filling the gap of understanding to explain the morphology of the longitudinal and seasonal irregularity distribution? McClure et al. (1998) suggested that the occurrence probability of equatorial F region irregularity is due to the existence of adequate levels of seeding and RT instability in the region at an earlier time. This implies, for a given equatorial F region irregularity, either seeds or instabilities are ubiquitous to change the F region instability term while the either factor falls below the threshold (e.g., Farley et al., 1970; Sultan, 1996). Previous studies also suggested that the presence of sufficient amplitude seeding could be the responsible mechanism for the morphology of irregularities often observed during seasons and regions, where the PRE drift is not large enough or below the threshold to initiate RT instability and hence irregularities, especially during the solstice (McClure et al., 1998; Rottger, 1981). The impact of GWs seeding on ionospheric dynamics and structures has been first suggested by Hines (1960). Since then, the localized GWs, which have a spatial scale of tens to thousands of kilometers and a temporal scale of minutes to hours, are considered as one of the potential candidates that provide adequate seeds to the bottom side ionosphere, enough to elicit ionospheric irregularity (Fritts et al., 2008; Fukushima et al., 2012; Hysell et al., 2017; Kelley & Miller, 1997; Li et al., 2016; Oberheide et al., 2015; Valladares & Sheehan, 2016).
Unlike the forcing from above which is more prominent and active only during geomagnetic storm periods (e.g., Yizengaw et al., 2018), the forcing from below (e.g., GWs) is active during both storm and quiet times. Quiet time GWs can be launched by meteorological weather fronts or any other sources in the troposphere and stratosphere and are capable of penetrating into the ionosphere (e.g., Vadas & Crowley, 2010), where they dissipate their energy and elicit seed perturbations in the bottom side F region (e.g., Hysell et al., 1990). The quiet time GWs cover all latitudes including the equatorial region where RF signals degradation, especially the HF and VHF scintillation, occur almost on a daily basis. On the other hand, storm time GWs, which are usually high-latitude events due to the Joule heating from the magnetosphere, propagate vertically and latitudinally as a consequence of buoyancy forces present in the atmosphere (e.g., Lu et al., 2016). These high-latitude GWs transfer energy and momentum to lower latitudes through traveling atmospheric disturbances (TADs) and cause density perturbations. The detail characteristics of GWs, such as how it reaches to the thermospheric altitudes, including its potential sources region, propagation direction, reflection in the upper atmosphere, and the generation of its secondary waves through upper mesospheric and thermospheric body forces are described in detail (e.g., Gavrilov & Kshetvetskii, 2014; Vadas & Crowley, 2010; Vadas & Liu, 2009; Yiğit et al., 2012).

Comparison with meteorological data shows that many of the possible GWs source regions appear to lie in the proximity of the jet stream or the tropospheric mesoscale convective complexes (MCCs) near the vicinity of the Intertropical Convergence Zone (ITCZ). The ITCZ is the region of maximum tropospheric upward convection and is located at place where the northeast and southeast trade winds converge. The GWs are also generated close to regions of typhoons, thunderstorms, tornadoes, hurricanes, and earthquakes (e.g., Manzano et al., 1998; Yizengaw & Groves, 2018). The upward convection occurs within 100 to 1,000 km (or 1° to 10° latitudes) of ITCZ location where the sea surface temperature (SST) or continental temperature is relatively high and a large inflow of atmospheric latent heat is evident. The ICTZ does not have common latitudinal locations but swings north-south directions depending on season and longitudes. This implies the seasonal and longitudinal morphology of equatorial GWs amplitude and hence irregularity distributions are controlled by the seasonal migration of the ITCZ locations which somewhat follow the subsolar point though not exactly at all longitudes (Waliser & Gautier, 1993). However, this assumption has never been demonstrated through observations, except modeling and limited observation over a specific region. Thus, in this paper, for the first time, we demonstrate the one-to-one similarity between the global morphology of seasonal and longitudinal distribution of ionospheric irregularities and GWs amplitude at 90 km median altitude. The morphologies clearly exhibited quite similar behavior/trend, including the June solstice morphologies in the African sector where irregularity occurrence is stronger but PRE drift is weaker.

2. Data

The amplitude scintillation ($S_4$ index) measured by VHF receivers has been used for this study to characterize the day-to-day dynamics and structure of quiet time ionospheric irregularities. We used data from the 250 MHz VHF receivers that are deployed in the proximity of geomagnetic equators at different longitudes under the umbrella of U.S. Air Force funded Scintillation Network Decision Aid (SCINDA) project (Groves et al., 1997) to characterize the spatial and temporal variability of irregularities. Similarly, the seasonal and longitudinal statistical distribution of ionospheric irregularities is also characterized by the rate of change of TEC index (ROTI), extracted from TEC measurements by GNSS receivers both on the ground and onboard LEO satellites. The ROTIs are estimated from TEC observations with an elevation angle greater than 30°, using the technique described in, for example, Pi et al. (1997), and irregularities due to multipath effects are confidently removed from our analysis. However, the elevation angle for space-based TEC is relaxed to a minimum of 15° since the multipath effect is not an issue for GNSS observations onboard LEO satellites. The dusk time upward vertical drifts statistical distribution is also obtained from measurements of Ion Velocity Meter (JVM) instrument onboard Communications-/Navigation Outage Forecasting System (C/NOFS) satellite (de La Beaujardière et al., 2009) when the satellite was below 500 km altitude and within ±8° geomagnetic latitude.

For this study, the GWs structure is extracted from the temperature profiles observed by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) limb-sounding infrared radiometer onboard Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. The temperature
profiles (altitude range from 20 to 110 km) are retrieved from 15 μm infrared emissions with a precision of better than 1°K for all time measurements. Since the temperature profile is estimated from CO₂ infrared emission lines, the fluctuation in the temperature profiles is caused by GWs and Tides. We extracted the GWs structure from the temperature profiles using the technique described in Fetzer and Gille (1994), Preusse et al. (2002), and Yamashita et al. (2013). The technique described in Ward et al. (1999) has also been applied to remove the contribution of the diurnal migrating tides. The background temperature profiles that contain mean temperature, as well as stationary planetary waves, are also subtracted from the remaining temperature profiles of descending and ascending temperature passes to obtain the final residual that shows only GW structures. However, all GWs extracted from the temperature profile may not penetrate or reach the ionosphere altitude. Therefore, a band-pass filter is applied to isolate the GWs component that can reach the ionosphere altitude. The GWs with vertical wavelengths (4 km < λ_v < 30 km) and horizontal wavelength of 100 to 250 km can reach the ionosphere (Hysell et al., 1990; Fritts et al., 2008; Vadas & Crowley, 2010). Finally, the GWs with vertical wavelengths (4 km < λ_v < 30 km) structure are reconstructed in the altitude versus latitude plane by binning the residual temperature profiles into 2.5° × 2 km (latitude × altitude) grids. The detailed step-by-step procedures we used to extract the GWs structure from temperature profiles observation can be found in Preusse et al. (2002) and Yizengaw and Groves (2018).

3. Results and Discussion

The PRE is believed to be the responsible postsunset driver for creating ionospheric conditions conducive to the generation of small-scale plasma density irregularities via RT instability mechanism. This has been widely studied and well documented (e.g., Basu et al., 1996; Fejer et al., 1999; Kil et al., 2009; Huang & Hairston, 2015; Yizengaw & Groves, 2018). However, still there are several issues that are not properly addressed that include the following: (a) Is the PRE drift always critically important parameter to initiate ionospheric irregularity formation? (b) If it is, what is the required threshold value of PRE drift to generate ionospheric irregularity? Different authors suggested different threshold PRE plasma drift values. While Basu et al. (1996) suggested that a PRE plasma drift of 20 m/s is required to generate equatorial irregularity during solar minimum periods, Fejer et al. (1999) found that strong ionospheric irregularities occur when the PRE peak reaches ~10 and ~50 m/s during solar minimum and maximum periods, respectively. Similarly, Anderson et al. (2004), using VHF data for irregularity characterization and ionosonde for drift estimation, suggested that a threshold vertical \( \mathbf{E} \times \mathbf{B} \) drift value of 20 m/s is required just after sunset to observe scintillation with \( S_4 \) index greater than 0.5.

In order to characterize these different suggested threshold PRE drift values and ionospheric plasma irregularities, we utilized all available PRE drifts observed by the radar located at Jicamarca Radio Observatory (JRO) and scintillation data from Ancon VHF receiver. Figure 1 shows the one-to-one comparison between the vertical plasma drift and VHF scintillation as a function local time. The top panels depict VHF scintillation \( S_4 \) index observed at Ancon in Peru as a function local time. Different colors represent different days that are randomly selected. The vertical plasma drift values as a function of local time for the corresponding dates are shown in the middle panel. The JRO average drift data have a temporal resolution of 5 min. The horizontal red and black dashed lines mark the 20, 10, and 0 m/s drift values. The dashed vertical black lines in the middle panel mark the typical local time range for PRE drift, and the colored vertical solid lines depict the local sunset time at 300 km altitude on the corresponding dates. On each day the vertical drift values just after the local sunset are nearly below the dash-dot horizontal red line (or below 10 m/s). This means the strong scintillation shown in the top panel was observed when the postsunset vertical plasma drifts were nearly below 10 m/s or even when the drift turned downward, exhibiting that PRE drift is not the only required driver for the generation of plasma bubbles that result in such strong scintillation.

In order to confirm our case studies further, we collected all JRO drift data collected from 2008–2013, though the radar provides drift measurements only for limited days per year. The vertical drifts observed between 18:30 and 20:30 LT are then extracted from all available 6 years JRO observations. The VHF scintillation observed between 19:00 and 22:00 LT during the corresponding days and years is also collected. Finally, the statistical distribution of VHF \( S_4 \) index (observed during 19:30–21:30 LT) is plotted as a function of PRE drift (recorded during 18:30–20:30 LT) as shown at the bottom panel in Figure 1. We only use one \( S_4 \) value (the maximum value) for every 5 min bin just to make an equal number of scintillation data points.
as the drift data for the scatter plot. The VHF $S_4$ values shown in the scatter plot are sorted into three groups: Scintillation is observed when PRE drifts are (a) greater than 10 m/s (blue dots), (b) vertically upward but less than 10 m/s (black dots), and (c) vertically downward (red dots). The most important feature is that only 40% of scintillations (blue dots) are observed on the same days when JRO sampled PRE drifts that satisfied the lowest suggested threshold vertical drift value (~10 m/s) mentioned above. It is understandable that the threshold plasma drift derived at one longitude may not be directly applied to other longitudes, and for that reason, we took 10 m/s—the threshold value suggested by Fejer et al. (1999)

**Figure 1.** (Top panel) VHF scintillation $S_4$ value as a function of local time; different color represents different days. (Middle panel) the vertical drift estimated from JRO observation during the corresponding days; the horizontal dashed and dash-dot red lines and black dashed line mark 20, 10, and 0 m/s, respectively. The colored vertical solid lines represent the local sunset time at 300 km altitude on the corresponding days. (Bottom panel) the scatter plot of scintillation versus PRE drifts ($V_{PRE}$); the blue, black, and red dots represent scintillations observed when $V_{PRE} > 10$ m/s, $0 < V_{PRE} < 10$ m/s, and $V_{PRE} < 0$, respectively.
as it was calculated at JRO longitudes where our observations were performed. The critical question is, must the PRE drift reach this threshold value to generate plasma bubbles or not? About 60% of scintillations shown in the bottom panel of Figure 1 (black and red dots) were observed when PRE drifts were below the threshold value of 10 m/s, asserting plasma bubbles can be generated without PRE drift. Therefore, both randomly picked daily scintillation and drift values (top and middle panels), as well as the statistical distribution (bottom panel), clearly confirmed that the PRE drift with certain threshold values, as suggested by different studies, may not be always a requirement for the generation of plasma bubbles. In fact, about 32% of strong scintillations (up to $S_4 = 1$) were observed when post-sunset vertical drift turned downward. This demonstrated that other factors, such as GWs seeding, can also create ionospheric conditions favorable for the formation of plasma bubbles. Thus, to demonstrate the role of GWs for the formation of plasma bubbles when the PRE drifts are either below the required threshold values, we checked the GWs structure on those specific days given in Figure 1. Except on 14 February 2008, strong GWs amplitudes with a vertical wavelength between 20 and 30 km were observed on those days. On 14 February there were no TIMED satellite passes near Ancon, so were unable to check the presence or absence of GWs.

Figure 2 shows the quiet time ionospheric scintillations along with the corresponding GWs drivers observed on 14 and 20 September 2009—when PRE drifts were below the threshold value as shown in Figure 1. The top panels depict the TIMED satellite passes that crossed the equator at about 23:16 and 23:01 LT on the 14 and 20 September 2009, respectively. The second panels from the top show the amplitude scintillation observed by a VHF receiver located underneath the satellite pass (red dot in the top panel). The blue and red curves are 1 and 5 s averaged scintillation $S_4$ index data. The VHF data exhibit the presence of strong density irregularity during quiet time ($K_p < 3$) and when PRE drifts are very weak (see Figure 1), indicating that the RT instability triggering mechanisms—the PRE drift—may not be responsible for such strong scintillation. During a magnetically quiet period, where no penetration electric field and no enhanced dynamo electric field occur, the PPE drift is very weak—below the threshold value—and unable to initiate RT instability and create ionospheric conditions conducive to the generation of plasma density irregularities. Thus, the localized tropospheric GWs seeding, which is not dependent on geomagnetic activity and can occur during quiet and storm times, may be the potential triggering mechanisms for the formation of such strong quiet time scintillations. The third panels from the top show the fluctuating temperature profiles (blue curves), observed by SABER infrared radiometer onboard TIMED satellite in which its ground tracks are shown in the top panels. The red curves depict the background temperature profiles, which are estimated using the technique described in Yamashita et al. (2013). The bottom panels indicate the 2-D (altitude x latitude) GWs structures extracted from the fluctuating temperature profiles, showing strong GWs amplitude with a vertical wavelength between 20 and 30 km. This indicates that the GWs structure shown at the bottom panel could be responsible for initiating the RT instability for the irregularities that resulted in such strong scintillation activities. This clearly demonstrated that the forcing from a lower thermosphere might cause a significant threat to RF communication and navigation systems by launching GWs that can penetrate to bottomside ionosphere and trigger ionospheric irregularities and degrade the quality of signals passing through.

The bottom panels in Figure 2 also clearly exhibit good alignment between GW’s phase fronts and the geomagnetic field lines (white curves) at the geomagnetic equator. Near the geomagnetic equator (indicated by the dashed vertical white line), the angle between the horizontally structured GWs amplitude peaks (indicated by horizontal dash-dot lines) at different altitudes and the geomagnetic field lines (white curves) is nearly equal to zero. Tsunoda (2010) demonstrated the effect of GW’s phase alignment with the geomagnetic field on the polarization electric field generation in the horizontal plane. Since the total magnetic field at the equator is nearly horizontal, the alignment at the magnetic equator shown in the bottom panel can be taken as the alignment between the horizontal phase fronts of GWs and the horizontal geomagnetic field. This means if one can cut a horizontal plane at a fixed altitude, the phase front still aligned with the horizontal geomagnetic field at the geomagnetic equator. The GW’s penetration to the bottom side $F$ region becomes effective primarily when the phase front of GWs at different altitudes is aligned with the geomagnetic field line (Huang & Kelley, 1996; Tsunoda, 2010). The alignment makes the GWs amplitude capable enough to transfer enough perturbations to the plasma by reducing the loss of excess charges. However, if the GW phasefronts were not aligned with magnetic field lines, the positive and negative excess charges (separated by half a wavelength distance and are accumulated along the phase front) and hence the transport of the plasma by the polarization electric field that accompanies the excess charges would be reduced (e.g., Huang &
Kelley, 1996). Tsunoda (2010) also suggested that GW’s amplitude produce sufficient seeding that elicits irregularity when the angle between phase front and magnetic field line is less than \( \tan^{-1} \left( \frac{\sqrt{\sigma_P}}{\sigma_0} \right) \), where \( \sigma_P \) and \( \sigma_0 \) are the Pedersen and direct conductivities, respectively. At the base of the F layer (say 300 km), \( \sqrt{\sigma_P}/\sigma_0 \) would be less than \( 10^{-4} \), which means the magnetic aspect angle would have to be less than 0.007°. However, for the GWs generated near the magnetic equator, the phase front is mostly aligned with the horizontal geomagnetic field lines, and the threshold angle mentioned above must often be satisfied, especially during solstice when the tropospheric convection is located along the vicinity of the geomagnetic equator. This indicates that the GWs seeding appears to be the strongest driver for equatorial irregularity occurrence pattern for solstice season.

Although much has been learned about equatorial density irregularities, including its seasonal occurrence rate variability, the controlling factor for its strong longitudinal variabilities remains a mystery. Several
mechanisms have been suggested as the possible factor for the longitudinal variability of irregularities, including the postsunset vertical PRE drifts (e.g., Dubazane & Habarulema, 2018; Eccles, 2004; Hysell et al., 2002; Thampi et al., 2009; Tsunoda et al., 2012) and neutral wind-driven gradient drift instability (e.g., Kudeki et al., 2007). However, recent coordinated observations (e.g., Huang, 2018; Yizengaw, 2021) revealed neither the drift nor neutral winds fully control the longitudinal dependence of density irregularities. The question is, what else controls the strong longitudinal dependence of density irregularities often observed from space and on the ground? Do the localized seeding mechanisms from the lower atmosphere such as GW seeding play a role in controlling this longitudinal dependence? Although the possibility of GWs seeding for the generation of bubbles is discussed above and has been reported before (e.g., Huang & Kelley, 1996; Li et al., 2016), its role for the longitudinal variability of irregularities has never been investigated. Thus, to investigate this, coordinated observations of VHF scintillation at different longitudes during magnetically quiet time (Kp < 3) along with the corresponding GWs structures extracted from SABER temperature profiles have been utilized as shown in Figure 3.

The red dots and blue curves in the top panel of Figure 3 depict the VHF receivers and the corresponding nearby TIMED satellite ground tracks at 21:17 LT during quiet time (Kp < 1) on 25 September 2012. The panels at the right side show the quiet time ionospheric scintillation observed by VHF receivers located at different longitudes, which is given at the top of each panel. The VHF observations at different longitudes show strong quiet time scintillation amplitudes throughout the night, including during the postmidnight local time sector. The left panels depict the 2-D (altitude x latitude) GWs amplitude structures extracted from the fluctuating temperature profiles along the corresponding nearby satellite tracks shown at the top panel. For the reason described above, we focused on GWs amplitude peaks at the equator that are horizontally structured and well aligned with the horizontal geomagnetic field. The GWs amplitude peaks at the geomagnetic equator show different strength at different longitudes, indicating the sources of GW are not global, rather there are localized source that generate different GWs structure with different amplitudes. This indicates that the localized GWs can seed and modulate the bottom side ionosphere differently and elicit different density irregularity structures at different longitudes as shown in Figure 3. The most interesting features evidenced from these typical examples of VHF scintillations include (a) the scintillation amplitude periodically fluctuates, more prominently in the African sector; (b) the postmidnight scintillation occurred even at latter local time (after 02:00 a.m.) in the African sector compared to that of American and Pacific sector scintillation that occur before 02:00 a.m.; and (c) at all longitudes the postmidnight scintillations appeared as an isolated feature—not a continuation from per-midnight features—after nearly 2 hr break from premidnight scintillations in the African sector and less than an hour break in the American and Pacific sector. These features, especially the occurrence of quiet time postmidnight strong scintillation at different longitudes, provide further evidence that the forcing from a lower thermosphere not only plays a significant role in degrading the HF and VHF communication and navigation but also controls the longitudinal variability of ionospheric density irregularity.

Furthermore, independent multi-instrument observations have shown similar seasonal and longitudinal irregularity occurrence trend, stronger during October through March equinoxes and weaker during June solstice at most longitudes (Burke et al., 2004; Kil et al., 2008; Gentile et al., 2011; Yizengaw & Groves, 2018). It is well understood that the maximum irregularity occurrence rate during equinoxes is due to RT instability enhancement when the terminator and geomagnetic magnetic field lines are well aligned (Tsunoda, 1985). However, the terminator and field alignment hypothesis cannot explain the strong longitudinal dependence that has been observed during June solstice, stronger in the African and almost none in the American sectors. Thus, there should be other mechanisms that can explain the physics behind the longitudinal dependence during seasons when the terminator and geomagnetic field lines are not aligned.

Figure 4 presents the dusk sector (18:00–24:00 LT) seasonal and longitudinal distribution of irregularity occurrence rate, observed by multi-instrument on the ground and onboard LEO satellites. The top panel shows the statistical (2009–2016) topside ionosphere irregularity distribution characterized through ROTI estimated from GNSS receiver onboard different LEO satellites. Only topside TECs with elevation angle greater than 10° (or integrated density from LEO to GNSS satellite altitudes) are included for topside ROTI estimation. Occultation TECs are not considered for this study. Furthermore, only the topside ROTIs located only within ±10° geomagnetic latitudes are considered to characterize topside equatorial
irregularities. Finally, the topside ROTIs are binned into 10° longitude × 5 day bins and plotted in a longitude versus day of the year grids (top panel). The second panel from the top, with similar plotting format and bin size as for top panel, depicts the statistical (2009–2012) distributions of ROTI estimated from ground-based GNSS receivers located within ±10° geomagnetic latitudes. Both ROTIs exhibit similar irregularity distributions, maximum during equinoxes, when the terminator and magnetic field lines are aligned indicated by the two black curves in each panel. However, while the ROTI estimated from ground-based GNSS shows another feature, enhanced irregularity over the African sector during June solstice, the topside irregularity distribution does not. This indicates the June solstice irregularities are only confined in the bottomside ionosphere and cannot be seen by upward looking GNSS antenna onboard LEO satellites above 400 km orbit altitude. However, this does not mean there are no bubbles at the topside. The topside GNSS signal could just not be detecting it due to at least the following two reasons: (a) The June solstice upward PRE drifts are very weak or even turned downward (see above), and those strong plasma bubbles have no chance to penetrate to higher altitudes and present within the field.
Figure 4. The dusk sector seasonal and longitudinal irregularity distributions observed by GNSS receivers onboard LEO satellites (top panel) and on the ground (bottom panel), gravity wave amplitude at about 90 km altitude (third panel), and vertical drift (bottom panel) from IVM observation onboard C/NOFS satellite. The two black curves in each panel depict the time at a given meridian where the sunset terminator and magnetic field lines are aligned.
of view of the upward looking topside GNSS antenna, and (b) the GNSS signals may not be sensitive enough to detect plasma bubbles within a very low background density at the nighttime topside ionosphere, but it can be detected by other highly sensitive instruments such as Langmuir Probe (LP) sensor onboard LEO satellites. In fact, the in situ plasma bubble observation by the LP sensor onboard Defense Meteorological Satellite Program (DMSP) exhibited strong irregularity occurrence rate over the African sector during June solstice (Burke et al., 2004; Gentile et al., 2011), which is consistent with the ground ROTI distribution shown in Figure 4 (second panel from the top). In addition to LP sensor's high sensitivity, the DMSP observation was also performed during the solar maximum period when more active periods with penetration of E-field occurred, which could enhance the June solstice PRE drift drove plasma bubbles into higher altitude. On the other hand, our observations were mostly performed during an extended solar minimum period (2009–2010) or during a very weak solar maximum period (2011–2012). Another point worth to mentioning here is how the DMSP bubble occurrence rate was estimated. The DMSP irregularity distribution was characterized by the manually counted bubble occurrence and does not provide information about the strength (either depth or width) of the bubbles—that is, very small or large LP density depletion were both counted as bubble occurrence. Thus, if those small LP density depletions were included in the DMSP bubble occurrence count, such small density depletion with very low background density at the topside ionosphere may not be detected by the GNSS signal. In general, both DMSP and our multi-instrument observations confirmed the presence of strong ionospheric irregularity only in the African sector during June solstice that can cause significant impact on communication and navigation systems.

The question is, which irregularity driving mechanism is responsible for irregularity features like the one observed over Africa during June solstice? The bottom two panels in Figure 4 present two different potential irregularities drivers. The bottom panel shows the statistical (2009–2012) dusk sector (18:00–19:30 LT) equatorial vertical drift obtained from IVM measurements onboard C/NOFS satellite only when the satellite was within ±8° geomagnetic latitude and below 500 km altitude. Since only the upward vertical drift destabilizes the bottomside ionosphere and initiation RT instability for the development of irregularity structures, the downward drift velocities are not included in the plot. Drift distribution is also stronger during equinox where the terminator and field lines are aligned, which is consistent with equinox irregularity distribution shown in the top two panels in Figure 4. However, during June solstice, the upward vertical drift appeared to be weaker or even no upward velocity in the American, African, and Asian sectors. This indicates the vertical drift is not responsible for the African sector enhanced irregularity observed during June solstice.

The third panel from the top in Figure 4 shows the statistical, seasonal, and longitudinal GWs amplitude (averaged between 80 and 95 km altitude) distribution, exhibiting stronger amplitude during equinoxes and weaker during June solstice at most longitudes except over the African sector where the ground-based instruments observed strong irregularity. This may further confirm the forcing from below is responsible for the June solstice longitudinal dependence of ionospheric irregularity distributions. The question is, why only in the African sector the GWs amplitude remain stronger almost throughout the year? It is well understood that the limit of the annual N-S migration of the ITCZ becomes an important parameter to explain the longitudinal and seasonal distribution of GWs amplitude. Thus, irregularity enhancement occurs whenever the mean ITCZ location becomes aligned with the dip equator. In the African sector the widening between ICTZ locations during June and December solstice is closer compared to other longitudes. Using the 29 years (1989–2018) data points where the northeast and southeast trade winds converge, Yizengaw and Groves (2018) demonstrated that the location of ITCZ in the African sector remains within ±20° geographic latitudes, which are close to the geomagnetic equator during all seasons. This suggests that strong GWs may be generated at the equatorial latitudes in the African sector more often and create favorable conditions for the development of irregularity in the region during all seasons compared to other longitude sectors. On the other hand, in the Asian sector, mainly 60° to 100°E longitudes where the SST is permanently high and has a relatively large release of atmospheric latent heat all year round, the N-S distance between the solstice ITCZ locations is larger, and the GWs amplitude appears to be weaker, and hence, the irregularity occurrence rate in the region is small or moderate. One thing that needs to be mentioned here is that only an extremely small subset of GWs that reach the bottom side ionosphere is responsible for seeding the density perturbations. For example, Tsunoda (2010) demonstrated that the meridional GWs that launch traveling ionospheric disturbances...
(TIDs) (e.g., Sterling et al., 1971) may not seed the bottom side and elicit density perturbation that leads to the full-blown irregularity structure.

4. Conclusion

We have analyzed multi-instrument observations to primarily determine the driving mechanism that controls the longitudinal and seasonal dependence of ionospheric irregularity occurrence rate. While VHF scintillation and GNSS ROTI are used to characterize irregularity occurrence, the vertical drifts from JRO and IVM onboard C/NOFS, as well as GWs amplitudes, extracted SABER temperature profiles are utilized to identify the potential driving mechanism to create ionospheric conditions conducive to the generation of small-scale plasma density irregularities at different longitudes and seasons. In general, the following points can be taken as the main contribution of this study.

- Using both case studies and statistical analysis of VHF scintillation and radar drift data, we clearly confirmed that the PRE drift, with certain threshold values as suggested by different previous studies, may not be always a requirement for the generation of equatorial plasma bubbles. In fact, about 32% of strong scintillations (up to $S_4 = 1$) from our statistical analysis were observed when postsunset vertical drifts were downward. Therefore, the postsunset upward drift through RT instability may not be the responsible mechanism for the formation of strong quiet time ($Kp < 3$) scintillations that we often observe at low-latitude regions using highly sensitive instruments such as VHF/UHF receivers.
- If it is not the PRE drift, what else cause for the generation of such strong irregularities during magnetically quiet periods? By combining independently but simultaneously (in time and space) observed temperature profiles and scintillation data, for the first time, we demonstrated the tropospheric GWs with a vertical wavelength ($4 \text{ km} < \lambda_v < 30 \text{ km}$) can reach the ionosphere altitude and provide enough seeding to the bottom side ionosphere and elicit density irregularity that can cause a significant threat to RF communication and navigation systems.
- Most importantly, for the first time, this paper demonstrated how the tropospheric GWs control the longitudinal variability of irregularity distributions. The localized GWs exhibited different amplitudes at different longitudes, confirming previous studies that asserted the sources of GWs are not global; instead, it is localized. The localized GWs then seed and modulate the bottomside ionosphere differently at different longitudes. The one-to-one comparison between the statistical GWs amplitudes and irregularity occurrence distributions clearly demonstrates the forcing from a lower thermosphere plays a critical role in modulating the longitudinal and seasonal dependence of equatorial density irregularities. The strong GWs amplitude structured evidenced during June solstice in the African sector shows excellent agreement with the strong irregularity occurrence—almost to the level of irregularity magnitude often observed during the equinox. On the other hand, the PRE drifts are very weak or turned downward and way below the threshold value required to initiate RT instability in the African sector.

In conclusion, it is becoming increasingly clear that understanding the forcing from the lower thermosphere (e.g., GWs) is critically important for the modeling community to predict and forecast the day-to-day and longitudinal variabilities of ionospheric irregularities. Reproducing the longitudinal dependencies of irregularity distributions has been a barrier for the modeling community. Existing models, such as WBMOD (Fremouw & Secan, 1984) and PBMOD (Retterer et al., 2005), fairly characterize the seasonal trends of the equatorial irregularity occurrence in the American sector but fail short in reproducing irregularity distribution at other longitudes. Especially, the models fail to reproduce the June solstice strong irregularity structure often observed in the African sector. Thus, incorporating the forcing from the lower thermosphere into the future modeling effort is critically important to accurately characterize the seasonal and longitudinal irregularity distribution.

Data Availability Statement

VHF and ground-based GNSS data are archived at Zenodo (https://zenodo.org/deposit/3903919), the space-based GNSS data are acquired online (through https://cdaac-www.cosmic.ucar.edu/cdaac/products.html), C/NOFS IVM data are available at NASA’s Space Physics Data Facility website (https://spdf.gsfc.nasa.gov/pub/data/cnofs/), and SABER temperature profiles are obtained online (from https://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/).
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