Climatology and Characteristics of Medium-Scale $F$ Region Ionospheric Plasma Irregularities Observed by COSMIC Radio Occultation Receivers

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Abstract

Medium-scale ionospheric ionization structures are a persistent global feature of the Earth’s ionosphere. Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) radio occultation measurements are well suited to address the incomplete global observational picture of plasma density irregularities, including the global climatology in both bottomside and topside $F$ region layers, and their structure in the vertical dimension. A climatological database of $F$ region ionospheric irregularities and their characteristics has been developed through detection of total electron content perturbations by Global Positioning System receivers onboard COSMIC satellites. This paper presents global occurrence rates and detailed characteristics of equatorial to midlatitude medium-scale irregularities under quiet geomagnetic conditions. The study covers 4 years, two during solar minimum (2008–2009) and two during the ascending phase of solar cycle 24 (2012–2013). Irregularities were found to occur frequently at high latitudes and during nighttime in equatorial to midlatitude regions in both bottom and topside $F$ region layers. Longitudinal-seasonal occurrence trends at equatorial and midlatitudes are consistent with previous irregularity climatology, which reaffirms that localized enhancements in plasma instability growth rates contribute to irregularity occurrence. Seasonal occurrence patterns also indicate a high occurrence of irregularities in regions corresponding to the solar terminator, confined primarily to altitudes below ~300 km. The local time-altitude distributions of equatorial and midlatitude irregularity occurrence, amplitude, and scale size provide further insight into irregularity generation mechanisms, and include features consistent with “spread $F$” irregularities and traveling ionospheric disturbances.

1. Introduction

The focus of this study is “mesoscale” (medium-scale) ionospheric ionization structures (irregularities) in the $F$ region ionosphere, with vertical scale sizes in the range of ~6–50 km. Medium-scale structures are generally larger than the “microscale” structures responsible for $L$ band scintillation and smaller than “macroscale” features such as storm enhanced densities and tongues of ionization. Kelley (1989) defined “mesoscale” structures as ionospheric irregularities with scale sizes of 50–1,000 km horizontally and 0.5–50 km vertically. Most Global Navigation Satellite System (GNSS) studies of plasma irregularities have employed ground-based receivers, which provide the high-resolution structure and propagation in the horizontal dimension (Jayachandran et al., 2011; Pilipenko et al., 2014; Watson, Jayachandran, Singer, et al., 2016), but miss out on critical information pertaining to the vertical irregularity structure and are primarily limited to landmasses. Global radio occultation (RO) measurements from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) provide a valuable opportunity to address this observational gap. COSMIC observations provide a unique and global perspective, which will help develop the statistical picture of irregularity occurrence and characteristics and provide further insight into the mechanisms that generate irregularities. Practical benefits of this more thorough observational picture include a greater ability to predict the location and severity of irregularity occurrence, which can benefit irregularity forecasting tools for radio communication links and GNSS precise positioning techniques such as real-time kinematics. Irregularities across a broad range of scale sizes interfere with ground- and satellite-based radio communication links through processes such as signal fading (Sauer & Wilkinson, 2008; Zaalov et al., 2003), while relative positioning techniques can lose accuracy of several meters due to density gradients associated with irregularities (Lejeune & Warrant, 2008).
Medium-scale plasma irregularities are known to arise from a number of external (to the ionosphere) and internal sources. Direct energy input from the solar wind and magnetosphere, such as coupling via precipitation of energetic particles and ultralow frequency geomagnetic pulsations, generate irregularities on a broad range of time and spatial scales (Pilipenko et al., 2014; Vorontsova et al., 2016; Watson, Jayachandran, & MacDougall, 2016a). Atmospheric gravity waves from sources such as tropospheric turbulence, aural disturbances, the solar terminator, solar eclipses, and natural and man-made hazards (e.g., earthquakes, tsunamis, thunderstorms, and nuclear tests) generate traveling ionospheric disturbances (TIDs) on a daily basis (Behnke, 1979; Hunsucker, 1982; Komjathy et al., 2016; Zhang & Tang, 2015). This coupling can occur through vertical plasma motion driven by the motion of atmospheric gravity waves (GWs) or by electric fields generated by GWs, and also by horizontal gradients in air motion that produce enhancements/depletions in the ionospheric plasma (MacDougall et al., 2009). Internal plasma instabilities, such as gradient-drift, Rayleigh-Taylor (RTI), or Perkins instabilities, are also known to generate or amplify medium-scale disturbances in all latitude regions (Kelley, 1989; Ossakow, 1981; Shiokawa et al., 2003). Instabilities can be seeded by plasma perturbations due to GWs (Chou et al., 2017) or arise from destabilization of sporadic E layers (Tsunoda, 2006). Periods of enhanced ionospheric disturbances are also linked to geomagnetic storms and magnetospheric substorms (e.g., Nicolls et al., 2004).

Several studies have employed ground and satellite-based measurements to investigate the climatological characteristics of medium-scale F region plasma irregularities. At midlatitudes, medium-scale features include medium-scale TIDs (MSTIDs), and midlatitude spread F (MSF). MSTIDs have large horizontal wavelengths (~100–300 km), oscillation periods on the order of ~1 hr, and equatorward-westward propagation. They are thought to be directly driven by GWs or result from the Perkins instability, which can be seeded by GWs (Behnke, 1979; Perkins, 1973; Shiokawa et al., 2003). Plasma perturbations due to MSTIDs may create conditions favorable for MSF formation via convective instabilities such as the Perkins instability (Hysell et al., 2016), although Shiokawa et al. (2003) reported MSF coincident with MSTIDs only 10–15% of the time.

In situ plasma density measurements of CHAMP, KOMPSAT-1, DMSP (Park et al., 2010), and ROCSAT-1 satellites (Su et al., 2006), in addition to topside-sounding of the ISS-B satellite (Earle et al., 2006), have provided climatology of midlatitude irregularities in the topside F region. These topside statistics were consistent in reporting predominantly nighttime irregularities with peak occurrence rate of up to 45% at or after midnight, a peak occurrence in the North/South American longitudinal sector around December solstice, peak occurrence in the Asian/Oceania sector around June solstice (September equinox in Earle et al., 2006), lower but more longitudinally uniform occurrence rates around equinox, and an anticorrelation in occurrence with solar activity. Park et al. (2010) reported a higher midlatitude occurrence rate in the summer hemisphere compared to the winter that was not observed in Earle et al. (2006) and Su et al. (2006), which may be related to the differences in observational techniques and the low inclination orbit of ROCSAT-1.

Ground-based measurements can provide the climatology of irregularities occurring in both bottomside and topside F layers but are confined to landmasses. Radio beacon studies of Evans et al. (1983) and Jacobson et al. (1995) in the North American sector have reported MSTID signatures primarily during daytime in winter months and nighttime during summer. More recent ground-based GNSS studies have confirmed this seasonal-diurnal trend (Hernández-Pajares et al., 2006; Wautelet & Warnant, 2013). Kotake et al. (2006) observed quasi-sinusoidal "wavelike" Global Positioning System (GPS) total electron content (TEC) perturbations during the daytime most often in winter, and more irregular nighttime perturbations most often in summer, with nighttime seasonal-longitudinal trends similar to those observed in the in-situ satellite climatology. Afraimovich, Edemskiy, Voeykov, et al. (2009) used a network of ground-based GNSS receivers to observe small-amplitude (<0.2 TECU) wave-like structures in the TEC that closely corresponded to passage of the sunrise and sunset terminators and extended across much of the dayside. MacDougall and Jayachandran (2011) reported TIDs coincident with sunrise and sunset terminators in the midlatitude northern hemisphere based on ionosonde observations of the bottomside F region. Galushko et al. (1998) also observed terminator-associated TIDs in incoherent scatter radar measurements that they attributed to the solar terminator. Using accelerometer measurements of the CHAMP satellite, Forbes et al. (2008) observed perturbations in thermospheric neutral densities that appeared to be associated with the solar terminator, indicating that some midlatitude TIDs could be a signature of terminator-generated GWs.
Airglow imager observations of MSTIDs during night revealed statistical features similar to the in situ satellite and ground-based GNSS climatology, namely, a peak occurrence rate of 65% in summer and anticorrelation in occurrence with solar activity (Garcia et al., 2000; Shiokawa et al., 2003). Shiokawa et al. (2003) also noted a smaller peak in MSTID occurrence rate of 40% in winter during low solar activity years and observed similar statistical trends in the occurrence rate of MSF signatures in ionosonde data.

Equatorial spread F (ESF) irregularities associated with convective equatorial ionospheric storms (CEIS) have been extensively studied since the first ionosonde observations of Booker and Wells (1938). ESF irregularities over a broad range of scale sizes tend to have similar climatological features due to the multi-scale cascading process involved in ESF formation. Satellite observations have been used for in situ climatological studies of plasma density perturbations in the topside F region (Burke, Gentile, et al., 2004; Burke, Huang, et al., 2004; Huang et al., 2002; McClure et al., 1998; Su et al., 2006). Seasonal-longitudinal distributions in topside ESF occurrence have shown peak occurrence in the African sector around June solstice and equinoxes, including a minor peak in the southeast Asia sector near June solstice, and a shift in peak occurrence towards the American sector around December solstice. F region scintillation climatology of COSMIC RO measurements at low latitudes show very similar seasonal, longitudinal, and local time distributions compared to the in situ density perturbations (Carter et al., 2013; Dymond, 2012; Yue et al., 2016).

Seasonal-magnetic local time (MLT) topside ESF distributions of Su et al. (2006), based on ROCSAT-1 in-situ density measurements at 600-km altitude, showed a peak irregularity occurrence around equinox at 20 MLT, which gradually decayed through the night and into the early morning hours. The same distributions at June and December solstice showed ESF onset around 20 MLT, but with a gradual rise in occurrence towards midnight, and higher occurrence during postmidnight hours compared to equinox. Compared to periods of low solar radio flux, Su et al. (2006) also observed an ~30–40% increase in occurrence during high solar flux output, particularly in the evening at equinox. Ground ionosonde (Glover, 1960) and ISR (Chapagain et al., 2009) observations have indicated similar seasonal, local time, and solar cycle dependencies in the onset and occurrence of ESF. Chapagain et al. (2009) observed 1- to 2-hr delays between ESF onset at lowest altitudes (250–450 km) and the extension of the plume to higher altitudes, with larger delays during low solar activity. They also observed peak plume heights of 700 km at solar minimum and 1,400 km at solar maximum.

Radio occultation studies of medium-scale plasma structures are currently very limited. One study by Coïsson et al. (2015) presented COSMIC TEC observations of medium-scale F region irregularities below 400 km associated with the Tohoku earthquake off the coast of eastern Japan in 2011. The authors observed TEC perturbations with amplitude of up to 1 TEC unit (TECU; 1e16 electrons/m^3) and vertical scale sizes of ~50 km, which agreed with the characteristics of simulated ionospheric disturbances predicted by an ocean-atmosphere-ionosphere coupling model.

The objective of this study is to improve the global observational picture of medium-scale ionospheric plasma irregularities and investigate the detailed characteristics of irregularities in localized regions. Note that in the present study we consider all medium-scale irregularities regardless of their source (i.e., MSTIDs and ESF). Since ground-based ionospheric observations are limited to land-masses, while in situ satellite observations are constrained to the satellite orbit altitude, there are large observational gaps in the existing irregularity climatology. As demonstrated in the results, COSMIC observations provide a global picture of irregularity occurrence and offer a new perspective for observing irregularity structure and occurrence with high resolution in the vertical dimension. At low- and midlatitude regions discussed in this paper, the vertical distribution of irregularity occurrence and characteristics provides new insight into the physical processes that govern irregularity generation and structure. In addition, irregularity detection and analysis techniques presented in this paper may be applied in future RO missions, such as COSMIC 2.

Section 2 of this paper describes the COSMIC TEC data and development of the irregularity database. Section 3 presents the global climatology of irregularities detected by COSMIC RO measurements, in the form of geomagnetic latitude/local time and geographical distributions at various altitude ranges. Sections 4 and 5 present the MLT and altitude distributions of irregularity occurrence, amplitude and scale size, for equatorial and midlatitude regions, respectively.
2. Measurements and Analysis Procedure

Radio occultation TEC measurements of the COSMIC precise orbit determination GPS receivers and associated antennas are used for irregularity detection. The absolute TEC measurements are contained in podTec files in the COSMIC Data Analysis and Archive Center (http://cdaac-www.cosmic.ucar.edu) database and are available at a temporal resolution of 1 Hz. In tangent point altitude spacing in the F region, 1-Hz resolution corresponds to 0.01–3 km, with larger spacing as altitude decreases. TEC is electron volume density integrated along the GPS satellite-to-receiver ray path, which is calculated by taking the differential phase of L1 and L2 signals at the receiver. Only TEC data during occultation events were analyzed in this study, for tangent point altitudes of 120–720 km. This altitude range was selected in order to avoid effects of sporadic E, which typically occurs below 110 km, and artificial TEC perturbations due to the data processing sometimes observed near COSMIC satellite altitude (~800 km).

Figure 1 shows examples of medium-scale irregularities observed in (a and d) the nighttime equatorial region and (e and h) the nighttime midlatitude region in the northern summer. Figure panels show (a and e) the coordinates of the RO tangent point, (b and f) absolute TEC, (c and g) detrended TEC, and (d and h) the TEC dynamic power spectra (S-transform; Mansinha et al., 1997; Stockwell et al., 1996). The RO tangent point is the point at which the GPS satellite-to-receiver ray path is closest to the Earth’s surface, assuming a straight line propagation path. To estimate spatial scales of ionospheric irregularities, the 1-Hz TEC is interpolated onto a uniform grid of tangent point altitudes, where the spatial resolution of the grid was taken as the spatial resolution of the tangent point at 120 km (since the vertical motion of the tangent point is faster with decreasing altitude). In order to reveal the “medium-scale” perturbations in the TEC, the interpolated TEC (Figures 1b and 1f) is detrended with a third-order high-pass Butterworth filter, which removes TEC variations with vertical scales larger than ~50 km (Figures 1c and 1g).

As in Figure 1c, TEC perturbations that exceed 1 TECU in amplitude are often observed in the nighttime equatorial region, where CEIS and associated ESF irregularities are a well-known phenomenon. These equatorial irregularities are observed over a broad range of altitudes and scale sizes. Less intense irregularities over a broad range of altitudes are often observed in nighttime midlatitude regions (Figure 1g), while small amplitude perturbations in the lower F region are often observed near the sunrise and sunset terminators.

An automated algorithm is used to detect individual irregularities and calculate their characteristics. For each individual occultation event, the algorithm takes the interpolated TEC series TEC (h), where h is tangent point altitude, and computes the S-transform ST (h, λ), where λ is the wavelength of TEC perturbations. The S-transform, a generalized short-term Fourier transform that features a frequency-independent amplitude response, provides the spectral power of TEC localized in time and frequency (or for our purposes, altitude and wavelength). A Gaussian window function with width equivalent to the inverse of the frequency is applied in the S-transform. The irregularity detection algorithm then identifies isolated spectral components in time-frequency space that have peak spectral powers above a predefined threshold, while ignoring artificial features such as cycle slips, which can appear as simultaneous enhancements in the spectral power across a broad range of frequencies. Individual spectral components in the dynamic power spectra (Figures 1d and 1h) that correspond to TEC perturbations larger than 0.1 TECU are designated as individual irregularities, with scale size and perturbation amplitude recorded for each observed irregularity. This 0.1 TECU cutoff falls well above the ~0.02 TECU sensitivity of the COSMIC TEC measurement but avoids subtle artificial perturbations that may arise in the data processing such as the detection and correction for cycle slips. The current study is limited to irregularities observed during quiet geomagnetic conditions (Kp < 4).

The global occurrence rate of irregularities, as well the occurrence and characteristics of irregularities in equatorial and midlatitude regions, will be presented in the following sections. For purposes of this study, we take low/equatorial latitudes as −25° to 25° magnetic latitude (MLAT), midlatitudes as ±25° to ±60° MLAT, and high latitudes as >60° and <-60° MLAT. Equatorial and midlatitude results in sections 4 and 5 are presented using latitude ranges of −10° to 10° MLAT and ±25° to ±50° MLAT, respectively. These latitude ranges were chosen to limit contamination from neighboring regions (e.g., to limit the influence of high latitude features in the midlatitude results) but maintain a sufficient sample of measurements to
produce statistically significant climatological results. Climatological results are presented according to season, where seasonal date ranges are set as ±46 days from June/December solstice and March/September equinox. Four years of COSMIC data were analyzed to develop the irregularity climatology: two near solar minimum (2008–2009) and two during the ascending phase of solar cycle 24 (2012–2013). Figure 2a plots the daily f10.7 solar flux for 2006–2014 (source: Natural Resources Canada; http://www.spaceweather.gc.ca/solarflux/sx-5-en.php), with gray shaded regions indicating the time periods covered in this analysis. Figures 2b–2d summarize the monthly COSMIC data availability and irregularity detection rate over the 4-year period. The lower data volume during 2012–2013 is evident and is due to degradation of COSMIC satellites. However, the global rate of irregularity detection was higher during these solar active years. Overall, a total of 11,147,249 irregularities were detected by our algorithm, corresponding to 0.8% of the 1-Hz TEC observations during the 4-year period.

In order to generate maps of irregularity occurrence and characteristics, statistical results are organized in bins of 0.25 hr MLT, 2° MLAT, and 2.5-km altitude. For each bin, occurrence rate is calculated as
Occurrence \[\frac{N_{\text{irregularity}}}{N_{\text{total}}}\] (1)

where \(N_{\text{irregularity}}\) is the number of 1-Hz TEC observations that contain a detected irregularity and \(N_{\text{total}}\) is the total number of TEC observations. Average irregularity characteristics (char), either amplitude or scale size, are calculated by taking the cumulative amplitude or scale size of all detected irregularities divided by the total number of detected irregularities, for each respective bin.
where \( \text{char}_i \) is the amplitude/scale size of the \( i \)th detected irregularity.

### 3. Global Irregularity Occurrence Rate

Figures 3 and 4 show irregularity occurrence rates in geomagnetic coordinates for years 2008–2009 and 2012–2013, respectively. Occurrence maps are organized according to season (horizontally) and tangent point altitude (vertically). Occurrence rate contours at 65% are highlighted by black lines in the color contour plots. As shown in Figures 3 and 4, there is a general decrease in irregularity occurrence with increasing altitude, as well as higher occurrence rates in years of higher solar activity (2012–2013) compared to near solar minimum (2008–2009). At lowest \( F \) region altitudes (120–220 km), persistent irregularities are observed at high latitudes, in equatorial regions extending from the evening to early morning hours, and in middle- to low-latitude regions close to the sunrise/sunset terminator. A solar terminator dependence is evident when examining the seasonal occurrence patterns at low- to midlatitudes in Figures 3 and 4a–4d, where “V-shaped” bands of high occurrence (up to 86%) extend across the dayside in the winter hemispheres, with persistent irregularities near sunset (16:00–20:00 MLT) across a broad range of latitudes around equinox, and to a lesser extent near sunrise (04:00–08:00 MLT). These apparent terminator irregularities appear to be limited to the

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**Figure 3.** Irregularity occurrence rate plotted in magnetic local time and latitude for 2008–2009, organized according to season (horizontally) and tangent point altitude (vertically). The contours at 65% are highlighted by black lines.
lower $F$ region due to the absence of similar patterns at higher altitudes. Daytime low- to midlatitude patterns appear to be consistent with observations of TEC perturbations coincident with sunrise and sunset terminators by Afraimovich, Edemskiy, Voeykov, et al. (2009), Afraimovich, Edemskiy, Leonovich, et al. (2009), as well as the high occurrence of TEC perturbations in the daytime winter hemisphere reported by Kotake et al. (2006), Hernández-Pajares et al. (2006), and Wautelet and Warnant (2013). MacDougall and Jayachandran (2011) observed both a winter and summer maximum in the amplitude of terminator TIDs detected in ionosonde measurements at a northern midlatitude station (43°N, 81°E) and noted that a relatively large $N_{mF2}$ associated with the winter anomaly could contribute to the winter proclivity for TIDs observed in the TEC data.

Several mechanisms have been proposed for terminator TID generation. Kotake et al. (2006) attributed a rapid increase in TEC perturbation activity at dawn during equinox and winter seasons to the sudden increase in solar photoionization, while Afraimovich, Edemskiy, Leonovich, et al. (2009) argued that magneto-conjugate observations of TEC perturbations indicated that terminator-generated ion-acoustic waves and subsequent interhemispheric magnetohydrodynamic propagation were involved in the observed ionospheric disturbances. Terminator-associated neutral density perturbations observed by CHAMP (Forbes et al., 2008) could also generate the observed terminator TIDs.

High-latitude irregularities are observed across a broad range of altitudes, with >80% occurrence rates observed even at highest altitudes (>420 km) in 2012–2013 (Figures 4m–4p). Peak high-latitude occurrence rates of 97% were observed in 2012–2013 for tangent point altitudes of 220–320 km. A summer
hemisphere preference for high-latitude irregularity generation is evident across all altitudes, while occurrence patterns around equinox are more hemispherically symmetrical. A clear peak around noon is evident in the winter hemisphere during solar quiet years (Figures 3c, 3g, 3k, and 3o). The occurrence and characteristics of high latitude irregularities have a strong dependence on solar wind conditions and geomagnetic activity, which will be discussed in detail in a forthcoming manuscript. The climatological characteristics of medium-scale ionization structures observed using ground-based GPS receivers in the northern polar cap were presented in Watson, Jayachandran, and MacDougall (2016a) and Watson, Jayachandran, and MacDougall (2016b).

Nighttime irregularities near the magnetic equator are also observed over a broad range of altitudes, particularly in years of high solar activity near equinox when high-altitude occurrence rates approach 45% at 20:00–24:00 MLT (Figures 4n and 4p). Lower F region (<320 km) equatorial irregularities are persistent from 20:00 to 03:00 MLT, with a small (~5%) increase in occurrence around March and September equinox for −10° to 10° MLAT, relative to June and December solstice. On average, equatorial occurrence is ~11% higher in 2012–2013 compared to 2008–2009. Irregularities associated with CEIS, or so-called spread F irregularities, are a well-known feature of the equatorial region. Details of the characteristics of these irregularities are discussed in Section 4.

Low- and midlatitude irregularities (~10° to 60° MLAT) are more commonly observed during night compared to daytime hours and occur more often in the summer hemisphere where occurrence rates of 45–75% and 50–85% are observed in the lower F region (<320 km) in 2008–2009 and 2012–2013, respectively. These irregularities also extend to high altitudes, particularly in northern summer during 2012–2013 (Figure 4o), where occurrence rates up to 42% were observed at highest altitudes from 21:00 to 03:00 MLT. Detailed characteristics of midlatitude irregularities are discussed in section 5.

Aside from the apparent solar terminator irregularities in the lower F region, a prominent dayside feature in Figures 3 and 4 is enhanced irregularity occurrence rates in regions corresponding to the equatorial ionization anomaly (EIA; 10°–30° MLAT). These dayside features were commonly observed well above 220 km, where enhanced occurrence rates up to 50% are visible in North and South Hemispheres around March and September equinox, and predominantly in the summer hemisphere near solstice. Peak occurrence of these features is around noon, extending into the afternoon/evening sector. Occurrence is slightly higher during years of high solar activity, with rates of up to 40% observed at altitudes of 320–420 km, and up to 17% above 420 km.

To investigate the seasonal-geographical distribution of irregularities observed in Figures 3 and 4, maps of global occurrence rates in geographic coordinates are shown in Figure 5 for tangent point altitudes of 120–220 km (a, d, g, and j), 220–420 km (b, c, h, and k), and 420–720 km (c, f, i, and l). Occurrence rates are averaged over the entire 4-year study period, and maps are organized vertically according to season. Note that for visualization purposes, the color contour scales are different for each altitude range. The magnetic dip equator is indicated by a solid white line, while the dashed white lines show ±25° MLAT. Persistent irregularities are again observed at high latitudes, with highest occurrence and greatest latitudinal extent generally observed in the summer hemisphere. A high irregularity occurrence rate at midlatitudes in the winter hemisphere is also evident in the lower F region in Figures 5a and 5g, with rates exceeding 65% observed across a broad range of longitudes. These irregularities are likely, in large part, due to the solar terminator-associated features in Figures 3 and 4. Note that these seasonal trends are opposite to the well-known sporadic E (Es) climatology, where peak Es occurrence is observed at middle- to low latitudes in the summer hemisphere (Arras et al., 2008). Because we only consider altitudes above 120 km, Es are not included in our statistical results. Localized regions of high occurrence do appear in the summer hemisphere at 120–220 km, particularly in the south Pacific region (Figure 5a) and East Asia/Northwest Pacific (Figure 5g). Midlatitude occurrence rates are more hemispherically symmetric around equinox (Figures 5d and 5j), with a patch of enhanced activity in the south Pacific around March equinox. Rates near the magnetic equator are relatively low compared to other latitudes at 120–220 km since we are averaging over all local times, including the relatively low equatorial daytime occurrence rates.

More localized geographical patterns emerge at higher altitudes in Figure 5, in both middle and equatorial regions. The bulk of the midlatitude irregularities in the winter hemisphere are again evidently confined to lower F region altitudes, given the large drop in occurrence at altitudes above 220 km. Around
December solstice (Figures 5b and 5c), peak occurrence of midlatitude and equatorial irregularities is in the American sector, with some irregularities observed across the Pacific at low southern latitudes. Around June solstice (Figures 5h and 5i), peak midlatitude occurrence is in the East Asia and Oceanic regions, while peak equatorial occurrence is over Africa and the western Pacific. There is a hemispherical asymmetry in midlatitudes, with higher occurrence in the summer hemisphere compared to the winter around both December and June solstice. During equinox, midlatitude irregularities are observed slightly more often in the North American, East Asia, and Oceanic sectors compared to other regions at 220–420 km (Figures 5e and 5k), but almost no equinox midlatitude irregularities are observed above 420 km (Figures 5f and 5l). Equatorial occurrence is highest above Africa during equinox (Figures 5e, f, k, and 5l), with a minimum in the Indian longitude sector, and patchy occurrence rates through other
sectors. It is interesting to note that seasonal-longitudinal distributions of equatorial and midlatitude irregularities are very similar, with the exception of high equatorial and low midlatitude occurrence rates in the African sector.

At midlatitudes, these seasonal-longitudinal distributions closely match distributions based on CHAMP (350-450-km altitude), KOMPSAT-1 (685 km), and DMSP (840 km) in situ plasma density measurements presented in Park et al. (2010), including the hemispherical asymmetry around solstice. Park et al. (2010) reported a decrease in occurrence with altitude, with peak solstice occurrence of ~30% at CHAMP altitudes, ~15% at KOMPSAT-1 altitudes, and ~10% at DMSP altitudes. The cause of the seasonal-longitudinal distributions observed in the in situ and COSMIC results is not clear at this point. Earle et al. (2006) discussed applying the mechanism governing the seasonal-longitudinal dependence of ESF to midlatitudes, where a sunset terminator more aligned with the local magnetic field is conducive to instability growth (Maruyama & Matuura, 1984). With no terminator-magnetic field alignment, electric fields required for instability growth can be shorted out since north-south footprints of magnetic flux tubes are simultaneously in sunlit and dark ionospheres. As shown in Figure 5, at altitude above 2200 km, peak occurrence during December (June) solstice is in regions of negative (positive) magnetic field declination, where the magnetic field and sunset terminator would be more closely aligned. However, as will be shown in section 5, midlatitude irregularity occurrence is spread throughout the night and peaks around midnight, and this explanation would be seemingly confined to irregularities around sunset. In the future, seasonal-longitudinal variations in atmospheric neutral winds, which can influence the generation of plasma instabilities, should be investigated as possible contributions to the observed plasma irregularity distribution.

The seasonal-longitudinal trends at equatorial latitudes in Figure 5 also closely match the climatology of equatorial plasma bubbles observed in the evening local time sector by DMSP (Burke, Huang, et al., 2004) at ~840-km altitude and ROCSAT-1 (Su et al., 2006) at ~600-km altitude. These patterns are possibly related to global distributions in energetic particle precipitation, which can increase ionospheric Pederson conductivity and suppress RTI growth rates, particularly in the South Atlantic Anomaly region. Global distributions in seeding mechanisms such as GWs, a maximum F region uplift when the sunset terminator is closely aligned with the geomagnetic field, and instability suppression due to seasonal-longitudinal variations in meridional neutral winds (Kil & Heelis, 1998; McClure et al., 1998) may also play a role in the observed equatorial patterns. Note that the distributions of medium-scale irregularities shown here are similar to the seasonal-longitudinal distributions of equatorial F region scintillations observed in GNSS RO data (Carter et al., 2013; Dymond, 2012; Yue et al., 2016).

4. Equatorial Irregularity Characteristics

Figure 6 shows the occurrence rate of equatorial (~10° to 10° MLAT) irregularities as color contours during low (a–d) and high (e–h) solar activity years, in addition to line plots (i–l) of occurrence rate at altitudes of 220 km (solid lines) and 520 km (dashed lines) during 2008–2009 (blue lines) and 2012–2013 (red lines). The color contours are plotted with respect to tangent point altitude and MLT, and the panels are organized horizontally according to season. Each plot is centered on 24 MLT. Occurrence rates in Figure 6 are generally lowest during daytime hours. An increase in irregularity occurrence is generally observed starting in late afternoon or evening, with a peak occurrence prior to midnight, and a decay in irregularity occurrence rates into the early morning hours. At low altitudes (<300 km), a steady increase in irregularity occurrence is observed starting in late afternoon and into the postsunset hours, which may be related to TIDs generated by the sunset terminator and/or the onset of bottomside spread F irregularities. Note that late afternoon occurrence at low altitudes is higher near solar minimum compared to solar active years, where occurrence rates at 17:00 MLT in 2008–2009 are ~70–75%, compared to 45–55% in 2012–2013. The occurrence rates at low altitudes are consistently high (>75%) through most of the night, with evening/postmidnight peaks in 2008–2009, and a single midnight peak in 2012–2013. At altitudes above 300 km, the evening increase in occurrence rates begins later in the evening, starting around 18:00–20:00 MLT in 2008–2009, and peaking around 22:00–24:00 MLT. In 2012–2013, the increase in topside occurrence is more significant beginning around 17:30–18:00 MLT, and peaking around 21:00 MLT at December solstice and equinox, and 22:00–22:30 MLT around June solstice. Irregularities are more commonly observed at topside altitudes during years of high solar activity and during equinox. The high-altitude occurrence trends here are consistent with the
seasonal-solar cycle dependencies of equatorial density perturbations shown in Su et al. (2006), based on ROCSAT-1 observations at ~600 km.

Figures 7 and 8 show average irregularity amplitude (i.e., peak-to-peak TEC variation) and average vertical scale size, with panels organized as in Figure 6. While values shown here represent the average characteristic features in each MLT-altitude bin, irregularities over a broad range of amplitudes (0.1–5.5 TECU) and scale sizes (2.0–45.7 km) were observed in all local time regions. As shown in Figure 7, the most intense irregularities are generally observed in the postsunset hours, with larger amplitudes in high solar activity years and during equinox, and lowest amplitudes during June solstice. In 2008–2009 (Figures 7a–7d), peak average amplitudes of 0.7–1.0 TECU occur at altitudes of 250–350 km and around 21:00–23:00 MLT. In 2012–2013 (Figures 7e–7h), peak amplitudes of 1.2–1.7 TECU are observed at altitudes of 400–510 km at 20:30–22:00 MLT. The altitude of peak intensity tends to decrease towards midnight, with significantly less intense irregularities observed in the postmidnight hours. The appearance of more intense irregularities closely coincides with the onset of increased irregularity occurrence rates above 300 km in Figure 6, while the time of peak intensity is within 30 min of when enhanced occurrence rates reach peak altitude. Compared with other seasons, the altitude of peak intensity is highest around December solstice during both 2008–2009 (~340 km) and 2012–2013 (~510 km), and lowest around June solstice in 2012–2013 (~400 km). Intensity also peaks at later local times during June solstice compared to other seasons, at ~23:00 MLT in 2008–2009 and ~22:00 in 2012–2013.
As shown in Figure 8, irregularities prior to 20:00 MLT tend to have large vertical scale sizes of up to ~37 km (on average). Average irregularity scale size generally decreases during nighttime ESF occurrence, with smaller scale sizes observed at higher altitudes. After ~20:00 MLT, an increase in irregularity intensity coincides with an average decrease in irregularity scale size across all altitudes, with scale sizes of 22–25 km and 17–22 km corresponding to peak intensities in 2008–2009 and 2012–2013, respectively. At local times closer to midnight, the low altitude (<300 km) decrease in scale size also corresponds to an increase in irregularity amplitude. Average scale size below 300 km and near midnight is 5–10 km smaller in 2008–2009 compared to 2012–2013. As the night progresses, there is an increase in scale size at all altitudes that corresponds to a gradual decrease in irregularity occurrence and intensity. The increase in scale size occurs at earlier local times at higher altitudes, and after midnight at lowest F region altitudes. This general trend across the evening-to-early morning sectors is particularly noteworthy in 2012–2013 during equinox (Figures 6f and 6h and 8f and 8h), where we have an initial high-altitude increase in irregularity occurrence of very intense and relatively small-scale irregularities, with a delayed appearance of intense small-scale irregularities at gradually lower altitudes. Peak intensity occurs about 2–3 hr after the initial onset of these irregularities and is followed by the appearance of less intense but larger scale size irregularities, again delayed with respect to altitude. These trends are likely related to the sudden intense increase and gradual decay of RTI growth rates and associated ESF irregularities following sunset. The decrease in altitude of intense irregularity appearance may be related to a gradual drop in F layer height following sunset and thus decrease in altitude of initial bubble growth.

Figure 7. Same format as Figure 6, except for average irregularity amplitude in the equatorial region.

As shown in Figure 8, irregularities prior to 20:00 MLT tend to have large vertical scale sizes of up to ~37 km (on average). Average irregularity scale size generally decreases during nighttime ESF occurrence, with smaller scale sizes observed at higher altitudes. After ~20:00 MLT, an increase in irregularity intensity coincides with an average decrease in irregularity scale size across all altitudes, with scale sizes of 22–25 km and 17–22 km corresponding to peak intensities in 2008–2009 and 2012–2013, respectively. At local times closer to midnight, the low altitude (<300 km) decrease in scale size also corresponds to an increase in irregularity amplitude. Average scale size below 300 km and near midnight is 5–10 km smaller in 2008–2009 compared to 2012–2013. As the night progresses, there is an increase in scale size at all altitudes that corresponds to a gradual decrease in irregularity occurrence and intensity. The increase in scale size occurs at earlier local times at higher altitudes, and after midnight at lowest F region altitudes. This general trend across the evening-to-early morning sectors is particularly noteworthy in 2012–2013 during equinox (Figures 6f and 6h and 8f and 8h), where we have an initial high-altitude increase in irregularity occurrence of very intense and relatively small-scale irregularities, with a delayed appearance of intense small-scale irregularities at gradually lower altitudes. Peak intensity occurs about 2–3 hr after the initial onset of these irregularities and is followed by the appearance of less intense but larger scale size irregularities, again delayed with respect to altitude. These trends are likely related to the sudden intense increase and gradual decay of RTI growth rates and associated ESF irregularities following sunset. The decrease in altitude of intense irregularity appearance may be related to a gradual drop in F layer height following sunset and thus decrease in altitude of initial bubble growth.

Spread F statistics of Chapagain et al. (2009), based on Jicamarca ISR observations, indicated spread F onset at 19:30–20:00 MLT at solstice and 19:15–19:30 MLT and equinox, independent of solar activity level. Onset
altitudes of 270–425 km at solstice and 275–450 km at equinox were also reported, with a linear increase in onset altitude with solar flux. The Jicamarca onset times closely match the times where occurrence begins to increase at altitudes above ~320 km in Figure 6. Chapagain et al. (2009) also found plume onset times of 20:45–21:30 MLT at solstice, and 20:20–21:20 MLT at equinox, with later onset times during low solar activity. Plume onset altitudes were 300–400 km around June solstice, 350–500 km around December solstice, and 325–500 km at equinox, with higher onset altitudes during high solar activity periods. These plume onsets correspond to time and altitude of peak topside intensity in 2012–2013 in Figure 7. Peak intensities occur at lower bottomside altitudes in 2008–2009.

5. Midlatitude Irregularity Characteristics

Figure 9 shows the occurrence rate of midlatitude irregularities in (a–c) northern (25° to 50° MLAT) and (c–f) southern (–50° to –25° MLAT) hemispheres, during years of both low and high solar activity. Occurrence color contours are plotted in coordinates of tangent point altitude versus MLT, while line plots show occurrence rates at altitudes of 220 km (solid lines) and 520 km (dashed lines) over MLT. Irregularities are generally confined to low altitudes (below 300 km) during the day but are frequently observed at higher altitudes at night. Enhanced low-altitude occurrence rates of 75–85% in the evening and 55–80% in the morning are likely, in large part, due to TIDs associated with the solar terminator. In the evening, a peak occurrence is observed at 16:00–17:00 MLT and 150–170 km altitude in the winter hemisphere, which shifts to 20:00–20:30 MLT and 210–230 km altitude in summer, while the occurrence patterns around equinox are intermediate to this trend. Evening occurrence is 10–20% higher around June and December solstice compared to
occurrence rates around equinox. In the morning, peak winter occurrence is at 07:00–08:00 MLT and 150–170-km altitude, which shifts to 06:30–07:00 MLT and 150– to 170-km altitude around equinox. Morning occurrence is lowest in the summer hemisphere, peaking at 50–60% around 09:00–10:00 MLT and 150– to 170-km altitude. These seasonal patterns in the evening and morning may reflect a seasonal dependence.
on the generation of irregularities around the solar terminator or may result from combination of terminator and other evening/nighttime mechanisms.

Dayside irregularity occurrence has a small apparent solar cycle dependence. An ~3–7% decrease with solar activity is observed at sunset in the summer hemisphere, at sunrise around June solstice, and at equinox sunrise in the southern hemisphere. All other occurrence rates near the solar terminator are 3–8% larger during 2012–2013 (Figures 9b and 9e) compared to 2008–2009 (Figures 9a and 9d). Also notable in the dayside summer hemisphere is an increase in irregularity occurrence at altitudes above ~300 km, mostly during high solar activity years. These are not insignificant (>20%) occurrence rates up to ~500-km altitude, which are observed mostly in the morning and dissipate during postnoon hours. These enhanced summer occurrence rates are evident in Figures 3 and 4 and could be linked to terminator TIDs. MacDougall and Jayachandran (2011) reported an increase in daytime TID activity in northern summer, which they attributed to sunrise terminator TIDs. Based on ground GNSS data, both Hernández-Pajares et al. (2006) and Wautelet and Warnant (2013) reported an increase in winter daytime irregularity occurrence in high solar activity years, while Kotake et al. (2006) observed no such solar cycle dependence.

Occurrence rates during the night in Figure 9 have clear seasonal and solar cycle dependencies. Irregularities are observed much more frequently and at higher altitudes in the summer hemisphere compared to the winter, with a peak midnight occurrence of ~80% at 260–280 km in the summer, compared to peak rates of 50–65% in winter in the pre- and postmidnight sectors. Nighttime occurrence rates around equinox fall in between the summer and winter extremes.

In the summer hemisphere and around equinox there is a clear increase in nighttime occurrence during high solar activity years, with irregularities observed more frequently at higher altitudes compared to solar minimum years. A clear midnight peak around 80% is also evident in the summer hemisphere during 2012–2013 (Figures 9b and 9e), distinct from the peak around 20:00 MLT observed during both low and high solar activity years. Interestingly, the solar cycle dependence of nighttime occurrence rates in the winter hemisphere is opposite to that of other seasons, where there is a clear decrease of 10–20% in irregularity occurrence in 2012–2013 compared to 2008–2009 in both northern (Figures 9a and 9b) and southern (Figures 9d and 9e) winter. A clear minimum in occurrence is observed around 23–24 MLT in northern winter and 01:00–02:00 MLT in southern winter. However, despite an overall higher occurrence near solar minimum in the winter hemisphere, higher altitude (above ~320 km) irregularities are observed more often in 2012–2013 during winter. For example, the occurrence rate at 01:00 MLT and 220 km in northern winter is 68% in 2008–2009 (Figure 9a) and 52% in 2012–2013 (Figure 9b), while at 420 km the rate is 12% in 2008–2009 and 31% in 2012–2013.

Both the seasonal and local time trends of midlatitude topside irregularity occurrence observed here are in general agreement with climatology of in situ MSTIDs of Park et al. (2010) and Su et al. (2006), while the overall summer nighttime and winter daytime occurrence trends agree with ground-based GNSS TEC observations of Hernández-Pajares et al. (2006), Kotake et al. (2006), and Wautelet and Warnant (2013). There are, however, some discrepancies in the solar cycle dependence of nighttime irregularities. While Figure 9 shows significantly higher nighttime occurrence in 2012–2013 compared to 2008–2009, a large number of climatological studies have reported a decrease in MSTID occurrence at night during years of high solar activity. These reports have been based on in situ satellite data (Park et al., 2010; Su et al., 2006), ground-based airglow imagers (Garcia et al., 2000; Shiokawa et al., 2003) and ground-based TEC data (Kotake et al., 2006; Wautelet & Warnant, 2013). However, Hernández-Pajares et al. (2006) reported a strong positive correlation in MSTID amplitude with solar activity using ground-based TEC observations. Discrepancies in reported solar cycle dependencies may arise from different observational techniques or variable irregularity detection algorithms. For example, unlike other studies, Kotake et al. (2006) calculated TEC disturbance amplitude relative to the background TEC. In addition, the anticorrelation in occurrence with solar activity in Park et al. (2010) was based on an ~5–15% increase in CHAMP irregularity occurrence in 2006–2007 compared to 2001–2002. However, the altitude of CHAMP decreased by 50–100 km from 2002 to 2006, which could account for the observed increase in topside irregularity occurrence given the substantial decrease in occurrence with altitude (Figure 9).

Figures 10 and 11 show the average amplitude and vertical scale size of TEC variations observed at midlatitudes, with panels organized as in Figure 9. Large amplitude (> 1 TECU), large-scale (25–40 km) perturbations
are evident at low altitudes on the dayside, with largest dayside amplitudes around equinox and in the winter hemisphere, and lowest dayside amplitudes in the summer hemisphere. Although observed less frequently than terminator and nighttime irregularities, the intense daytime irregularities are consistent with intense MSTID activity observed during equinox and winter by Hernández-Pajares et al. (2006) at European midlatitudes. Park et al. (2014) also used in situ CHAMP satellite observations of thermospheric density perturbations at 300–400 km to show that dayside GW intensity was strongest in the winter hemisphere. While irregularity amplitudes are largest across noon on the dayside, irregularity scale sizes in Figure 11

Figure 10. Same format as Figure 9, except for average irregularity amplitude at midlatitudes.
tend to be largest in the afternoon and morning sectors, near the location of high occurrence rate in Figure 9 corresponding to the sunset/sunrise terminators.

Nighttime irregularities are most intense in the summer hemisphere, around 20:00–21:00 MLT in 2008–2009 (Figures 10a and 10d) and 00:00–01:00 MLT in 2012–2013 (Figures 10b and 10e), with larger amplitude irregularities observed during solar active years. A similar, but weaker pattern is observed in other seasons, with generally more intense irregularities observed in the northern hemisphere. Based on Figure 11, the average
scale size of nighttime midlatitude irregularities tends to be smaller than daytime irregularities across all altitudes, with smaller average scale size during years of high solar activity.

In Figures 10a and 10b, a curious feature is evident in the evening-nighttime intensities in northern winter, and to a lesser degree at northern equinox and summer, where the intensity patterns are similar to those observed in evening equatorial regions in Figure 7. The peak northern winter intensities at 20:40 MLT and 320 km in Figure 10a, and 20:30 MLT and 510 km in Figure 10b correspond to low occurrence rates (<15%) in Figure 9. One concern is that ESF characteristics are leaking into the midlatitude climatology, given the assumption of irregularity localization at the RO tangent point. However, a directly north-south occultation geometry is not possible at these latitudes, and a GPS-to-receiver signal with tangent point at midlatitude would pass through much higher altitudes in the equatorial region. To test a potential ESF contamination in midlatitude climatology, altitude-MLT maps for midlatitude occurrence and intensity were generated using a lower cutoff latitude of ±35° (not shown). This resulted in no significant change in the occurrence and intensity distributions. It may be possible that this northern winter intensity pattern is related to the formation of MSF irregularities, similar to the formation of ESF at equatorial latitudes. However, if this were the case, one would expect a similar feature in the southern hemisphere at midlatitudes, which is absent in the observations. More detailed investigation, such as climatological analysis of irregularity characteristics based on satellite-to-receiver signal path orientation, will hopefully shed some light on this midlatitude feature.

6. Conclusions and Future Work

COSMIC radio occultation TEC measurements provide a global picture of medium-scale (6–50 km) F region irregularities and allow for investigation of the characteristics of irregularities from a new and unique perspective. Global irregularity distributions indicate persistent medium-scale irregularity occurrence at high latitudes, nighttime middle and equatorial latitudes, and in dayside regions corresponding to the sunrise and sunset terminators. Terminator irregularities were primarily observed at bottomside (<220 km) F Region altitudes. Seasonal-longitudinal occurrence distributions indicate that nighttime mid and equatorial latitude irregularities tend to form in geographically localized regions that vary with season. These distributions are largely consistent with previous in situ and ground-based observations.

At equatorial latitudes, a postsunset increase in irregularity occurrence was observed across a broad range of altitudes, followed by a gradual decrease in occurrence into the early morning. In the equatorial region, the medium-scale irregularities observed by COSMIC are primarily connected to ESF. Irregularities were most intense and had smallest scale sizes immediately following ESF onset. This pattern is consistent with the rapid RTI instability growth and gradual decay beginning at sunset. High irregularity occurrence at bottomside F region altitudes, peaking around midnight, may be related to persistent bottomside ESF. High ESF occurrence and intensity during equinox and years of high solar activity are consistent with known climatology.

At midlatitudes, irregularity occurrence during nighttime was highest around midnight during summer, while occurrence during daytime was highest during winter, consistent with previous climatology developed using in situ and ground-based measurements. Intense, large scale daytime irregularities were confined primarily to the bottomside F region, with some irregularities observed at higher altitudes in summer, during years of high solar activity. Nighttime irregularities were observed across a broad range of altitudes. Nighttime irregularity occurrence was correlated with solar activity across all altitudes during summer and equinox, while occurrence at bottomside altitudes in winter was anticorrelated with solar activity. This solar cycle dependence contradicts previous observational results, which have mostly reported an anti-correlation in nighttime MSTID occurrence with solar activity.

As demonstrated in this paper, COSMIC RO measurements are capable of detailed global irregularity climatology, particularly in the vertical dimension. These climatological results enhance the global observational picture of medium-scale irregularities and may be beneficial for applications that require irregularity forecasting, such as GNSS precise positioning techniques. A forthcoming study will report the irregularity occurrence and characteristics at high latitudes, while ongoing studies include irregularity analysis during transient events such as geomagnetic storms, magnetospheric substorms, and sudden stratospheric warming
References


