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Northward-propagating nighttime medium-scale traveling ionospheric disturbances observed with SuperDARN Hokkaido HF radar and GEONET

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Abstract We report on the characteristics of nighttime medium-scale traveling ionospheric disturbances (MSTIDs) propagating northward observed with the SuperDARN Hokkaido HF radar, which has a field of view to the north of Japan, and occasionally with the GNSS Earth Observation NETwork (GEONET), which provides total electron content (TEC) data over Japan. From statistical analysis of MSTIDs observed with the Hokkaido radar during nighttime (1700–0700 LT) from January 2007 to July 2009, we find that these MSTIDs traveling northward, although rare in comparison with those traveling southwestward, have a relatively high occurrence rate after sunset and around midnight in May and August, which is partly consistent with the occurrence rate of MSTIDs over Japan observed with GEONET in 2002, when the MSTID event database is available. We also use the data from simultaneous observation of nightside MSTIDs by the Hokkaido radar and GEONET to find that when the HF radar observed northward-propagating MSTIDs, GEONET did not always observe such MSTIDs with the same propagation direction. Judging from this result and considering the HF radar field of view located to the north of the GEONET coverage area, we speculate that some physical parameters of the ionosphere/thermosphere over Japan differ from those to the north of Japan, which may result in the inconsistency of MSTID propagation direction. The present results provide new knowledge of MSTIDs propagating northward using the Hokkaido radar, whose field of view was not covered by GEONET.

Keywords **SuperDARN Hokkaido radar, GEONET, MSTID**

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1 Introduction

Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) have wavelike structures in the ionosphere, with horizontal wavelengths of 100–1 000 km and periods less than 60 min[1]. MSTIDs were generally considered an ionospheric manifestation of the passage of atmospheric gravity waves (AGWs) that propagate either equatorward from the auroral ionosphere or upward from the lower atmosphere. With the advent of two-dimensional imaging of the ionospheric plasma by means of multiple GPS satellites, all-sky airglow imagers and others, nighttime MSTID characteristics have been investigated. Two-dimensional distributions of MSTIDs propagating southwestward with phase fronts aligned northwest-southeast were identified for the first time by all-sky imagers and a dense GPS network in Japan, referred to as the Global Navigation Satellite System (GNSS) Earth Observation NETwork (GEONET)[2-3]. Statistical studies showed that most nighttime MSTIDs propagate southwestward[4-6]. This preferred propagation direction cannot be explained in terms of the classical theory of gravity waves[7-8]. Electrodynamical force related to perturbations in electric field, which may be caused by plasma instabilities, is another possible mechanism for generating MSTIDs[9-12]. However, fields of view of GEONET and all-sky imagers in Japan are limited to the region over Japan. Given this limitation, it was not possible

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to study MSTIDs to the north of the country.

The Super Dual Auroral Radar Network (SuperDARN)[13] is a useful tool for studying MSTIDs. SuperDARN HF radar measures backscatter echoes from decameter-scale irregularities in the E and F regions of the ionosphere, as well as echoes backscattered from the ground or sea[14]. Three parameters can be derived from the Doppler spectra-echo power (signal-to-noise ratio), Doppler velocity (corresponding to line-of-sight plasma velocity or proportional to vertical motion of the ionosphere), and Doppler spectral width. Bristow et al.[15] and Stocker et al.[16] used the SuperDARN radar data to discuss characteristics of TIDs and their relation to atmospheric gravity waves. He et al.[17] used the SuperDARN Tasman International Geospace Environment Radar (TIGER) to examine statistical characteristics of MSTIDs observed in the Southern Hemisphere. Ogawa et al.[18] used the SuperDARN Hokkaido radar with the GEONET and an all-sky imager to examine MSTID characteristics at high to low latitudes simultaneously. These studies focused on MSTIDs propagating mainly equatorward.

In this study, we statistically study MSTID occurrence rate observed by the SuperDARN Hokkaido radar, as a function of propagation direction, season and local time. In addition, we perform multiple-event analysis of simultaneous MSTID observation by the Hokkaido radar and GEONET. Based on these analyses, we show detailed MSTID propagation characteristics observed by the Hokkaido radar and GEONET as a function of latitude, which provides some clues to propagation mechanisms of MSTIDs.

2 Instrumentation

Figure 1 is a combined plot of the SuperDARN Hokkaido radar field of view (FOV) and GEONET receiver distribution. The radar has 16 beam directions (Beams 0 to 15). Beam 0 is closest to geographic north, and Beam 15 covers the eastern edge of the radar FOV. The maximum number of range gates shown in the figure is 75.

The SuperDARN Hokkaido radar (geographic coordinates 43.5°N, 143.6°E) is one of the mid-latitude SuperDARN radars. It is located at the lowest geomagnetic latitude (AACGM coordinates 36.5°, −145.3°), and began operation in November 2006. The radar has multiple beam directions and can observe the two-dimensional distribution of F and E region ionospheric echoes, plus ground/sea scatter echoes that are often modulated by MSTIDs[19]. The radar has 75 to 110 range gates and 16 beam directions. Here, we use data from radar frequencies between 10 and 12 MHz. Temporal resolution of the two-dimensional data is 1 to 2 min, depending on integration time of each beam direction (3, 4 or 8 s) and operational radar mode.

GEONET is operated by the Geospatial Information Authority of Japan (GSI). The system commenced operation in 1994. At present, about 1 230 GPS receivers are operational. These receivers can be used for monitoring changes in ionospheric Total Electron Content (TEC), and are separated by approximately 25 km. We use the GPS TEC data with temporal resolution 30 s. The GPS TEC data have spatial resolution 0.15°×0.15° in latitude and longitude. Using this dense GPS network, we can obtain spatially and temporally high-resolution TEC maps over Japan for 1997 onward[10]. We use the perturbation components of TEC derived by detrending slant TEC data with one-hour running average for each line-of-sight between receiver and satellite, which were converted to vertical TEC data. Details of the TEC data derivation and two-dimensional mapping technique are given by Tsugawa et al.[6] and references therein.

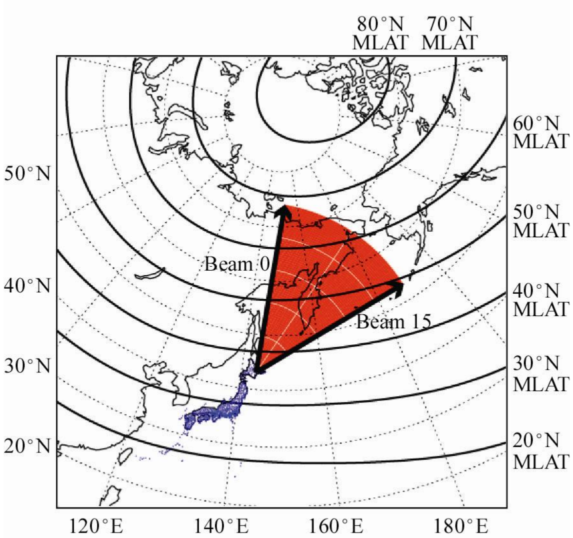

Figure 1 Combined plot of SuperDARN Hokkaido HF radar FOV and GEONET receiver distribution.

Using the SuperDARN Hokkaido HF radar and GEONET, we can simultaneously observe ionospheric disturbances from high to low latitudes over a 4 000 km horizontal distance[18].

3 Observation

We introduce a typical example of a nighttime MSTID observed by the SuperDARN Hokkaido radar. Figure 2 shows Range-Time-Parameter plots of echo data observed by Hokkaido radar Beam 5 on 10 May 2008, as a function of local time and geographic latitude. From the top, each panel shows echo power, Doppler velocity and Doppler spectral width. From the echo power plot, we see an MSTID propagating northward from 9–15 UT (18–24 LT). This is confirmed by other beam data. The echoes were identified as ground scatter echo, since absolute values of the Doppler velocity and Doppler spectral width are very small (less than 50 m·s^{-1} and 20 m·s^{-1}, respectively)[18].

3.1 Statistical studies of MSTIDs observed by SuperDARN Hokkaido radar

We used two-dimensional maps and Range-Time-Intensity

(RTI) plots of the echo power data for statistical analysis. We characterized the propagation direction of MSTIDs for each event by eight azimuth bins (0°–45°, 45°–90°… and 315°–360°), where 0° is toward geographic north. We assumed this propagation direction to be perpendicular to the wave surface seen in the two-dimensional data. In addition, we also examined the period and amplitude of echo power oscillation associated with MSTIDs from the RTI-plot. We defined MSTIDs as echo power perturbations satisfying the following criteria: (1) The peak echo power perturbation exceeds 10 dB. (2) The period of the echo power oscillation is less than 60 min. (3) The echo power perturbation has more than two wavefronts, which propagate to either direction on the two-dimensional maps. We used both ionospheric and ground scatter echo data for identification of radar MSTIDs. Although simultaneous use of both kinds of echoes for obtaining the MSTID propagation characteristics could lead to incorrect estimation of propagation velocity, this does not affect identification of propagation direction, which is the main topic here.

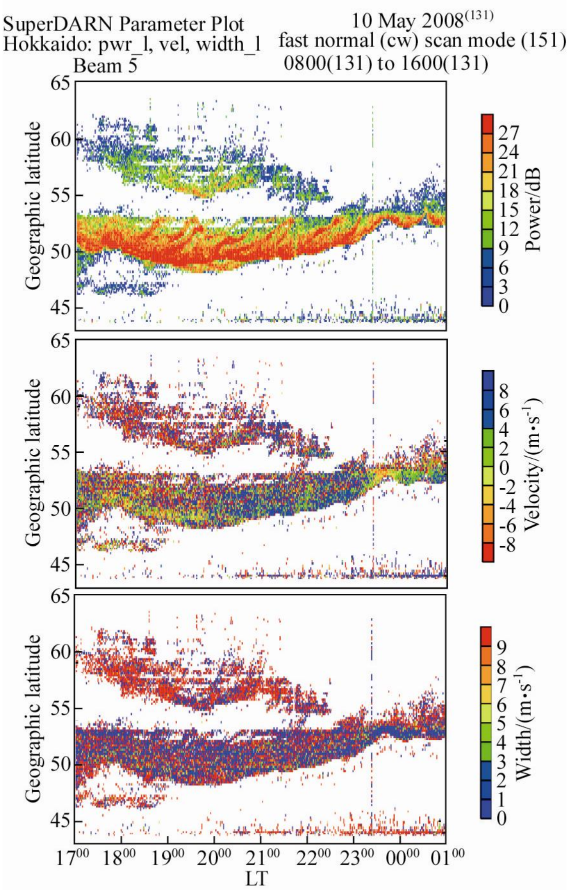

Figure 2 Range-Time-Parameter plot of radar echo power (in dB), Doppler velocity, and Doppler spectral width observed on Beam 5 on 5 May 2008. LT at radar location=UT+9 h.

Figure 3 shows local time variation of MSTID propagation direction observed by the Hokkaido radar and identified using the above criteria, as a function of propagation direction and local time between 8 and 22 UT (17–07 LT) from January 2007 to July 2009. 0 degrees (180° or –180°) indicates MSTIDs propagating northward (southward) and 90 degrees (–90°) signifies eastward (westward). The radar observed 74 cases of nighttime MSTIDs propagating northward and 201 cases of nighttime MSTIDs propagating southward between January 2007 and July 2009. The figure shows that the radar observed numerous nighttime MSTIDs propagating northward or northeastward, although the majority propagated southward or southwestward. Nighttime MSTIDs observed over Japan mainly propagate southwestward (e.g., Shiokawa et al.[5]), whereas detailed studies of such MSTIDs propagating northward have not yet been done. Using the Hokkaido radar data, we discuss the statistical characteristics of nighttime MSTIDs north of Japan, which have not been investigated.

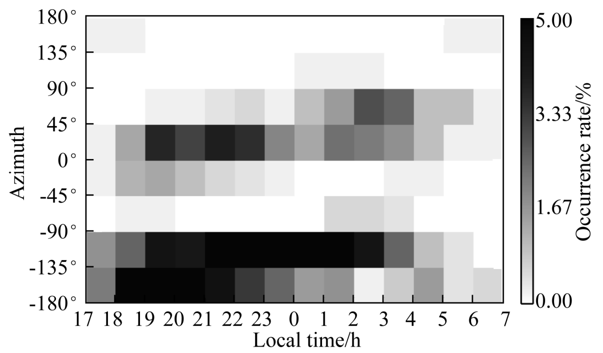

Figure 3 Distribution of nighttime MSTIDs observed by SuperDARN Hokkaido radar as a function of local time and propagation direction during January 2007 to July 2009. 0° corresponds to northward propagation, and 180° to southward.

Figure 4a shows seasonal and local time variation of the occurrence rate of MSTIDs with a northward propagation component (−90° to 90°). This was obtained by dividing the total number of hours of events by those of radar operation, as a function of local time and month during January 2007 to July 2009. Figure 4b shows the occurrence rate of northward-propagating MSTIDs observed by GEONET with the same format, but throughout 2002. The method of Otsuka et al.[20] was used to identify the MSTIDs and calculate their occurrence rate. Figure 4a indicates that nighttime MSTIDs propagating northward observed by the Hokkaido radar had relatively high occurrence rates after sunset in May and August, and before midnight (21 to 23 LT) in May. From Figure 4b, the statistical analysis of MSTIDs over Japan using GEONET-TEC data from 2002 also revealed high occurrence rates at sunset in May and August. However, MSTID occurrence rates around midnight in May were lower than those observed by the Hokkaido radar.

It is possible that the SuperDARN Hokkaido radar observed northward-propagating MSTIDs because it observed "back-lobe" echoes of southward-propagating MSTIDs to the south of the radar[21]. To examine whether this is true,

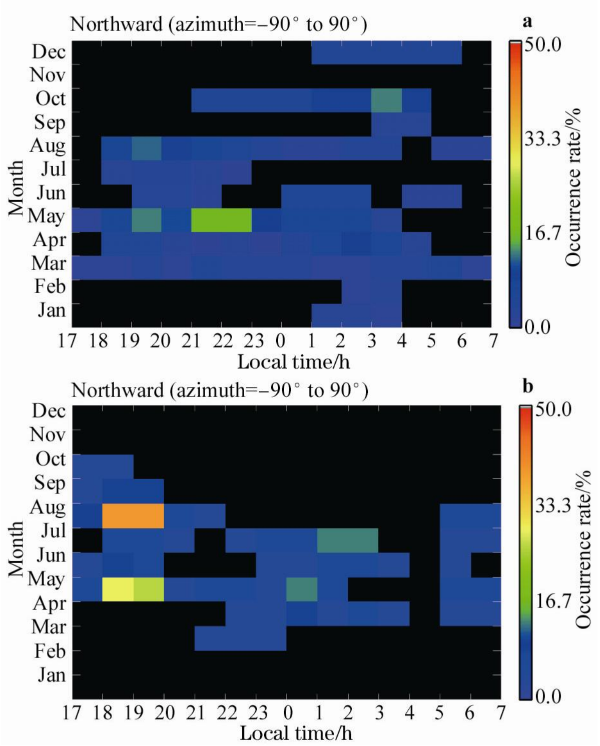

Figure 4 Contour plots for occurrence rate of northward-propagating MSTIDs versus local time for various months, observed by SuperDARN Hokkaido radar during January 2007 to July 2009 (**a**), and GEONET during 2002 (**b**).

we used interferometer (elevation angle) data to examine true beam direction for the observed echoes based on the discussion of Milan et al.[21]. Figure 5 shows the Hokkaido radar elevation angle data every 30 min between 8 and 16 UT (17–01 LT) on 10 May 2008, as a function of beam and range gate numbers. Red (blue) colors show high (low) elevation angles. From these images, we see that disturbances propagating northward were observed by the main lobe, not by the back-lobe, because elevation angle decreases with the range gate number, although aliased between 0 and a certain value, and is independent of beam number (see Figure 4 of Milan et al.[21]). If the radar echoes were observed by the back lobe, a characteristic pattern should be observed in which the contours of constant elevation angle are bent into curves symmetric about the radar bore site. Also, along a given beam, the angle should increase with range, although aliased between 0 and a certain value[21]. Thus, the data indicate that the echoes were observed by the main lobe beam. We also used elevation angle data for 42 other examples of nighttime MSTIDs propagating northward observed by the Hokkaido radar from November 2007 to July 2009, since the radar began acquiring elevation-angle data properly in November 2007. As a result, we confirmed that all 42 examples, like that on 10 May 2008, were observed by the main lobe beam.

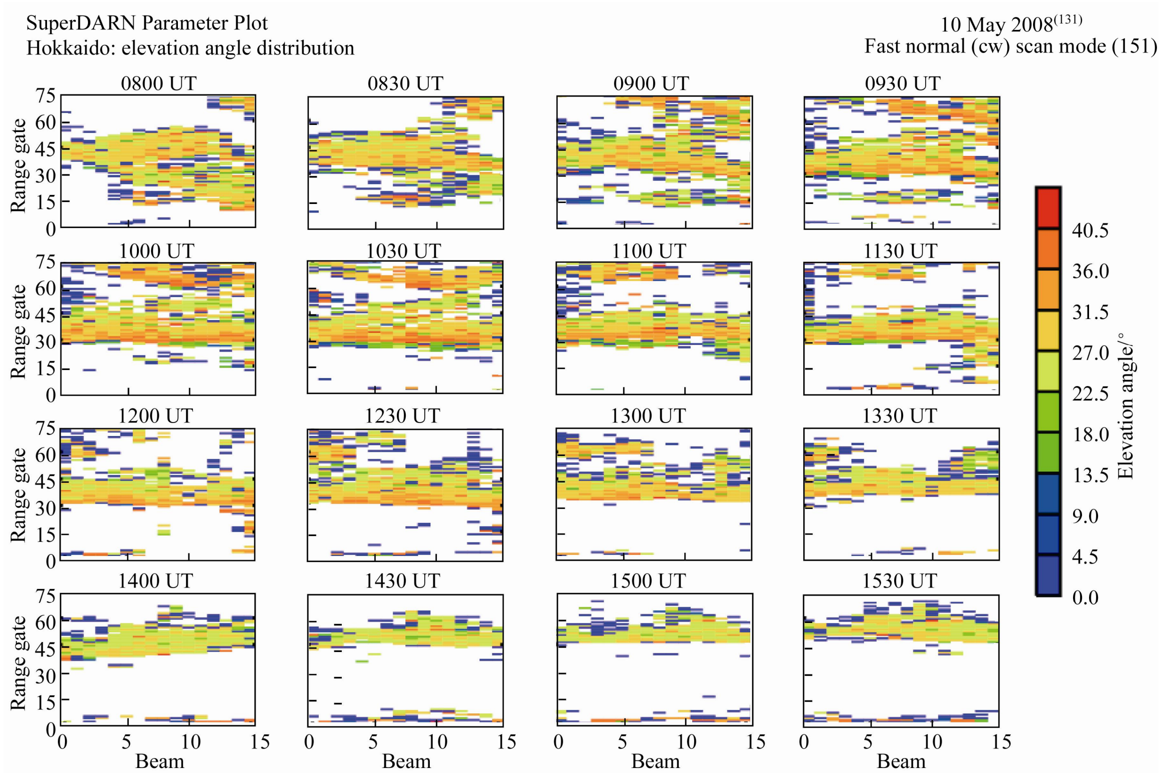

Figure 5 SuperDARN Hokkaido radar elevation angle distribution every 30 min between 8 and 16 UT (17–01 LT) on 10 May 2008, as a function of beam number and range gate number. Red (blue) colors show high (low) elevation angle values.

3.2 Simultaneous observation by the SuperDARN Hokkaido radar and GEONET

From statistical studies of MSTIDs observed by the Hokkaido radar, we found that the statistical characteristics of radar-observed MSTID propagation direction do not necessarily coincide with those observed by the GEONET. Given this, it is believed that the Hokkaido radar observed MSTIDs beyond the FOV of the GEONET, which have different propagation characteristics.

We analyzed data from simultaneous observation of the Hokkaido radar and GEONET to determine whether nighttime MSTIDs propagating northward were observed by both the radar and GEONET simultaneously. We used the 74 cases of MSTIDs propagating northward observed by the Hokkaido radar from January 2007 through July 2009.

Figure 6a shows an example of a combined two-dimensional plot of SuperDARN echo power data and GEONET-TEC data at 0218 LT on 19 May 2008. Perturbation components of the TEC values were derived by subtracting a 60-min running average. To show temporal variation of the disturbances, we sampled data along the arrow shown in the figure, and plotted the temporal variation of the data along this sampling line.

Figure 6b shows GEONET-TEC data and Hokkaido radar Beam 11 echo power data between 23 and 05 LT on 19 May 2008. In the SuperDARN panel, red colors show higher echo power. In the GEONET panel, TEC values were subtracted by a 60-min running average and then averaged along a line orthogonal to the arrow to increase spatial coverage and resolution of the data, as in Hayashi et al.[22] and Ogawa et al.[23]. The red color indicates enhanced TEC.

Between 0150 and 0320 LT, the SuperDARN data showed disturbances propagating northward, with echo power amplitudes larger than 10 dB. GEONET-TEC data showed corresponding signatures (disturbances propagating northward), indicating that MSTIDs propagating northward were observed by the radar and GEONET simultaneously. In contrast, for another period in this figure, i.e., 2300 to 0150 LT, the MSTID propagation direction observed by the Hokkaido radar does not coincide with that observed by the GEONET. That is, the radar observed northward propagating MSTIDs whereas GEONET observed southward propagation.

Table 1 shows the number of MSTID propagation direction events observed by GEONET when the Hokkaido radar observed northward propagation. From this table, we conclude that GEONET mainly observed MSTIDs propagating southwestward when the radar observed northward propagation.

Figure 7 shows the local time distribution of MSTID propagation direction observed by GEONET when the Hokkaido radar observed nighttime MSTIDs propagating northward. This figure reveals that MSTIDs propagating north-northwestward were observed by GEONET at dusk, southwestward propagation before midnight, and northeastward or southwestward propagation was observed at

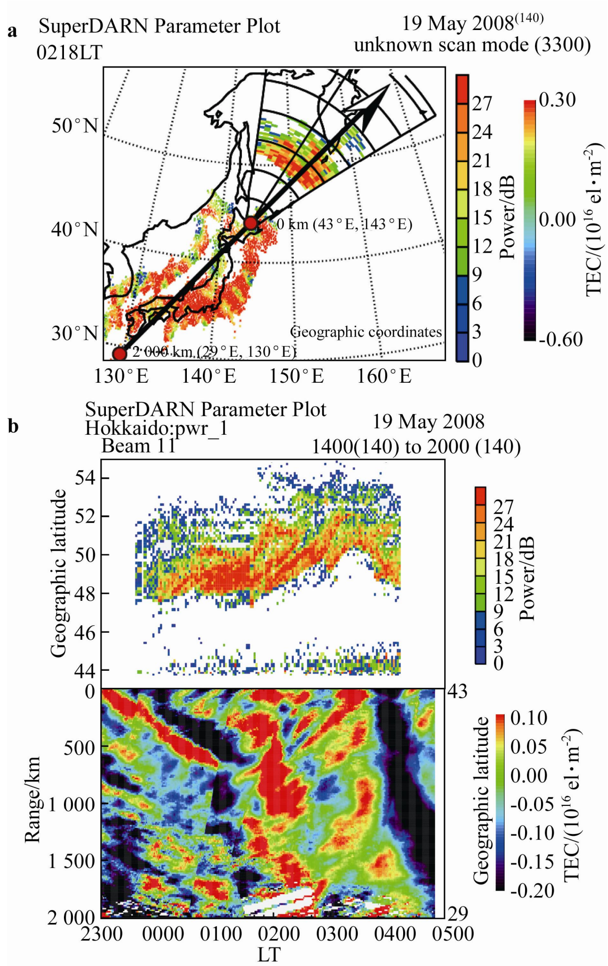

Figure 6 Combined 2-D plot of SuperDARN Hokkaido radar and GEONET data at 0218 LT. Arrow passes through Beam 11 of Hokkaido radar and eastern end of GEONET FOV (**a**). Combined Beam 11 echo-power data from Hokkaido radar and perturbation component of TEC values obtained with GEONET (**b**), sampled along arrow in a and plotted as a function of LT and geographic latitude. In SuperDARN panel, red colors show higher echo power. In GEONET panel, TEC values were subtracted by a 60-min running average and then averaged along a line orthogonal to the arrow. Red color indicates increasing TEC.

Table 1 Number of MSTID propagation direction events observed by GEONET when SuperDARN Hokkaido radar observed northward propagation

Propagation direction of MSTIDs observed by GEONET	Number of events
Southwestward-propagating nighttime MSTIDs	46
North-northwestward-propagating nighttime MSTIDs	5
Northeastward-propagating MSTIDs	8
No MSTIDs	24

midnight. This result implies that MSTID propagation direction observed by the radar does not necessarily coincide with that observed by the GEONET, and it is highly likely that the propagation direction has latitudinal dependence.

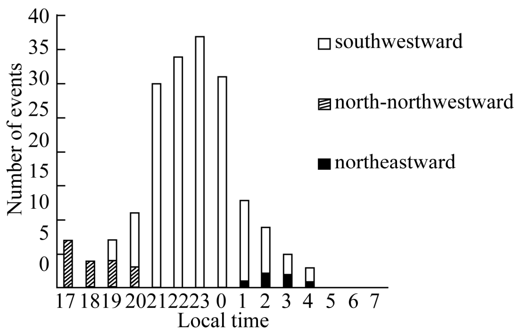

Figure 7 Local time distribution of MSTID propagation direction observed by GEONET when SuperDARN Hokkaido radar observed northward propagation.

4 Discussion

We performed statistical analysis of nighttime MSTIDs observed by the SuperDARN Hokkaido radar during January 2007 to July 2009 and data analysis of simultaneous observation by the Hokkaido radar and GEONET.

He et al.[17] used SuperDARN TIGER radar data to investigate statistical characteristics of MSTID propagation direction in the Southern Hemisphere, as a function of local time and season. Their results show that most observed MSTIDs propagate equatorward (northward in the Southern Hemisphere), although some propagate poleward (southward), which is consistent with the present result. However, they did not mention the poleward-propagating MSTIDs. Therefore, to the best of our knowledge, this is the first report to address characteristics of mid-latitude MSTIDs propagating poleward.

High northward propagating MSTID occurrence rates were observed at summer dusk by both the Hokkaido radar and GEONET. Furthermore, MSTID north-northeastward propagation observed by the radar nearly coincided with that observed by GEONET at dusk. This feature is consistent with that of MSTIDs observed at the sunset terminators by incoherent scatter radar measurements at Millstone Hill (42.6°N, 71.5°W)[24]. Based on characteristics of the observed MSTIDs, the authors suggested that they could be caused by gravity waves generated by the solar terminator. It is possible that the dusk MSTIDs observed by the Hokkaido radar and GEONET are caused by gravity waves generated at the evening terminator. One problem is that in our events, the dusk MSTID wavefronts (east-southeast to west-northwest) are not parallel to the sunset terminator in summer (north-northeast to south-southwest). We need to investigate this in greater detail in future studies.

Next, we discuss the reason why the propagation direction of MSTIDs observed by the Hokkaido radar was different from that observed by GEONET at premidnight and postmidnight. Shiokawa et al.[25] reported northeastward motion of MSTIDs observed at Paratunka in far eastern Russia (52.97°N,158.25°E), using an all-sky 630-nm airglow imager at 2000–2300 LT on 19 August 2007. They referred to the model of Kelley and Makela[11], who tried to explain the systematic southwestward motion of nighttime MSTIDs at mid-latitudes. In addition to a northeastward or southwestward electric field causing growth of MSTIDs, Kelley and Makela[11] introduced the idea of additional northwestward electric field and finite extent of the density-depleted region of the MSTID for causing southwestward $\boldsymbol{E}\times\boldsymbol{B}$ drift, owing to the polarization electric field. Shiokawa et al.[25] pointed out that if wind direction turns from southeastward to northwestward, the directions of the Pedersen current, polarization electric field, and thus MSTID propagation direction would turn to the opposite direction. Shiokawa et al.[25] then indicated that the poleward neutral wind enhancement (or decrease of tidal equatorward wind at nighttime thermosphere), propagating equatorward as a large-scale wave (referred to as a large-scale traveling ionospheric disturbance or LSTID), possibly caused the observed turning of MSTID propagation direction from southwestward to northeastward. A problem with the above scenario is that the turning of the neutral wind establishes a situation in which MSTID density perturbation structures are suppressed (e.g., Kelley and Makela[11]). Furthermore, if the large-scale wave (LSTID) with typical period 1–2 h causes the turning of MSTID propagation direction, that direction should oscillate at the same period. Such a feature is not seen in our data. A more detailed discussion is beyond the scope of this paper, because we do not have F region neutral wind velocity data.

Another possible factor that might affect a difference in MSTID propagation direction is coupling between the E and F regions by electromagnetic force through the magnetic field lines. Periodic structures of the Es layer echo associated with nighttime MSTIDs have been reported[18,26-27]. Saito et al.[28] reported Es layer echoes that changed their direction of echo area when the background neutral wind changed their direction, as observed by the Lower Thermosphere Profiler Radar (LTPR), which was located in Tanegashima, Japan during the Sporadic-E Experiment over Kyushu 2 (SEEK-2) campaign. Yokoyama et al.[29] explained the southwestward preference of MSTID propagation in terms of southward neutral winds in the Es layer, by three-dimensional simulation of E- and F-region instabilities. It is possible that the difference of background neutral wind characteristics of the Es layer north of and over Japan leads to the difference of propagation direction of MSTIDs observed by the Hokkaido radar and GEONET.

5 Conclusion

We performed statistical analysis of nighttime MSTIDs observed by the SuperDARN Hokkaido radar from January 2007 to July 2009. The radar observed multiple cases of nighttime MSTIDs propagating northward, although there were more observations of southwestward propagation, consistent with previous work. Next, we compared seasonal and local time variation of MSTID northward propagation observed by the Hokkaido radar during January 2007 to July 2009 with that observed by GEONET during 2002. As a result, the MSTID occurrence rate observed by GEONET at midnight in May was less than that observed by the radar. Furthermore, we analyzed data from simultaneous observation by the radar and GEONET to determine whether nighttime northward-propagating MSTIDs were observed by both systems simultaneously. We found that MSTID propagation direction observed by the Hokkaido radar does not necessarily coincide with that observed by the GEONET, suggesting that the propagation direction has latitudinal dependence.

To the best of our knowledge, ours is the first statistical study of nighttime northward-propagating MSTIDs observed by the SuperDARN Hokkaido radar and GEONET, whose FOVs cover a wide latitudinal range (about 30°–55° in geographic coordinates). The next step is to compare the radar and GPS receiver data with other observed data such as from an optical imager, and to investigate the statistical relationship between northward-propagating MSTIDs and background neutral wind in the ionosphere. In addition, the use of North American data is promising, not only because of better latitudinal coverage but also simultaneous observation of the same region by GPS receivers and SuperDARN radars.

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References

1 Hunsucker R D. Atmospheric gravity waves generated in the high latitude ionosphere: A review. Rev Geophys, 1982, 20(2): 293-315.

2 Kubota M, Shiokawa K, Ejiri M K, et al. Traveling ionospheric disturbances observed in the OI 630-nm nightglow images over Japan by using a multipoint imager network during the FRONT campaign. Geophys Res Lett, 2000, 27(24): 4037-4040.

3 Saito A, Nishimura M, Yamamoto M, et al. Traveling ionospheric disturbances detected in the FRONT campaign. Geophys Res Lett, 2001, 28(4): 689-692.

4 Garcia F J, Kelley M C, Makela J J, et al. Airglow observations of mesoscale low-velocity traveling ionospheric disturbances at midlatitudes. J Geophys Res, 2000, 105(A8): 18407-18415.

5 Shiokawa K, Ihara C, Otsuka Y, et al. Statistical study of nighttime medium-scale traveling ionospheric disturbances using midlatitude airglow images. J Geophys Res, 2003, 108, A1, 1052, doi: 10.1029/2002JA 009491.

6 Tsugawa T, Kotake N, Otsuka Y, et al. Medium-scale traveling ionospheric disturbances observed by GPS receiver network in Japan: A short review. GPS Solut, 2007, 11(2): 139-144, doi: 10.1007/s10291-006-0045-5.

7 Miller C A, Swartz W E, Kelley M C, et al. Electrodynamics of midlatitude spread F: 1. Observations of unstable, gravity wave-induced ionospheric electric fields at tropical latitudes. J Geophys Res, 1997, 102(A6): 11521-11532.

8 Kelley M C, Miller C A. Electrodynamics of midlatitude spread F3. Electrohydrodynamic waves? A new look at the role of electric fields in thermospheric wave dynamics. J Geophys Res, 1997, 102(A6): 11539-11547.

9 Perkins F. Spread F and ionospheric currents. J Geophys Res, 1973, 78(1): 218-226.

10 Saito A, Miyazaki S, Fukao S. High resolution mapping of TEC perturbations with the GSI GPS network over Japan. Geophys Res Lett, 1998, 25(16): 3079-3082.

11 Kelley M C, Makela J J. Resolution of the discrepancy between experiment and theory of midlatitude F-region structures. Geophys Res Lett, 2001, 28(13): 2589-2592.

12 Shiokawa K, Otsuka Y, Ihara C, et al. Ground and satellite observations of nighttime medium-scale traveling ionospheric disturbance at midlatitude. J Geophys Res, 2003, 108, A4, 1145, doi: 10.1029/2002JA009639.

13 Greenwald R A, Baker K B, Dudeney J R, et al. DARN/SuperDARN: A global view of the dynamics of high-latitude convection. Space Sci Rev, 1995, 71(1-4): 761-796.

14 Greenwald R A, Baker K B, Hutchins R A, et al. An HF phased-array radar for studying small-scale structure in the high-latitude ionosphere. Radio Sci, 1985, 20(1): 63-79.

15 Bristow W A, Greenwald R A, Samson J C. Identification of high-latitude acoustic gravity wave sources using the Goose Bat HF radar. J Geophys Res, 1994, 99(A1): 319-331.

16 Stocker A J, Arnold N F, Jones T B. The synthesis of travelling ionospheric disturbance (TID) signatures in HF radar observations using ray tracing. Ann Geophys, 2000, 18(1): 56-64.

17 He L S, Dyson P L, Parkinson M L, et al. Studies of medium scale travelling ionospheric disturbances using TIGER SuperDARN radar sea echo observations. Ann Geophys, 2004, 22(12): 4077-4088.

18 Ogawa T, Nishitani N, Otsuka Y, et al. Medium-scale traveling ionospheric disturbances observed with the SuperDARN Hokkaido radar, all-sky imager, and GPS network and their relation to concurrent sporadic E irregularities. J Geophys Res, 2009, 114, A03316, doi: 10.1029/2008JA013893.

19 Samson J C, Greenwald R A, Ruohoniemi J M, et al. Goose Bay radar observations of Earth-reflected, atmospheric gravity waves in the high-latitude ionosphere. J Geophys Res, 1990, 95(A6): 7693-7709.

20 Otsuka Y, Onoma F, Shiokawa K, et al. Simultaneous observations of nighttime medium-scale traveling ionospheric disturbances and E region field-aligned irregularities at midlatitude. J Geophys Res, 2007, 112, A06317, doi: 10.1029/2005JA011548.

21 Milan S E, Jones T B, Robinson T R, et al. Interferometric evidence for the observation of ground backscatter originating behind the CUTLASS coherent HF radars. Ann Geophys, 1997, 15(1): 29-39.

22 Hayashi H, Nishitani N, Ogawa T, et al. Large-Scale traveling ionospheric disturbance observed by SuperDARN Hokkaido HF radar and GPS networks on 15 December 2006. J Geophys Res, 2010, 115, A06309, doi: 10.1029/2009JA014297.

23 Ogawa T, Nishitani N, Tsugawa T, et al. Giant ionospheric disturbances observed with the SuperDARN Hokkaido HF radar and GPS network after the 2011 Tohoku earthquake. Earth Planets Space, 2012 (in press).

24 Galushko V G, Paznukhov V V, Yampolski Y M, et al. Incoherent scatter radar observations of AGW/TID events generated by the moving solar terminator. Ann Geophys, 1998, 16(7): 821-827.

25 Shiokawa K, Otsuka Y, Nishitani N, et al. Northeastward motion of nighttime medium-scale traveling ionospheric disturbances at middle latitudes observed by an airglow imager. J Geophys Res, 2008, 113, A12312, doi: 10. 1029/2008JA013417.

26 Otsuka Y, Kotake N, Shiokawa K, et al. Statistical study of medium-scale traveling Ionospheric disturbances observed with a GPS receiver network in Japan. IAGA Special Sopron Book Series, 2011, 2: 291-299, doi: 10.1007/978-94-007-0326-1_21.

27 Saito S, Yamamoto M, Hashiguchi H, et al. Observational evidence of coupling between quasi-periodic echoes and medium scale traveling ionospheric disturbances. Ann Geophys, 2007, 25(10): 2185-2194.

28 Saito S, Yamamoto M, Fukao S, et al. Radar observations of field-aligned plasma irregularities in the SEEK-2 campaign. Ann Geophys, 2005, 23(7): 2307-2318.

29 Yokoyama T, Hysell D L, Otsuka Y, et al. Three-dimensional simulation of the coupled Perkins and Es-layer instabilities in the nighttime midlatitude ionosphere. J Geophys Res, 2009, 114, A3, A03308, doi: 10.1029/2008JA013789.