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Seasonal dependence of MSTIDs obtained from 630.0 nm airglow imaging at Arecibo

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[1] All-sky imaging data of 630.0 nm airglow emissions are used to study the seasonal and solar activity dependence of medium-scale traveling ionospheric disturbances (MSTIDs) over Arecibo, Puerto Rico (18.3° N, 66.7° W, 28° N mag lat). MSTIDs are typical F-region signatures at midlatitudes, yet limited statistical results in the American sector hindered the progress in our understanding of these dynamical structures. This study compiles data from 2002 to 2007 and shows for the first time that optically-determined MSTIDs at Arecibo present a semiannual pattern with peak occurrence at both solstices. In the Japanese longitude sector, a similar pattern has been found, but one with a main peak during local summer. This paper explains the high occurrence rate during local winter at Arecibo via E-layer/F-layer coupling and inter-hemispheric coupling, thus accounting for a consistent morphology between the two longitude sectors.

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1. Introduction

[2] Arecibo is a site usually located poleward of the northern crest of the Equatorial Ionization Anomaly and thus susceptible to processes driven by both low and mid-latitude electrodynamics. Among the thermospheric structures observed there are those known as medium-scale traveling ionospheric disturbances (MSTIDs) [*Bowman*, 1990]. Other processes closely linked to equatorial dynamics, like the equatorial midnight temperature maximum [*Colerico et al.*, 2006] and equatorial spread F [*Martinis and Mendillo*, 2007] occur less frequently in this region.

[3] The first optical observations of dark/bright bands, now related to MSTIDs, were carried out at Arecibo [*Mendillo et al.*, 1997], and they were assumed to be the airglow signatures of thermospheric gravity waves. Subsequent studies showed that plasma instabilities were embedded inside the bands [*Miller et al.*, 1997]. *Shiokawa et al.* [2003] used optical data to show that MSTIDs in the Japanese sector exhibited a semi-annual occurrence pattern, with a main peak in local summer (June–July) and a secondary peak during local winter (December–January). In addition, observations using all-sky imagers in the Japanese-Australian longitudinal sector showed that MSTIDs occurred simultaneously at conjugate locations [*Otsuka et al.*, 2004], providing further evidence of these features being more than a passive response of the ionosphere to atmospheric gravity waves in a single hemisphere.

[4] The initial explanations to characterize the properties of MSTIDs were related to Perkins instability theory [*Behnke*, 1979]. Recently, models that add coupling of E-region structures with the F-region are bringing more light upon the physical mechanisms driving these complex midlatitudes structures [*Cosgrove and Tsunoda*, 2004; *Cosgrove*, 2007; *Yokoyama et al.*, 2009].

[5] There are limited statistical studies of ground based optically-determined MSTIDs in the American sector. *Garcia et al.* [2000] used data from Arecibo from January 1997 to March 1998 and showed a peak of MSTIDs activity during December–January months. That study, with no data available during June–July months, contributed to the general notion that in the northern hemisphere in the American sector, MSTIDs peak occurrence was during the winter solstice months (December–January). A statistical study in the southern hemisphere was carried out by *Candido et al.* [2008] who found a peak occurrence rate of band-like structures during June–July months (local winter). That study did not include data from the December–January period due to bad weather conditions. Thus, prior optical studies of MSTIDs in both American sector hemispheres suffered from a lack of data during local summer solstice.

[6] To explain the local winter peak at Arecibo, *Shiokawa et al.* [2003] noted that at this location (~20° of latitude lower than the Japanese observations) the strong winter mesospheric wind would not be efficient in suppressing the upward propagation of atmospheric gravity waves, which can produce MSTIDs. As a consequence, a peak of activity can appear during December–January solstice, while in the Japanese sector only a secondary peak is observed. Thus, *Kotake et al.* [2006], referencing the results from *Garcia et al.* [2000] and *Shiokawa et al.* [2003], suggested that the seasonal variation of MSTIDs occurrence should be different between the American and Japanese longitudinal sectors. A study by *Otsuka et al.* [2008] also tried to explain this apparent difference by noting that the local winter peak at Arecibo was caused by the influence of a strong sporadic E-layer plasma density in the opposite hemisphere, i.e., a conjugate instigation effect from the summer hemisphere.

[7] Studies using *in-situ* satellite data have shown that the occurrence rate of MSTIDs tends to peak during solstice periods [*Park et al.*, 2010], i.e., a semiannual pattern is observed at different longitudinal sectors. *Kotake et al.* [2006] used worldwide GPS data to study the peak amplitude of daytime and nighttime total electron content (TEC) variations (not the occurrence rate) during the years 1998, 2000 and 2001. The GPS receivers in the Arecibo longitudinal sector (at latitudes between 38° and 45°) showed nighttime peak

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amplitudes of ΔTEC of ~1–2% higher during both solstices in 1998 and 2000. Only the year 2001 showed a clear June–July peak (similar to *Shiokawa et al.*'s [2003] result). A subsequent study by *Kotake et al*. [2007] used 350 GPS receivers in Southern California and found a distinctive peak of occurrence (~40%) during the June–July solstice, i.e., an annual pattern. Thus the non-optical studies show mixed results regarding the seasonal dependence of MSTIDs activity. It is worth mentioning that the different studies presented above were sampling different height ranges and, as a result, one could expect differences in the results. Ground-based 630.0 nm imaging provides information of processes occurring at ~250 km. Thus the MSTIDs detected by Arecibo's imager are from a much lower height than the ones detected using line-of-sight GPS-TEC and *in-situ* satellite data (from ~400 to 840 km).

[8] The lack of reliable annual statistics of ground based-determined MSTIDs in the American sector, and in particular at Arecibo, led to the notion of an apparent difference when compared to the Japanese/Australian sector. This paper fills the existing statistical gap and investigates the seasonal dependence of MSTIDs at Arecibo during a five-year period, from 2002 to 2007 that includes data during all seasons.

2. Data

[9] The Boston University all-sky imaging system [*Baumgardner et al.*, 1993] at Arecibo has been operational since May 2002 (quick-look images and movies can be found at www.buimaging.com). The wavelength of interest in this study is the OI red line at 630.0 nm. This emission peaks at ~250–300 km and is produced by a two-step process that begins with neutral-ion charge exchange reactions involving primarily O_2 and O^+, followed by the dissociative recombination of O_2^+ and e^-. The resulting atomic oxygen de-excites by emitting a photon at 630.0 nm. Weak 630.0 nm airglow represents a region with low electron density or an ionosphere with peak electron density at very high altitude where the O_2 abundance is low. Thus band-like structures (or MSTIDs) observed at midlatitudes (whether by radar or optical signatures), have long been associated with undulations in the electron density profile [*Behnke*, 1979; *Mendillo et al.*, 1997].

[10] The data set analyzed consists of 942 nights of observations. Data were taken during the 5-year descending phase of solar cycle 23 (<F10.7> varied from ~150 to ~80). We counted a "night" when three or more hours of observations were available. The criterion to define a "clear night" was that weather conditions allowed background airglow (with or without any structuring) to be seen for three or more hours. Thus, our statistical study is based on the total number of clear nights observed and the total number of nights showing structures.

[11] Figure 1 shows different examples of the band-like patterns observed at Arecibo. These structures do not always present wave-like characteristics. Sometimes single dark structures are observed, a result indicating upward motions of the F-layer. A variety of patterns that included non-wave like structures was also observed by *Garcia et al.*'s [2000] and *Shiokawa et al.*'s [2003] studies. Common properties in such studies in the northern hemisphere are the direction of propagation (southwestward) and the scale sizes (~100–500 km). All of the cases analyzed here exhibited a distinct southwestward motion.

[12] Figure 2 shows the seasonal variation of MSTIDs at Arecibo, a pattern with peaks observed at both solstices. Also shown are the number of clear nights (gray bars) and the number of events observed (black bars). Their ratio represents the occurrence rate per month (line plot). This pattern emerges from a good statistical distribution of clear nights for each 4-month season (179 for December solstice, 172 for equinoxes, and 195 for June solstice). This seasonal behavior is in agreement with observations in the Japanese longitude sector [*Shiokawa et al.*, 2003] showing a semi-annual pattern with minimum activity during equinoxes.

[13] We investigated the relationship between solar activity and the occurrence rate of MSTIDs. Figure 3 shows this relation during the solstice months of peak activity (May to Aug and Nov to Feb). The circles represent monthly averages and the X's are the weighted means (i.e., means weighted by the number of contributing clear nights) after binning the data points into 30 units of F10.7. Uncertainty bars represent the error-of-the-mean for the calculated averaged points. Figure 3 suggests that an anti-correlation may be present, with higher occurrence rate during low solar activity period.

3. Discussion

[14] The main findings of this study are two-fold: (1) the higher occurrence rate of MSTIDs during both solstices (Figure 2), and (2) an inverse occurrence rate with solar activity conditions during those solstice periods (Figure 3). The semiannual pattern observed at Arecibo, with high occurrence rate during both solstices is similar to the one in the Japanese sector, although there is no indication of primary and secondary peaks as found in that sector. To understand this result we need to consider (1) the coupling between local E- and F-region layers and (2) inter-hemispheric flux-tube coupling that takes into account parameters and processes occurring in the geomagnetically conjugate ionosphere.

3.1. E and F-Region Coupling

[15] Studies of correlation between E and F region processes at mid-latitudes have recently provided new insights into ionospheric coupling at midlatitudes. It is known that typical E-region processes (such as Sporadic-E (Es) layers, quasi-periodic echoes (QP), unstable Es, and Es layer instability) tend to peak during local summer months [*Haldoupis et al.*, 2003; *Arras et al.*, 2008]. Observational and modeling studies have shown that the coupling between these E-region processes and the F-region, via the mapping along magnetic field lines of E-region polarization electric fields, plays a key role in the formation of MSTIDs [*Saito et al.*, 2007; *Otsuka et al.*, 2008; *Cosgrove*, 2007; *Yokoyama et al.*, 2009]. Thus local summer months should present high occurrence rate of MSTIDs, as *Shiokawa et al.* [2003] showed in the Japanese sector, and *Kotake et al.* [2007] showed in the Western American sector. But, *Park et al.* [2010] showed that the occurrence rate of midlatitude ion density undulations from *in-situ* satellite data peaks not only during local summer months but also during local winter months. They used satellite data from CHAMP (at ~400 km), KOMPSAT-1 (at ~680 km) and DMSP-15 (at ~840 km) to study occurrence rates of MSTIDs. For low solar activity (2006 and 2007), only

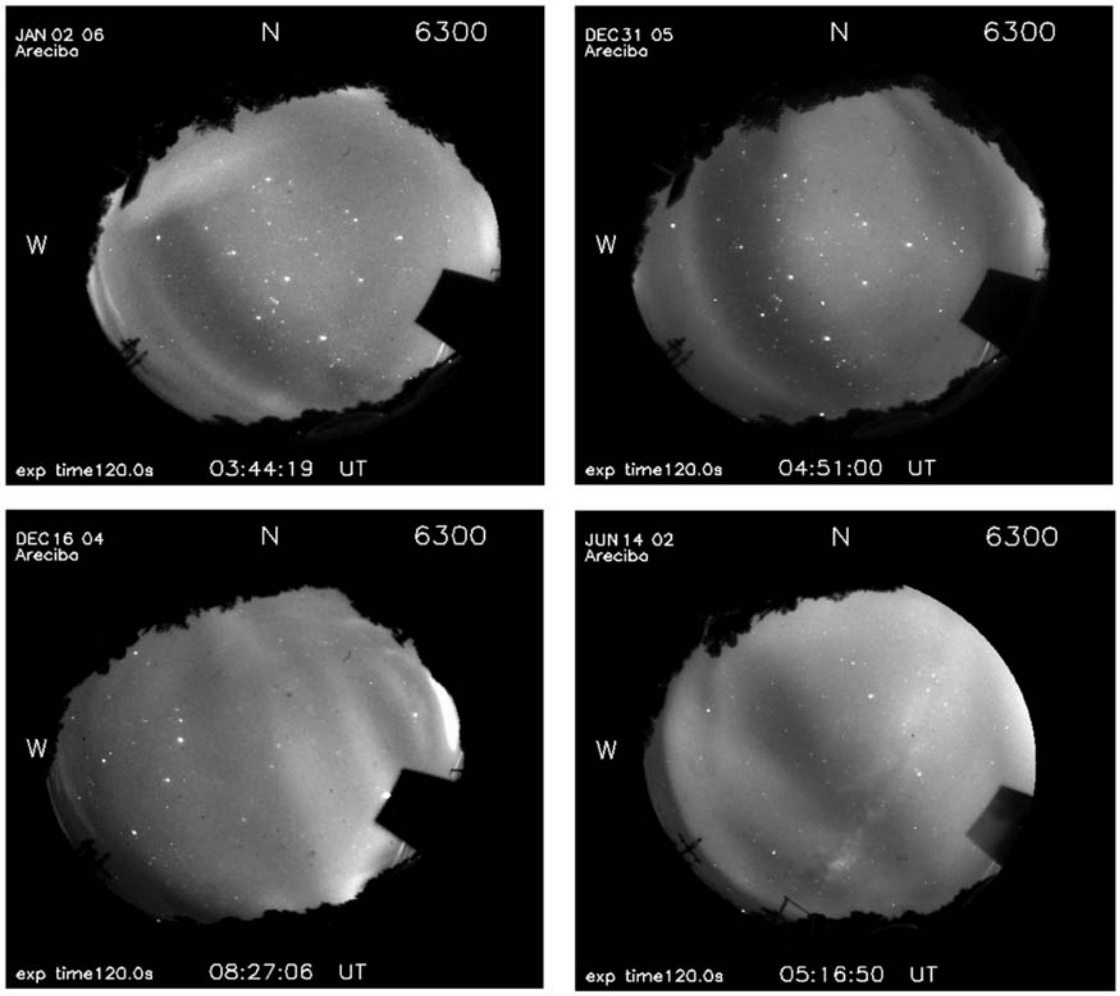

Figure 1. Band-like structures observed with the Boston University all-sky imager at the Arecibo Observatory on four different nights spanning the years 2002–2006. North is at the top and west to the left of each image. The structures for each night are aligned from North–West to South–East and propagate southwestward.

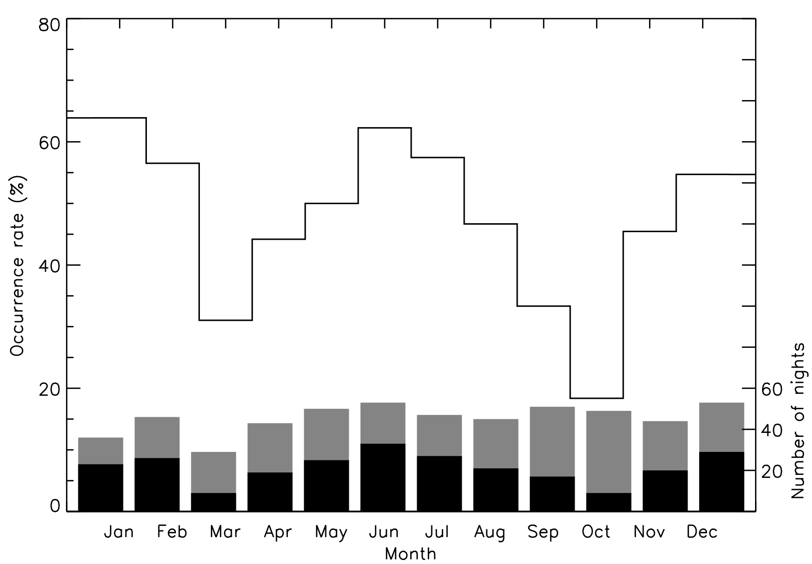

Figure 2. (top) Seasonal dependence of the occurrence rate of midlatitude structures showing band-like behavior (left axis). (bottom) Gray bars indicate the number of clear nights (179 for the Nov–Feb solstice period, 172 for Mar–Apr and Sep–Oct equinoxes, and 195 for the May–Aug solstice period); black bars show the number of MSTIDs observed in a given month (right axis). The occurrence rate per month is the ratio between the dark and gray bars.

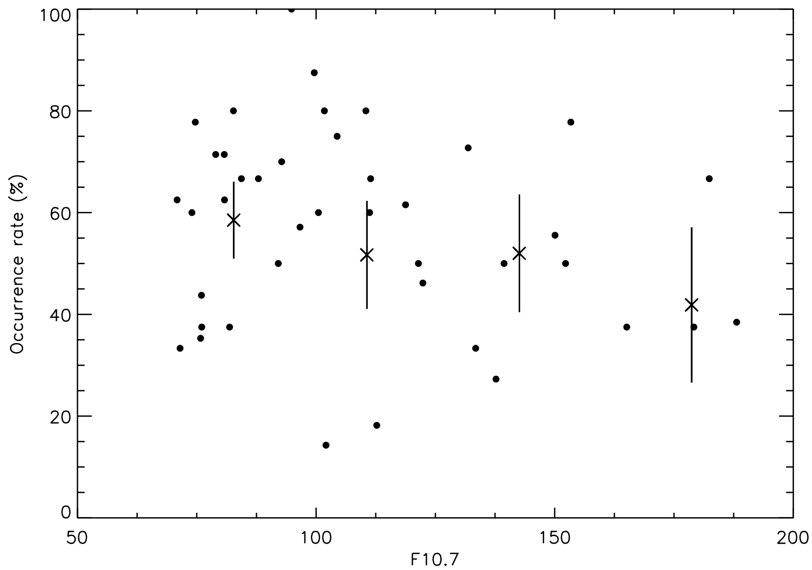

Figure 3. Solar activity dependence of the occurrence rate of MSTIDs. Circles are monthly averages for the solstice periods May–Aug and Nov–Feb (44 points). Data binned every 30 units of F10.7 are shown as X's symbols. Uncertainty bars are also shown.

CHAMP data were used and the results indicated broad longitudinal peak occurrence rates during local summer solstices and a relatively high occurrence rate during December–January solstice only in the northern hemisphere in the American sector (see Figure 5 of *Park et al.* [2010]). A local E and F- region coupling mechanism is not enough to explain these observational results.

3.2. Inter-hemispheric Coupling

[16] The key to understanding a high occurrence rate at both solstices in the northern hemisphere in the American sector (as shown by the all-sky imager and CHAMP satellite) is related to the inter-hemispheric flux-tube coupling with the conjugate ionosphere. If the electric field generated in the conjugate hemisphere (experiencing local summer) maps along the field line to affect local ionospheric conditions at Arecibo (in winter) then ion density undulations, i.e., MSTIDs, could be generated. As shown by *Saito et al.* [1995] and *Otsuka et al.* [2004], MSTIDs and associated electric field fluctuations tend to occur simultaneously in both hemispheres. Having established a mechanism by which MSTIDs can occur during both solstices we need to explain the high occurrence rate during winter solstice at Arecibo (when compared to the Japanese sector).

[17] Different studies have shown that Es plasma density structures in the American southern hemisphere are high during December–January solstice. For example, *Wu et al.* [2005] showed that summertime Es activity in South America between 30° S and 60° S is higher than the pattern observed in Australia. This implies that the MSTIDs occurrence rate should also be higher in South America. Inter-hemispheric coupling [*Otsuka et al.*, 2004] then leads to a peak of MSTIDs activity in the northern hemisphere during local winter that is higher than the one observed in the Japanese sector [*Shiokawa et al.*, 2003]. However, *Arras et al.* [2008] showed similar levels of activity between the American and Australian southern hemispheres during December–January solstice. Thus another contributing mechanism is needed to explain our results. This could be related to the geometry of the geomagnetic field in the American sector that has an important role in interhemispheric mapping [*Martinis and Mendillo*, 2007]. The geomagnetic field morphology shows the strongest departures from a dipolar field and, as a consequence, the intensity of the magnetic field in the conjugate hemisphere is not the same. For structures larger than 10's km, the electric potential is mapped without attenuation along the field lines [*Saito et al.*, 2005], and thus an electric field generated in the southern hemisphere will be stronger in the northern hemisphere and thus could be more effective for the generation of MSTIDs.

3.3. MSTIDs Occurrence Rate and Solar Activity

[18] Figure 3 shows an apparent anti-correlation between MSTIDs and solar activity. Similarly, although with a reduced number of cases (28 nights over a 7-year period), the statistical study by *Candido et al.* [2008] showed that most MSTIDs occurred during low solar activity, some during moderate conditions and none during high solar activity. Our study includes data mostly from low solar activity conditions ($\langle F10.7 \rangle \sim 80$) and few data from moderate conditions ($\langle F10.7 \rangle \sim 150$). A potential explanation for the anti-correlation between MSTIDs and solar activity can be found in the growth rate of the Perkins instability being inversely proportional to the neutral density. Thus, a contracted thermosphere during solar minimum years results in nighttime F-layer electron densities experiencing fewer collisions than during solar maximum years. This anti-correlation is also found with the occurrence rate of mid-latitude spread-F [*Bowman*, 1992]. Although there is no conclusive evidence pointing to a one-to-one correlation between mid-latitude spread F and MSTIDs [*Shiokawa et al.*, 2003], both processes share many common characteristics. These results imply an important role played

by the neutral atmosphere in the generation and propagation of the ionospheric structures and instabilities at mid-latitudes.

4. Summary

[19] The most common 630.0 nm optical signatures found at Arecibo, midlatitude structures showing band-like features, a.k.a. MSTIDs, present a semiannual variation, with occurrence peaks during solstice months. This pattern is similar to that observed in the Japanese sector, although the peaks found here indicate similar levels of activity during both solstices. The observed semi-annual patterns support the suggestion of a key role played by E-region structures and inter-hemispheric coupling in the generation mechanism of MSTIDs. The maximum during December-January solstice might be a consequence of unique characteristics in the American sector: (1) Es layer activity in the southern hemisphere can be significantly higher than that found in other longitude sectors, and (2) the behavior of the Earth's magnetic field morphology strongly departs from a dipolar field, affecting the mapping of electric fields from one hemisphere to the other. Previously, limited datasets in the American sector were insufficient to show MSTIDs occurrence patterns in a statistically robust way, and alternative mechanisms had been proposed to explain the apparent longitudinal difference in seasonal patterns between the American and the Japanese sectors. Thus the results presented here provide observational support for a strong E-layer influence upon the generation mechanisms for MSTIDs by inter-hemispheric electrodynamics.

[20] We also showed that as solar activity decreased the occurrence rate of MSTIDS was somewhat higher. This result is in agreement with interpretations that emphasize the key role played by the neutral atmosphere and its plasma coupling within the midlatitude ionosphere.

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References

Arras, C., J. Wickert, G. Beyerle, S. Heise, T. Schmidt, and C. Jacobi (2008), A global climatology of ionospheric irregularities derived from GPS radio occultation, *Geophys. Res. Lett.*, *35*, L14809, doi:10.1029/2008GL034158.

Baumgardner, J., B. Flynn, and M. Mendillo (1993), Monochromatic imaging instrumentation for applications in aeronomy of the Earth and planets, *Opt. Eng.*, *32*, 3028–3032, doi:10.1117/12.149194.

Behnke, R. A. (1979), F layer height bands in the nocturnal ionosphere over Arecibo, *J. Geophys. Res.*, *84*, 974–978, doi:10.1029/JA084iA03p00974.

Bowman, G. G. (1990), A review of some recent work on mid-latitude spread-F occurrence as detected by ionosondes, *J. Geomagn. Geoelectr.*, *42*, 109–138.

Bowman, G. G. (1992), Upper-atmosphere neutral-particle density variations compared with spread-F occurrence rates at locations around the world, *Ann. Geophys.*, *10*, 676–682.

Candido, C., A. Pimenta, J. A. Bittencourt, and F. Becker-Guedes (2008), Statistical analysis of the occurrence of medium-scale traveling ionospheric disturbances over Brazilian low latitudes using OI 630.0 nm emission all-sky images, *Geophys. Res. Lett.*, *35*, L17105, doi:10.1029/2008GL035043.

Colerico, M., M. Mendillo, C. Fesen, and J. Meriwether (2006), Comparative investigations into the equatorial electrodynamics and low to mid latitude coupling of the thermosphere-ionosphere system in the American sector, *Ann. Geophys.*, *24*, 503–513.

Cosgrove, R. B. (2007), Generation of mesoscale F layer structure and electric fields by the combined Perkins and Es layer instabilities, in simulations, *Ann. Geophys.*, *25*, 1579–1601.

Cosgrove, R. B., and R. T. Tsunoda (2004), Instability of the *E-F* coupled nighttime midlatitude ionosphere, *J. Geophys. Res.*, *109*, A04305, doi:10.1029/2003JA010243.

Garcia, F., M. Kelley, J. Makela, and C.-S. Huang (2000), Airglow observations of mesoscale low-velocity traveling ionospheric disturbances at midlatitudes, *J. Geophys. Res.*, *105*(A8), 18,407–18,415, doi:10.1029/1999JA000305.

Haldoupis, C., M. Kelley, G. Hussey, and S. Shalimov (2003), Role of unstable sporadic-E layers in the generation of midlatitude spread F, *J. Geophys. Res.*, *108*(A12), 1446, doi:10.1029/2003JA009956.

Kotake, N., Y. Otsuka, T. Tsugawa, T. Ogawa, and A. Saito (2006), Climatological study of GPS total electron content variations caused by medium-scale traveling ionospheric disturbances, *J. Geophys. Res.*, *111*, A04306, doi:10.1029/2005JA011418.

Kotake, N., Y. Otsuka, T. Ogawa, T. Tsugawa, and A. Saito (2007), Statistical study of medium-scale traveling ionospheric disturbances observed with the GPS networks in southern California, *Earth Planets Space*, *59*, 95–102.

Martinis, C., and M. Mendillo (2007), Equatorial spread F-related airglow depletions at Arecibo and conjugate observations, *J. Geophys. Res.*, *112*, A10310, doi:10.1029/2007JA012403.

Mendillo, M., J. Baumgardner, D. Nottingham, J. Aarons, B. Reinisch, J. Scali, and M. Kelley (1997), Investigations of thermospheric-ionospheric dynamics with 6300 Å images from the Arecibo Observatory, *J. Geophys. Res.*, *102*(A4), 7331–7343, doi:10.1029/96JA02786.

Miller, C., W. Swartz, M. Kelley, M. Mendillo, D. Nottingham, J. Scali, and B. Reinisch (1997), Electrodynamics of midlatitude spread F: 1. Observations of unstable, gravity wave-induced ionospheric electric fields at tropical latitudes, *J. Geophys. Res.*, *102*(A6), 11,521–11,532, doi:10.1029/96JA03839.

Otsuka, Y., K. Shiokawa, T. Ogawa, and P. Wilkinson (2004), Geomagnetic conjugate observations of medium-scale traveling ionospheric disturbances at midlatitude using all-sky airglow imagers, *Geophys. Res. Lett.*, *31*, L15803, doi:10.1029/2004GL020262.

Otsuka, Y., T. Tani, T. Tsugawa, T. Ogawa, and A. Saito (2008), Statistical study of relationship between medium-scale traveling ionospheric disturbance and sporadic E layer activities in summer night over Japan, *J. Atmos. Sol. Terr. Phys.*, *70*, 2196–2202, doi:10.1016/j.jastp.2008.07.008.

Park, J., H. Luhr, K. Min, and J. Lee (2010), Plasma density undulations in the nighttime mid-latitude F-region as observed by CHAMP, KOMPSAT-1 M, and DMSP F15, *J. Atmos. Sol. Terr. Phys.*, *72*, 183–192, doi:10.1016/j.jastp.2009.11.007.

Saito, A., T. Iyemori, M. Sugiura, N. C. Maynard, T. L. Aggson, L. H. Brace, M. Takeda, and M. Yamamoto (1995), Conjugate occurrence of the electric field fluctuations in the nighttime midlatitude ionosphere, *J. Geophys. Res.*, *100*(A11), 21,439–21,451, doi:10.1029/95JA01505.

Saito, S., M. Yamamoto, H. Hashiguchi, A. Maegawa, and A. Saito (2007), Observational evidence of coupling between quasi-periodic echoes and medium scale traveling ionospheric disturbances, *Ann. Geophys.*, *25*, 2185–2194.

Shiokawa, K., C. Ihara, Y. Otsuka, and T. Ogawa (2003), Statistical study of nighttime medium-scale traveling ionospheric disturbances using midlatitude airglow images, *J. Geophys. Res.*, *108*(A1), 1052, doi:10.1029/2002JA009491.

Wu, D. L., C. O. Ao, G. A. Hajj, M. de la Torre Juarez, and A. J. Mannucci (2005), Sporadic E morphology from GPS-CHAMP radio occultation, *J. Geophys. Res.*, *110*, A01306, doi:10.1029/2004JA010701.

Yokoyama, T., D. L. Hysell, Y. Otsuka, and M. Yamamoto (2009), Three-dimensional simulation of the coupled Perkins and Es -layer instabilities in the nighttime midlatitude ionosphere, *J. Geophys. Res.*, *114*, A03308, doi:10.1029/2008JA013789.

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