Review of ionospheric irregularities and ionospheric electrodynamic coupling in the middle latitude region

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Key Points:

- We review and discuss current research related to ionospheric irregularities in the middle latitude region.
- The generation of mid-latitude ionospheric irregularities depends on the effects of electric fields and neutral winds.
- We also discuss the effect of electrodynamic coupling processes on the evolution of ionospheric irregularities in the mid-latitude region.

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Abstract: This paper briefly reviews ionospheric irregularities that occur in the E and F regions at mid-latitudes. Sporadic E (E_s) is a common ionospheric irregularity phenomenon that is first noticed in the E layer. E_s mainly appears during daytime in summer hemispheres, and is formed primarily from neutral wind shear in the mesosphere and lower thermosphere (MLT) region. Field-aligned irregularity (FAI) in the E region is also observed by Very High Frequency (VHF) radar in mid-latitude regions. FAI frequently occurs after sunset in summer hemispheres, and spectrum features of E region FAI echoes suggest that type-2 irregularity is dominant in the nighttime ionosphere. A close relationship between E_s and E region FAI implies that E_s may be a possible source of E region FAI in the nighttime ionosphere. Strong neutral wind shear, steep E_s plasma density gradient, and a polarized electric field are the significant factors affecting the formation of E region FAI. At mid-latitudes, joint observational experiments including ionosonde, VHF radar, Global Positioning System (GPS) stations, and all-sky optical images have revealed strong connections across different scales of ionospheric irregularities in the nighttime F region, such as spread F (SF), medium-scale traveling ionospheric disturbances (MSTID), and F region FAI. Observations suggest that different scales of ionospheric irregularities are generally attributed to the Perkins instability and subsequently excited gradient drift instability. Nighttime MSTID can further evolve into small-scale structures through a nonlinear cascade process when a steep plasma density gradient exists at the bottom of the F region. In addition, the effect of ionospheric electrodynamic coupling processes, including ionospheric E-F coupling and inter-hemispheric coupling on the generation of ionospheric irregularities, becomes more prominent due to the significant dip angle and equipotentiality of magnetic field lines in the mid-latitude ionosphere. Polarized electric fields can map to different ionospheric regions and excite plasma instabilities which form ionospheric irregularities. Nevertheless, the mapping efficiency of a polarized electric field depends on the ionospheric background and spatial scale of the field.

Keywords: ionospheric irregularity; plasma instability; neutral wind; polarized electric field; ionospheric electrodynamic coupling

1. Introduction

The ionosphere is the region of the upper atmosphere that is partially ionized by high-energy solar radiation from about 60 km to thousands of kilometers above the Earth's surface; it is an important transition region connecting the lower atmosphere and magnetosphere in the near-earth space environment. As a result of photoionization and transport processes, the ionosphere is divided into the D region (60–90 km), E region (90–150 km), and F region (150–1000 km). During the day, the F region is further split

into the F_1 region (150–220 km) and F_2 region (220–1000 km).

The spatial and temporal distribution of charged particles in the ionosphere is influenced by many factors, including the electrodynamics of the Earth's magnetic field and other processes driven by neutral wind (Kelley, 2009). In addition, ionospheric charged particles can modulate the propagation of radio waves, significantly impacting communications, navigation, and radar systems (Ratcliffe, 1972).

Many studies have revealed large numbers of ionospheric irregularities with a spatial scale from meters to thousands of kilometers, manifesting as sporadic E (E_s) and spread F (SF) in ionograms (Bowman, 1990; Zhou C et al., 2017), field-aligned irregularities (FAIs), plasma bubbles in radar maps (Kelley et al., 1981;

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Yamamoto et al., 1991; Zhou C et al., 2018a; Liu Y et al., 2019), traveling ionospheric disturbances (TIDs) in optical images, and total electron content (TEC) perturbation maps (Ding F et al., 2011; Huang FQ et al., 2016). When radio waves transit an ionospheric irregularity, radio signals may undergo severe signal loss and phase cycle slips known as ionospheric scintillations (Basu et al., 1988), which can affect modern communication and navigation system performance.

The formation of irregularities is generally attributed to ionospheric instability mechanisms, including: wind shear theory for E_s (Mathews, 1998); two-stream instability (TSI) and gradient-drift instability (GDI) for E region FAIs at the equator and low latitudes (Farley, 1963; Simon, 1963); atmospheric gravity waves, GDI, Kelvin-Helmholtz instability (KHI), and E_s -layer instability for E region FAIs at mid-latitudes (Woodman, 1991; Larsen, 2000; Maruyama et al., 2000; Cosgrove and Tsunoda, 2002a); Rayleigh-Taylor (R-T) instability for plasma bubbles and equatorial SF (Dungey, 1956; Basu and Kelley, 1979; Fejer and Kelley, 1980; Abdu, 2001); and the breaking of atmospheric gravity waves and Perkins instability for SF and medium-scale TIDs (MSTIDs) at mid-latitudes (Perkins, 1973; Bowman, 1990, 1991; Liu Y et al., 2019). In all of the above instability mechanisms, electric fields and neutral winds play dominant roles in the generation of ionospheric irregularities.

Unlike the equatorial and polar regions, the significant dip angle and equipotentiality of magnetic field lines in the mid-latitude regions cause an apparent electrodynamic coupling relationship between ionospheric irregularities in the E and F regions. The importance of electrodynamic coupled processes in generating ionospheric irregularities has been extensively investigated using observations and numerical simulations, suggesting that ionospheric instabilities could be easily excited by coupled processes along magnetic field lines (Bowman, 1960; Haldoupis et al., 2003; Kelley et al., 2003; Cosgrove and Tsunoda, 2004; Yokoyama et al., 2009; Zhou C et al., 2018b; Liu Y et al., 2019, 2020).

In this paper, we focus on the morphological characteristics and generation mechanisms of ionospheric irregularities in the mid-latitude region, especially ionospheric electrodynamic coupling processes. Recent observational studies of ionospheric irregularities in this region using ionosondes, Very High Frequency (VHF) radar, airglow imagers, the Global Navigation Satellite System (GNSS) network, the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) radio occultation (RO) measurements, and low Earth orbit (LEO) satellites are presented. E region irregularity, F region irregularity, and ionospheric electrodynamic coupling phenomena are reviewed in Sections 2, 3, and 4, respectively.

2. E Region Irregularity

E_s and E region FAIs are two significant irregular phenomena in the mid-latitude region whose morphological features have been widely studied for over 70 years, with plasma electrodynamic processes generally considered to be the major influences (Larsen, 2000; Cosgrove and Tsunoda, 2002b). A strong linkage between E_s and E region FAI is also revealed by several studies (Ogawa, 2002; Zhou C et al., 2018a, b). Next, we review the recent research on E region irregularities.

2.1 Sporadic E

E_s , an enhanced metallic ionization layer, is frequently observed in the E region from 90–140 km. As far back as the 1950s, researchers studied the temporal and spatial distribution of E_s using ionosonde. Previous statistical studies have shown that E_s occurrence has a clear local time and seasonal dependence (Smith, 1957; Arras et al., 2008; Chu YH et al., 2014). E_s develops in the early morning at ~6 local time (LT), reaching a maximum intensity at around 14 LT and 20 LT for summer hemispheres in the mid-latitude region. The local time and seasonal variations of E_s occurrence rate observed by four ionosondes located at Mohe (122.37°E, 53.50°N), Beijing (116.25°E, 40.25°N), Wuhan (114.61°E, 30.53°N), and Hainan (109.13°E, 19.52°N), China, are shown in Figure 1 (Zhou C et al., 2017). The occurrence rate of E_s is calculated as the ratio of the number of E_s observations to the total number of ionograms in each bin in Figure 1. Intense E_s layer was more prevalent around local noon and after sunset during summer at all stations.

Neutral wind shear theory has been proposed to explain the formation of E_s in the mid-latitude region (Whitehead, 1960). Under the combined action of geomagnetic fields and zonal wind, metallic ions are pushed upward by eastward winds at lower altitudes and downward by westward winds at higher altitudes, converging near the shear node to form the thin E_s layer. The relationship between E_s occurrence rate and neutral wind shear (as shown in Figure 2) was recently described by Liu Y et al. (2018). A more frequent occurrence of E_s observed by measuring RO at mid-latitudes is also presented in Figure 2, consistent with previous studies (Arras et al., 2008; Chu YH et al., 2014). The global distribution of wind shear measured by TIMED/TIDI and simulated by Horizontal Wind Model 14 (HWM14) have similar seasonal and latitude characteristics with the rate of E_s occurrence (Figure 2). Furthermore, the annual variation of meteor deposition may explain the maximum occurrence of E_s during summer (Haldoupis et al., 2007).

Recent statistical studies also find that E_s occurrence rate may be affected by geomagnetic activity, although the relationship is complex and varies with local time and latitude (Zhang YB et al., 2015; Zhou C et al., 2017). Positive, negative, and no correlation between E_s occurrence and geomagnetic activity have all been reported (Maksyutin and Sherstyukov, 2005; Pietrella and Bianchi, 2009). The variation in E_s occurrence with K_p index measured by four ionosondes at mid-latitudes is presented in Figure 3. Under moderate ($3 \leq K_p < 6$) and active geomagnetic conditions ($6 \leq K_p < 9$), E_s occurs more frequently than under quiet geomagnetic conditions ($0 \leq K_p < 3$). The prompt penetration electric field (PPEF), zonal electric field disturbances in the MLT region, and changes in lower thermospheric composition during geomagnetic storms may be the mechanisms for the effect of geomagnetic activity on E_s occurrence (Abdu et al., 2013, 2014; Zhang YB et al., 2015).

A close relationship between E_s and atmospheric waves has been revealed by many studies (MacDougall, 1974; Wilkinson et al., 1992; Haldoupis et al., 2006; Haldoupis, 2012; Zhou C et al., 2017). 24-hour, 12-hour, and 8-hour tidal period components are frequently observed in critical frequency of E_s (f_oE_s) time series (Haldoupis et al., 2004). Planetary waves could also affect the forma-

Figure 1. E_s occurrence rate (%) at four ionosondes located at Mohe (122.37°E, 53.50°N), Beijing (116.25°E, 40.25°N), Wuhan (114.61°E, 30.53°N), and Hainan (109.13°E, 19.52°N) during 2011–2015. Distributions are binned function of local time (anti-clockwise direction) and critical frequency of E_s (f_oE_s) from 0 MHz to 15 MHz in steps of 1 MHz (radial direction), which sorted into spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February) (after Zhou C et al., 2017).

tion of E_s by modulating atmospheric tidal wave amplitude (Pancheva et al., 2003). A 14.5-day semimonthly lunar period component is found to cause the E_s layer variations during Sudden Stratospheric Warming (SSW) events as shown in Figure 4. During SSW events, the reversal of zonal winds as well as thermal temperature variations in the stratosphere and mesosphere could affect the propagation of lunar tides (Lindzen and Hong, 1974; Stening et al., 1997; Pedatella et al., 2012). The enhancement of the 14.5-day semimonthly lunar period component in the MLT region, eventually produces variations in the E_s layer, shown in Figure 5 (Tang Q et al., 2020).

2.2 E Region Field-Aligned Irregularity

E region FAIs have been observed using VHF radar since the 1960s. The first observation of E region FAIs was by Cohen and Bowles (1967) using Jicamarca VHF radar in the equatorial region. Radar spectral studies have found that E region FAIs could be divided into two types. Type-1 irregularities with a narrow spec-

trum could be excited by TSI, while type-2 irregularities with a broader Doppler width are associated with GDI. In the mid-latitude region, Yamamoto et al. (1991) first reported that E region FAI echoes could be classified into two types, continuous type echoes and quasi-periodic (QP) type echoes, according to different radar features. An example of E region FAIs observed using Wuhan VHF radar (30.54°N, 114.37°E) is shown in Figure 6. The radar data indicate that continuous-type echoes mainly occurred between 90–110 km after sunrise, whereas QP-type echoes appeared above 100 km within a 10–15 min post-sunset period. Recent observations provided by the second Sporadic E Experiment over Kyushu (SEEK-2) found a close connection between E region FAIs and E_s (Larsen et al., 2005). This correlation was further supported by numerical simulations (Maruyama et al., 2006; Li GZ et al., 2013, 2014), indicating that E region FAI echoes occur more often with a greater E_s density gradient (Figure 7).

The E region FAIs at mid-latitudes cannot be directly driven by TSI or GDI. According to the TSI mechanism, the external electric field

Figure 2. The seasonal distribution of global E_s occurrence rate observed by COSMIC, GRACE and CHAMP (first column) and wind shear occurrence measured by TIMED/TIDI (second column) and simulated by HWM14 (third column). Distributions are binned within a $5^\circ \times 5^\circ$ resolution during 2002–2016 (after Liu Y et al., 2018).

triggering TSI should be greater than 10 mV/m, which is difficult to reach at mid-latitudes. The type-1 irregularity echoes were first reported by Schlegel and Haldoupis (1994) using Sporadic E Scatter (SESCAT) radar. Haldoupis et al. (1996) proposed that when there is a steep horizontal ionospheric conductivity gradient of E_s along the zonal direction at night, zonal polarized electric field could be sufficiently excited to meet the threshold for triggering TSI. However, the spatial structure of the E_s layer rarely meets the conditions triggering TSI at mid-latitudes, which may explain why type-1 E region irregularity echoes are infrequently observed at in this region. Recent observations of E region FAI echoes at Wuhan show that type-2 irregularities occur more often during local night at mid-latitudes (Figure 8). Maruyama et al. (2000) described the formation of oblique stripes in E region FAI echoes is associated with GDI. The polarized electric field excited in the blocky E_s structure could map to the higher E layer and generate the sheet

plasma density structure along magnetic field lines, which triggers GDI on the side where the polarized electric field and plasma density gradient are parallel and eventually results in the generation of QP echoes in radar maps. Haldoupis and Schlegel (1996) and Yamamoto et al. (1991) have also attributed the generation of continuous-type echoes in the E region at mid-latitudes to GDI according to spectral characteristics. However, it should be pointed out that the electron density gradient of E_s is not perpendicular to the magnetic field, which is inclined at mid-latitudes. According to the GDI mechanism, when E_s is driven by an electric field or neutral wind, instability will be triggered on one side of E_s , while the other side will remain stable. Recent studies proposed that instabilities on one side of E_s will be inhibited by the mapping of a polarized electric field excited on the other side along magnetic field lines (Woodman et al., 1991).

E region QP echoes at mid-latitudes were first thought to be asso-

Figure 3. E_s occurrence rate (%) at four ionosondes located at Mohe (122.37°E, 53.50°N), Beijing (116.25°E, 40.25°N), Wuhan (114.61°E, 30.53°N), and Hainan (109.13°E, 19.52°N) during 2011–2015. Distributions are binned functions of local time and f_oE_s, which is categorized by Kp index (after Zhou C et al., 2017).

ciated with atmospheric gravity waves (Woodman et al., 1991 and Yamamoto et al., 1991, 1992). Gravity waves close to the Brunt-Väisälä frequency could excite QP echoes with a period of several minutes by modulating E_s. However, small-scale irregular structures (3 m characteristic scale) cannot be generated by simple gravity wave modulation. Woodman et al. (1991) suggested that the horizontal structure of E_s is gradually distorted into a jagged structure through gravity wave modulation, which results in the formation of an electron density gradient perpendicular to the magnetic field. Then GDI could be excited and generate a small-scale irregular structure; subsequent observations have confirmed this theory (Yamamoto et al., 1994). However, gravity wave theory cannot explain larger Doppler velocity in radar maps. In order to solve this problem, Tsunoda et al. (1994) further improved and developed the gravity wave mechanism, and proposed that the polarization process will be excited in the gravity wave modu-

lation process. The larger polarized electric field will drive the increased Doppler velocity in QP echoes.

According to gravity wave theory, there are very high requirements for gravity wave amplitude and wave number matching conditions, but there is not much observational evidence to show that suitable gravity wave structures could be frequently observed in the E layer at mid-latitudes. SEEK and SEEK2 experiments observed that the neutral wind also plays a key role in the excitation process of instability (Kagan and Kelley, 1998). Zonal wind shear can not only form E_s, but triggers GDI on both sides of E_s eventually leading to the excitation of instability and the generation of small-scale irregular structures. Larsen et al. (1998) and Larsen (2000) reported that the zonal wind shear strength at the E layer can be greater than 40 m·s⁻¹·km⁻¹, which is sufficient to induce Kelvin-Helmholtz instability (KHI) in the neutral atmosphere.

Figure 4. The time variations of f_oE_s spectrum observed by six ionosondes located at Mohe (122.37°E, 53.50°N), Wakkanai (141.75°E, 45.16°N), Kokubunji (139.49°E, 35.71°N), Yamagawa (130.62°E, 31.20°N), Wuhan (114.61°E, 30.53°N), and Okinawa (128.15°E, 26.68°N) during two SSW events. The warming onset is indicated by the red vertical dashed line, while the red horizontal dashed line denotes the 14.5-day period (after Tang Q et al., 2020).

Driven by KHI, E_s structure is destabilized by collision between plasma and neutral particles, and then evolves into the K-H structure, resulting in QP echoes in radar maps. Correlative studies have been performed by Sripathi et al. (2003) and Patra et al. (2009). A 2-D numerical model of the evolution of E_s in KHI modulation is shown in Figure 9 (Bernhardt, 2002). However, KHI theory cannot explain the extended nighttime E region QP echoes (2–8 hour) at mid-latitudes (Venkateswara Rao et al., 2008).

Recent models have indicated that neutral wind shear could excite a relatively large polarized electric field in E_s (Cosgrove and Tsunoda, 2001, 2002a). A new instability mechanism for generating E region irregularity, called E_s -layer instability, is proposed by Cosgrove and Tsunoda (2002b). Under the action of zonal wind shear, the nighttime E_s layer at mid-latitudes becomes unstable due to the modulation of the integral Hall conductivity along the magnetic field and height direction, resulting in a horizontal plane wave-like distribution. Earlier model calculations of E_s -layer instability growth rate predicted that E region irregularities align in a northwest-southeast (NW-SE) direction in the northern hemisphere, consistent with observations of the structure of E region irregularities. Cosgrove and Tsunoda (2003) first presented the 2-D evolution of E_s modulated by E_s -layer instability, and reported that the spatial scale of irregularities ranges from 100 m to 100 km (Figure 10). In addition, a polarized electric field larger than 10 mV/m could be excited in a Hall current-driven polarization process (Tsunoda et al., 2004).

3. F Region Irregularity

Plasma instability phenomena occurring in the ionospheric F region at mid-latitudes are usually grouped under the generic name SF based on earlier observations using ionosondes. Recent research found that some of the more violent disturbances that include TID and small-scale structure were also observed in the ionospheric F region. A close relationship among different scales of ionospheric irregularity structures was revealed through joint observations (Saito et al., 2002; Otsuka et al., 2009; Liu Y et al., 2019). Recent research on F region irregularities in the mid-latitudes is reviewed below.

3.1 Observations

A general nighttime ionospheric irregularity phenomenon, an extension of F layer trace with height and frequency in ionograms, has been identified as SF since it was first observed by Booker and Wells (1938). SF traces in ionograms are generally divided into four types: frequency SF (FSF), range spread F (RSF), mix spread F (MSF), and strong spread F (SSF) (Shi JK et al., 2011). Long-term observations have suggested that SF varies by latitude, longitude, local time, season, solar activity, and geomagnetic activity (Abdu et al., 1981, 1985; Dabas et al., 2007; Li GZ et al., 2010; Wang GJ et al., 2010; Wang N, 2018).

MSTID is a typical ionospheric wave-like electron density perturbation structure in the F layer at mid-latitudes, with a horizontal

Figure 5. Power spectra of neutral wind observed using meteor radar located at Mohe (122.37°E, 53.50°N), Beijing (116.25°E, 40.25°N), Wuhan (114.61°E, 30.53°N), and Sanya (109.60°E, 18.30°N) during two SSW events (2011–2012 top panels, and 2012–2013 bottom panels). The warming onset is indicated by the red vertical dashed line. The 14.5-day period is marked with a red horizontal dashed line. The left column is meridional wind, and the right column is zonal wind (after Tang Q et al., 2020).

wavelength of about several hundred kilometers, a horizontal phase velocity of 50–230 m/s, and a period of 20–70 min (Shiokawa et al., 2003; Kotake et al., 2007; Ding F et al., 2011; Chen GY et al., 2019). The characteristics of MSTID have been revealed us-

ing all-sky optical images and GNSS-TEC maps. According to long-term observations, MSTID can be categorized into daytime and nighttime forms (Figure 11). Daytime MSTID mainly occurs between 12–16 LT in winter hemispheres, and propagates to-

Figure 6. Example of E region FAIs observed by Wuhan VHF radar in Wuhan (30.54°N, 114.37°E) on June 17, 2016. (a) SNR, (b) Doppler Velocity, and (c) Doppler Width (after Zhou C et al., 2018a).

ward the equator. Conversely, nighttime MSTID mainly appears between 20–04 LT and reaches maximum in summer hemispheres. Most nighttime MSTIDs are aligned northwest–southeast (northeast–southwest) with preferential southwestward (northwestward) propagation in the northern (southern) hemisphere (Ding F et al., 2011; Martinis et al., 2019).

VHF radar data have revealed that there are FAI structures in the nighttime ionospheric F layer. Recent observations showed a close relationship between FAI, SF, and MSTID in the mid-latitude nighttime ionosphere (Fukao et al., 1988, 1991; Bowman, 1990; Swartz et al., 2000; Saito et al., 2002; Otsuka et al., 2009; Sun LC et al., 2015; Liu Y et al., 2019). The results of a joint observational experiment carried out in Wuhan are shown in Figure 12 (Liu Y et al.,

Figure 7. Correlation distribution between E region FAI echo power and E_s density gradient ($f_oE_s - f_bE_s$) (after Zhou C et al., 2018a).

2019). Nighttime F region FAI, SF, and MSTID could coexist and have some similar spatial and temporal distribution characteristics (Figure 12).

3.2 Formation Mechanisms

F region irregularities at mid-latitudes are thought to originate through gravity wave theory (Hines, 1960; Hooke, 1968; Vadas,

Figure 8. Doppler spectrum of E region FAI echoes at Wuhan during 2015–2016. Distributions are binned as a function of local time and height from 90 km to 160 km in steps of 5 km (after Zhou C et al., 2018a).

2007). Bowman (1990, 1991) proposed that the generation of SF in this region is generally caused by the breaking of atmospheric gravity waves. Xiao et al. (2012) studied the ionospheric response to typhoons and concluded that SF could be triggered by upward propagating gravity waves during the typhoon period. Through the collision between ions and neutral particles, ionospheric plasma density disturbances could be driven by the upward propagation of gravity waves from the lower atmosphere. Further observational evidence supporting this theory is presented by Ding F et al. (2011) and Kotake et al. (2006). The consistency of co-occurring daytime MSTID and atmospheric gravity waves is presented in Figure 13. The dominantly equatorward propaga-

Figure 9. The simulated results of QP density irregularity structure in the E region produced by KHI (after Bernhardt, 2002).

Figure 10. Simulation results of the evolution of E region irregularity modulated by E_s -layer instability (after Cosgrove and Tsunoda, 2003).

Figure 11. Local time-month distribution of MSTID occurrence rate in Hong Kong during the period of 2014–2017 (after Chen GY et al., 2019).

tion of daytime MSTID could also be explained by gravity wave theory due to the fact that the oscillation of neutral particles is larger along the magnetic field direction for equatorward propagating atmospheric gravity waves than for those propagating in other directions, which are more likely to cause significant plasma density disturbances (Otsuka et al., 2013). However, the morphological characteristics of nighttime MSTID obviously do not conform to the modulation results of gravity waves, which suggests that other plasma instabilities may generate MSTID in the nighttime ionospheric F layer.

An electrodynamic instability in the F region, as proposed by Perkins (1973), is a possible mechanism for exciting nighttime MSTID and SF. Due to the modulation of the integral Hall conductivity along the magnetic field and height direction, nighttime plasma density structure becomes unstable in the F layer. When the wave vector direction of plasma density disturbance lies between the effective background electric field and geomagnetic east direction, a Perkins instability would be triggered, generating an ionospheric irregularity with a horizontal structure along the northw-

Figure 12. Simultaneous observations of different scale nighttime F region irregularities at mid-latitudes based on joint observational experiments carried out in Wuhan (after Liu Y et al., 2019).

est–southeast direction in the northern hemisphere, explaining the observed horizontal structure of nighttime MSTID. The seasonal variations in nighttime MSTID could also be understood in terms of the linear growth rate of the Perkins instability (Hamza, 1999; Kelley, 2009). The statistical analysis of SF occurrence

presented in Candido et al. (2011) and Paul et al. (2019) demonstrates that MSTID related to the Perkins instability plays an important role in SF development. Jiang CH et al. (2019) reconstructed the ionograms during TID using ray tracing and further verified that ionospheric density wave structure leads to SF. Yokoy-

Figure 13. Local time variation of MSTID occurrence rate under different atmospheric activity conditions (after Chen GY et al., 2019).

ama et al. (2008) first produced a 3-D numerical model of the Perkins instability and simulated the evolution of the nighttime F layer plasma density irregularity. However, the Perkins instability cannot fully explain all the observed characteristics of nighttime MSTID at mid-latitudes. The excessively small linear growth rate (on the order of $\sim 10^{-4} \text{ s}^{-1}$) is completely inconsistent with the observations to date (Kelley and Fukao, 1991; Garcia et al., 2000). On the other hand, according to the Perkins instability mechanism, the wave structure excited by the instability propagates in the same direction as the background $\mathbf{E} \times \mathbf{B}$ drift at night, generally moving southeast in the northern hemisphere, contrary to the observations of nighttime MSTID (Makela and Otsuka, 2011). This suggests that there are other possible mechanisms generating nighttime MSTID at mid-latitudes in conjunction with the Perkins instability.

At present, the Perkins instability mechanism explains the formation of large-scale ($> 50 \text{ km}$) nighttime ionospheric F region irregularities at mid-latitudes, but there are still some problems in understanding the formation of small-scale structures. Basu et al. (1981) proposed that GDI might be the main reason for the formation of small-scale irregularities in the nighttime ionosphere at mid-latitudes. Based on MU radar observations, F region FAI echoes mainly appeared in the area where the plasma density gradient moves upward at the bottom of the F layer (Kelley and Fukao, 1991; Saito et al., 2002; Otsuka et al., 2009). Figure 14 illustrates the evolution of different scales of irregularity structures in the nighttime ionosphere. When there is the right direction of electric field or neutral wind in the nighttime ionospheric F region, the Perkins instability is triggered and excites MSTID. Under these conditions, MSTID in the electron density depletion areas could be further modulated by $\mathbf{E} \times \mathbf{B}$ drift through secondary plasma instability (GDI) and excited kilometer scale structure, which eventually evolves into meter scale irregularity through a nonlinear cascade process. Theoretical analysis shows that the duration of meter-scale FAI is related to $(k^2 D_p)^{-1}$, where k is the wave vector size of small-scale plasma waves and D_p is the electron diffusion coefficient in the direction perpendicular to the magnetic field (Mathews et al., 2001). The calculated time scale is 0.02–0.2 s; thus, it is impossible for meter scale structure to exist

alone for such a short duration, which is also confirmed by the joint observational experiment (Figure 12).

4. Ionospheric Electrodynamic Coupling

As mentioned in Sections 2 and 3, the formation of ionospheric irregularities in the E and F regions is closely related to electrodynamic processes, and the polarized electric field plays a significant role in the development of plasma instabilities (Tsunoda et al., 1994; Haldoupis et al., 1996; Yokoyama et al., 2003, 2004a, b). At mid-latitudes, a polarized electric field can map to different ionospheric regions, leading to ionospheric electrodynamics in the E and F regions that can influence each other along the magnetic field lines (Figure 15). Thus, ionospheric E-F coupling may affect the formation of plasma density irregularities in the E and F regions (Zhou C et al., 2018b; Liu Y et al., 2019, 2020). Moreover, the effect of ionospheric inter-hemispheric coupling on the formation of F region irregularities is evident in magnetic conjugate observations (Otsuka et al., 2004; Martinis et al., 2010; Duly et al., 2014; Burke et al., 2016; Valladares and Sheehan, 2016). Next, we review recent research on ionospheric electrodynamic coupling in the mid-latitude region.

4.1 Ionospheric E-F Coupling

Ionospheric E-F coupling was first reported by Bowman (1960). Subsequently, a large number of joint observational experiments have confirmed that ionospheric E-F coupling phenomena frequently occur in the nighttime ionosphere at mid-latitudes (Haldoupis et al., 2003; Otsuka et al., 2007; Hysell et al., 2018; Zhou C et al., 2018b; Liu Y et al., 2019, 2020). Figure 16 shows an example of ionospheric E-F coupling using VHF radar, ionosonde, and all-sky optical images around Wuhan. The observed E_s , SF, E region FAI echoes, and MSTIDs occurred simultaneously in the nighttime ionosphere (Zhou C et al., 2018b). As shown in Figure 17, the COSMIC data first elucidated the coexistence of nighttime plasma density disturbance structures in both E and F regions in both hemispheres (Liu Y et al., 2020). The statistical characteristics of ionospheric E-F coupling phenomena were also described by Zhou C et al. (2018b) and Liu Y et al. (2020).

Figure 14. Schematic diagram showing the evolution process for different scale ionospheric irregularity structures (after Liu Y et al., 2019).

Figure 15. Schematic diagram showing the nighttime ionospheric E-F coupling process (after Liu Y et al., 2019).

As mentioned above, researchers have noticed the close relationship between F region plasma density disturbance and E_s structure since 1960. Theoretical modelling by Farley (1959, 1960) has indicated that an electric field with a certain spatial scale can map between E and F regions due to its high conductivity along magnetic field lines. Based on the research of Haldoupis et al. (1996), Tsunoda and Cosgrove (2001) further explained the mechanism generating polarized electric fields in the nighttime ionosphere at mid-latitudes, and proposed that there might be a positive feedback loop between E_s structures and F region irregularities. Cosgrove and Tsunoda (2004) first derived the linear growth rate of the coupling mechanism including E_s -layer instability and Perkins instability, suggesting that the growth rate of coupling was much larger than that of a single instability, conducive to the formation and development of ionospheric irregularities. Figure 18 shows the first 3-D numerical model for studying the ionospheric E-F coupling process, illustrating the importance of polarized electric

fields in plasma irregularities (Yokoyama et al., 2009).

It is clear that the existence of E_s is not always accompanied by ionospheric E-F coupling (Liu Y et al., 2020). Farley (1959, 1960) proposed that the mapping efficiency of an electric field depends on its spatial scale and ionospheric background conductivity. Electric fields with a spatial scale larger than 10 km can map without loss from the E layer to the F layer. In addition, the mapping efficiency of electric fields is also affected by the integrated Pedersen conductivity of the F region ($\sum_p^F$), and is negatively correlated with the order of $\sum_p^F$. Recent numerical simulations have successfully reproduced the effect of ionospheric conductivity on the occurrence of ionospheric irregularities (Yokoyama et al., 2004b; Cosgrove, 2007).

4.2 Ionospheric Inter-Hemispheric Coupling

The coexistence of plasma density disturbances has been ob-

Figure 16. An example of joint observational experiments carried out around Wuhan by using ionosonde, VHF radar, and all-sky optical images (after Zhou C et al., 2018b).

served in the nighttime ionospheric F layer in magnetic conjugate regions (Figure 19). Otsuka et al. (2004) first observed the simultaneous occurrence of nighttime MSTID structures by using two all-sky optical imagers in the magnetic conjugate areas. Their results suggested that the local polarized electric field would be excited during MSTID and map to the conjugate ionosphere along magnetic field lines, which could induce plasma density disturbances through electrodynamic processes (Figure 20). Nighttime F region electric field fluctuations have been observed at magnetic conjugate points using incoherent scatter radar and the DE2 satellite (Burnside et al., 1983). The statistical characteristics of magnet-

ic conjugate observations of nighttime F region irregularities were first reported by Liu Y et al. (2020) using COSMIC satellites, which further demonstrated the importance of ionospheric inter-hemispheric coupling in generating ionospheric irregularities. Corresponding numerical simulation models have also been developed to study the ionospheric inter-hemispheric coupling process (Duly et al., 2014; Yokoyama, 2014).

5. Summary

In this paper, we reported on recent developments in the understanding of ionospheric irregularities in the E and F regions at

Figure 17. Examples of ionospheric irregularities in the E and F regions observed by COSMIC satellites at (a) 23:07 LT on 02 July 2011 in the northern hemisphere, and (b) at 21:40 LT on 11 January 2014 in the southern hemisphere (after Liu Y et al., 2020).

mid-latitudes and discussed the importance of ionospheric electrodynamic processes in generating ionospheric irregularities. The main points are summarized as follows:

5.1 E Region Irregularity

E_s and E region FAI are predominantly observed in the E region at mid-latitudes. The typical morphological features of E_s and E region FAI are:

- 1) E_s occurrence reaches a maximum ~ 14 LT and a secondary maximum at ~ 20 LT, while E region FAI mainly occurs after sunset.
- 2) Atmospheric wave components can be clearly observed in E_s layer distribution.
- 3) Spectrum features of E region FAI echoes show that type-2 irregularities are dominant in the nighttime ionosphere.
- 4) A strong correlation exists between E_s layer and E region FAI

structures. The seasonal variations of E_s and E region FAI occurrence have a similar distribution, with a maximum in summer (winter) in the northern (southern) hemisphere.

5) The effect of magnetic activity on E region irregularity occurrence is complex and varies with latitude, longitude, and local time.

6) The factors generating E region irregularity are neutral wind and electrical fields. Zonal wind shear can drive metallic ions to converge and excite large polarized electric fields at night, resulting in plasma instabilities and the generation of E region irregularities at mid-latitudes.

5.2 F Region Irregularity

Plasma density irregularities are frequently observed in the nighttime F region. A close relationship across different scales of ionospheric F region irregularities has been demonstrated in joint ob-

Figure 18. Simulation results of the coupled Perkins instability and E_s -layer instability in the nighttime ionosphere at mid-latitudes (after Yokoyama et al., 2009).

Figure 19. Examples of nighttime ionospheric F region irregularities in conjugate hemispheres observed by COSMIC satellites (a) on 31 January 2007 and (b) on 14 June 2007 (after Liu Y et al., 2020).

servational experiments. Plasma instabilities play a significant role in the development and evolution of ionospheric irregularity structures from large scale to small scale. The polarized electric field excited by the Perkins instability during nighttime MSTID can further modulate plasma density disturbances through $\mathbf{E} \times \mathbf{B}$ drift where the electron density gradient is upward and drives GDI to form small scale structures which finally evolve into smaller scale structures through nonlinear cascade processes.

5.3 Ionospheric Electrodynamical Coupling

Due to the significant dip angle and equipotentiality of magnetic field lines in the mid-latitude ionosphere, electric fields can map to different ionospheric regions and affect electrodynamic processes for generating plasma density irregularities. The importance of ionospheric E-F coupling and inter-hemispheric coupling

is revealed using various joint observational experiments. In addition, the spatial scale of electric fields and ionospheric background parameters, such as conductivity (the integrated Hall conductivity of E_s layer ($\sum_H^{E_s}$) and $\sum_p^f$), play important roles in the mapping efficiency of electrodynamic coupling.

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Figure 20. Simultaneous observations of nighttime MSTID structures using two all-sky optical imagers for magnetic conjugate areas at mid-latitudes (after Otsuka et al., 2004).

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