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Traveling ionospheric disturbances detected in the FRONT campaign

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Abstract. The *F*-region Radio and Optical measurement of Nighttime TID (FRONT) campaign was conducted to clarify the non-classical features of traveling ionospheric disturbances (TIDs) at mid-latitudes in May, 1998 and August, 1999. A cluster of all-sky CCD cameras and a GPS receiver network observed a wide area of the ionosphere over Japan to detect the spatial structure and temporal evolution of TIDs. The propagation direction of the nighttime TID detected during the FRONT campaign periods is restricted to the southwest. The time evolution of their amplitude indicates that the TID structure is intensified as it travels from high-latitudes to low-latitudes. The significant coincidence between the structures of 630 nm band airglow and total electron content indicates that the perturbations take place in the bottomside of the ionospheric *F* region. Coherent echoes from the field-aligned irregularities were observed by the MU radar in the nights when the TID activity was high.

1. Introduction

Traveling ionospheric disturbances (TIDs) have been detected with various observational techniques since the 1940s, and have been attributed to the perturbations of the ionized atmosphere modulated by acoustic gravity waves [*Hines*, 1964] Recent observations, however, have revealed several characteristics of TIDs that cannot be explained by this classical theory in the nighttime mid-latitude region [*Miller et al.*, 1997; *Kelley and Miller* 1997; *Saito et al.*, 1998a]. *Miller et al.* [1997] observed intense electric fields inside of several TIDs indicating that the ionized atmosphere is not merely a passive tracer of the passing atmospheric gravity waves. Rather, plasma plays an active role involving both the electrodynamic force in addition to collisions with the neutral atmosphere. Most of the nighttime TIDs at mid-latitudes have been observed to travel to the southwest direction [*Mendillo et al.*, 1997; *Taylor et al.*, 1998; *Saito et al.*, 1998b; *Garcia et al.*, 2000] This preferred direction is not consistent with the wind-filtering scenario of the classical TID theory [*Jacobson et al*, 1995; *Kelley and Miller,* 1997].

These studies show that it is now possible to record the two dimensional structure of TIDs and distinguish between spatial and temporal variations in detail. Using these novel optical and radio measurement techniques, the FRONT (F-region Radio and Optical measurement of Nighttime TID) campaign was carried out in May, 1998 and August, 1999 to clarify the characteristics of nighttime TIDs at mid-latitudes.

2. Observations

The FRONT campaign was designed to detect nighttime TIDs in a wide area and with multiple instruments in order to clarify the temporal and spatial variations of TIDs as well as the physical mechanism responsible for them. All-sky cameras were installed at five sites in the first campaign period in 1998 (FRONT-1) and six sites in the second campaign (FRONT-2). This cluster of all-sky CCD cameras detected the structure of the 630nm band airglow over Japan [*Kubota et al.*, 2000]. The field-of-view at 250km altitude was about 1.2×10^6 square kilometer for FRONT-1 and 1.7×10^6 square kilometer for FRONT-2. GEONET, a GPS receiver network operated by the Geographical Survey Institute, was used to observe the total electron content (TEC) of the ionosphere over Japan with a 30 second time resolution [*Saito et al.*, 1998b]. In addition to these wide coverage observations, the MU radar was used to observe coherent echoes from *F*-region field-aligned irregularities at 46.5 MHz frequency. The MU radar was also operated in the incoherent scatter mode. The height profile of the ionospheric electron density was derived with about a time resolution of about five minutes. The bottomside of the ionosphere was also measured by the ionosonde network operated by Communication Research Laboratory. The velocity of the neutral wind was measured at two locations by Fabry-Perot interferometers using the 630nm band airglow.

The distribution of the observational instruments is shown in Figure 1. Solid stars indicate the locations of the all-sky cameras in the FRONT-1 campaign. From north to south, they are Moshiri (44.4°N, 142.3°E), Zao (38.1°N, 140.5°E), Kiso (35.8°N, 137.6°E), Shigaraki (34.8°N, 136.1°E) and Bisei (34.7°N, 133.5°E). Open stars indicate additional sites for the FRONT-2 campaign, Rikubetsu (43.5°N, 143.8°E) is in the north, and Yamagawa (31.2°N, 130.6°E) and Okinawa (26.9°N, 128.3°E) in the south. The FRONT-2 campaign was focused on observing the southwest region of Japan to pursue the transit of TID for longer time duration. Thus, the FRONT-1 cameras at Moshiri and Bisei were removed for FRONT-2. The MU radar is located at Shigaraki. Fabry-Perot interferometers were installed at Shigaraki and Zao. The locations of the GEONET GPS receivers are repre-

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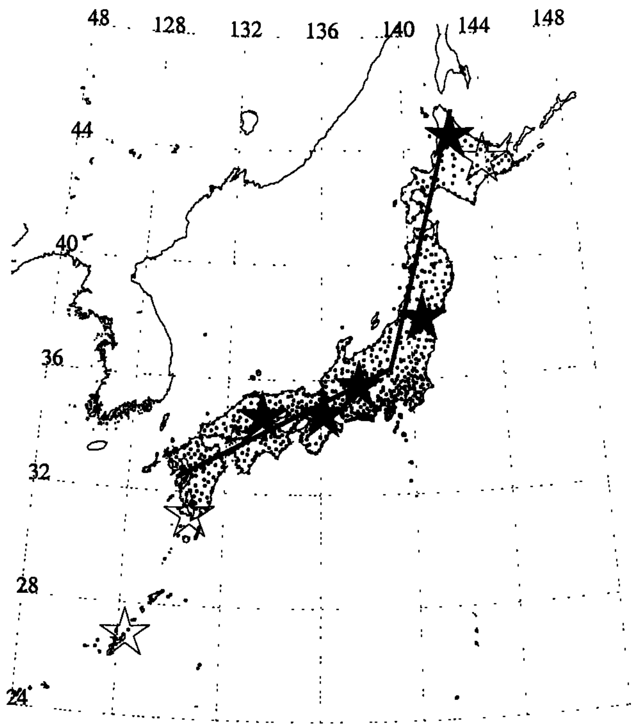

Figure 1. Observational sites of the FRONT campaign. Stars indicate the locations of the all-sky cameras. TEC along the solid line over Japan is displayed in Figure 3.

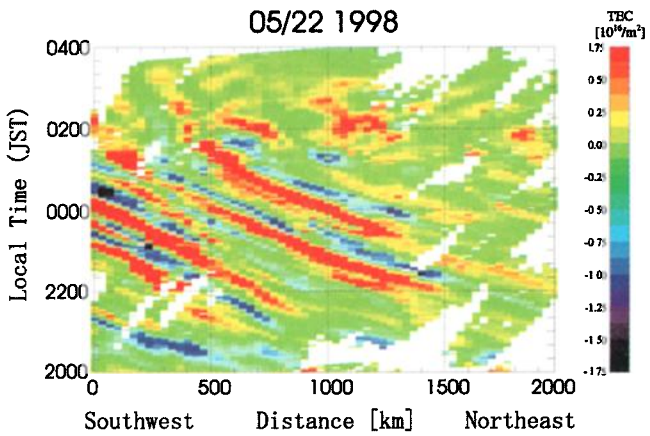

Figure 3. Temporal variation of TEC along the path indicated by the line in Figure 1 from 2000 on May 22 to 0400 of May 23 JST, 1998. Stripes of TEC show the transit of the nighttime TID over Japan.

sented by small solid circles. The number of receivers was about one thousand at the time of the campaign. The FRONT-1 campaign was conducted for nine nights from May 16 to 24, 1998, which was a new moon period. For four out of these nine nights, weather conditions were fine at all five sites [*Kubota et al.,* 2000]. The FRONT-2 campaign was carried out from August 8 to 18 in 1999. Weather conditions during FRONT-2 were not excellent, and there were no nights when all of all-sky camera sites had clear sky.

3. Results

The GEONET system, which does not require clear skies, detected traveling ionospheric disturbances in the nighttime mid-latitude ionosphere in most of the nights during both the FRONT-1 and FRONT-2 campaign periods. To show a typical example, the distribution of the perturbation component of TEC detected by GEONET at 23:20:00 JST on May 22, 1998 is plotted in Figure 2 (a). The large-scale structures of TEC are subtracted with the method described in *Saito et al.* [1998]. As many as 9 wave fronts of TEC stretching from the northwest to the southeast can be seen. This plot was made using TEC data from four GPS satellites: PRN08, PRN09, PRN23 and PRN26. The ionosphere is assumed to be a thin layer at 300km altitude. We believe this assumption is reasonable because the TEC structures derived with different satellites and elevation angles are consistent with each other. The intercomparison was not as good using the usual height of 450km for the center of electron density distribution [*Mannucci et al.,* 1998]. This indicates the perturbation of TEC occurred at the bottomside of the ionosphere. The peak to peak amplitudes of the TEC variations were about 2 TEC unit ($10^{16} el/m^2$). The background value of TEC over Japan estimated by the method of *Otsuka et al.* [2000] was 12.2 TEC unit at 2330 JST on May 22, 1998. Therefore, the ratio of the perturbation of TEC to the background is about 8 %. The wavelength of the structures is longer in the northern part of Japan than in the southern part while their amplitude is more intense in the southern part. At 0000 on May 22, 1998 JST, the wavelengths in the southwestern part of Japan were 160km, 240km, 320km and 400km, and those in the northeastern part of Japan were 320km and 500km. The peak to peak amplitudes of TEC variations around 0000 ware 1.59 TEC unit over Shigaraki and 0.32 over Moshiri. These tendencies were also seen in the other nights during the campaign.

Structures of 630 nm band airglow were detected over Japan with the five all-sky cameras during the FRONT-1 campaign and were studied in detail by*Kubota et al.,* [2000]. The cluster of all-sky CCD cameras observed wavefront structures of the airglow that are similar to the TEC structures. The composite map of the airglow around 2320 on May 22, 1998 JST is presented in Figure 2 (b). The emitting layer of 630 nm band airglow was estimated with the triangulation technique to be around 260km altitude. The structures of airglow shows significant coincidence with the TEC structures. Namely, the TEC peaks in the TID structures mostly correspond to the airglow peaks.

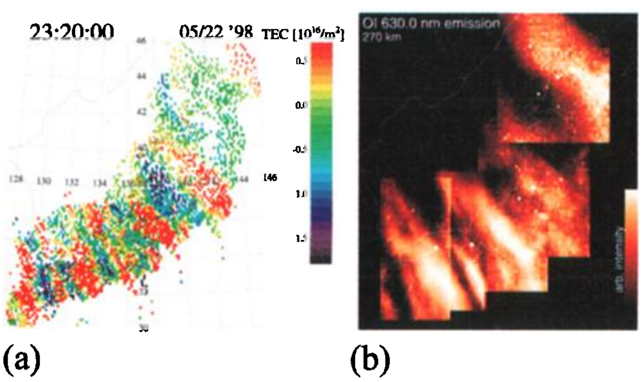

Figure 2. Two-dimensional distribution of total electron content at 23:20:00 (a) and 630nm band airglow between 23:17:34 and 23:21:39 (b) on May 22, 1998 (JST).

The temporal variation of TEC along the path indicated by the thick line in Figure 1 is plotted in Figure 3. It should

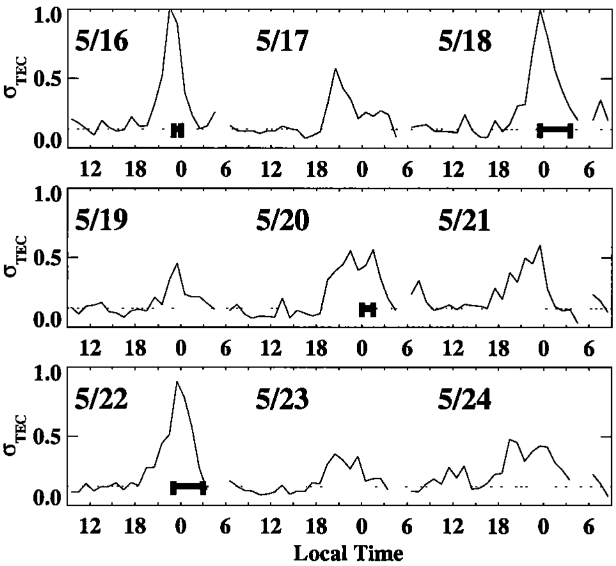

Figure 4. Standard deviation of TEC variations over Shigaraki within a one hour period for the nine consecutive days of FRONT-1. Horizontal thick bars show the period in which the coherent echo from the *F*-region FAI were detected by the MU radar.

be noted that this line bends in the middle to follow the geometry of the Japanese islands. The vertical axis of Figure 3 represents time (2000 JST on May 22, 1998 at bottom to 0400 JST on the subsequent day at top). The left side of the figure corresponds to the southwestern end of the line and the right side corresponds to the northeastern end. Several stripes are seen between 2100 JST and 0200 JST. They show the transit of the wave front structures of TEC over Japan. The propagation velocity of the TIDs, which can be measured by the slope of these stripes, is between 90 m/s and 130 m/s in the southwest direction. This result is very similar to those reported by *Garcia et al.* [2000] over Puerto Rico and Hawaii in the period from January 1997 to the middle part of 1998.

The propagation velocities are slightly different for each wave front. The amplitude of TEC variations is higher in the southwest region than that in the northeast region as seen in Figure 2. The TID structure that appeared at 2200 JST at the northeastern ends propagates to the southwest as its amplitude increases. The wavelength of the TID structure, the distance between enhancements and depletion, is shortest in the southwest part. Occasionally new wave fronts appear between the large wave fronts as they travel from the northeast to the southwest. The appearance of new wave fronts is seen at the position of 600km and 2250 JST and at 200km and 2305 JST. After 0200 JST, no clear wave front was formed.

To study the TID activity, the amplitudes of TEC variations, measured by the standard deviation of TEC within a one hour period in a region over Shigaraki (134° and 138° in longitude, and between 33° and 37° in latitude), are plotted in Figure 4 for nine consecutive days during the FRONT-1 campaign period. The horizontal axis starts at 0900 JST. The perturbation component of TEC is derived by subtracting large-scale structures of TEC along the satellite trajectories [*Saito et al.*, 1998]. Therefore, the amplitude of TEC variations would be affected by the configuration of GPS satellite trajectories and the TEC structures. GPS satellites that have a trajectory crossing Japan from the southwest to the northeast were selected for this analysis. As a result, there are no GPS data around 0530 JST in Figure 4. The dotted line is at 0.14 TEC unit, which is the average value found between 0900 and 1500 JST during FRONT-1 and corresponds to a background fluctuation or noise level. Comparing the stripes of TEC which represent the traversal of the May 22 TIDs seen in Figure 3 with the standard deviation of TEC on the same day, this standard deviation is found to precisely describe the activity of TIDs that have periods shorter than one hour. Although there are some day-to-day variations, the TID activity is generally high between 2000 to 0200 local time and has a maximum around midnight. In the FRONT-2 campaign, TIDs appeared in twelve out of fifteen consecutive nights. Therefore, the occurrence rate of TIDs is more than 85 % in the summer time mid-latitude ionosphere. The geomagnetic activity was generally quiet during the FRONT-1 period. The lowest geomagnetic activity days were May 19 (ΣKp: 11-) and 22 (ΣKp: 14-) and the highest were May 21 (ΣKp: 22) and 24 (ΣKp: 21). There is no obvious relation between the geomagnetic activity and the activity of TID detected by the GPS receiver array.

The MU radar detected coherent echoes from the 3-m scale *F*-region field-aligned irregularities (FAI) [*Fukao et al.*, 1991] on four nights in the FRONT-1 campaign period. The time period of the occurrence of FAI are shown by thick horizontal bars in Figure 4. The FAI occurrence shows significant coincidence with the TIDs. There is a tendency for the FAI to appear at the time when the TID activity reaches its maximum and to fade out as the larger scale structure ends. FAIs appeared on nights when the TID activity is either high or moderate. No FAI was observed on the night when the TID activity was low (May 19, 23 and 24). A westward propagation of FAI structures was observed using multi-beam observation by the MU radar on May 18. The propagation velocity was comparable to that of the TID structures measured by the GPS TEC observation. *Fukao et al.* [1991] used this same method and also reported a westward propagation component.

4. Discussion

Total electron content observations by GEONET in the FRONT campaign reveal some new aspects of traveling ionospheric disturbance in the nighttime mid-latitude ionosphere. The observation of 630 nm band airglow by a cluster of all-sky CCD cameras confirms these features. The coincidence between TEC and airglow gives added confirmation that the center of the electron density variation to which the TEC perturbation is attributed is centered around 300 km altitude. The emitting layer of 630 nm band airglow was estimated with the triangulation technique to be around 260km altitude [*Kubota et al.*, 2000]. The incoherent scatter observation between 2100 and 0200 JST on May 22, 1998 found the altitude of the *F*-region peak to be higher than 350km. Thus, the TID occurred mainly at the bottomside of the *F*-region ionosphere. *Kubota et al.* [2000] reported that the amplitude of airglow variations were about 26 %, which is higher than the amplitude of the TEC variation, 8 % . This fact also indicates that the variations of the electron density take place mainly in the bottom side of the ionospheric *F*-region.

The amplitude of airglow variations was larger in the southwestern part of Japan than in the northeastern part. The peak to peak amplitudes of airglow variations around 2330 on May 22 ware 65 Rayleigh in the southwestern part of Japan and 25 Rayleigh in the northeastern part. This again confirms the observation using the GPS network. The observation area is between 20 and 35 degrees, geomagnetic latitude, which is at higher latitudes than the location of the peak of electron density known as the equatorial anomaly. TEC in the mid-latitude ionosphere gradually decreases after sunset until sunrise due to the recombination of the ionized atmosphere. Therefore, the background value of TEC could be higher in the southwestern part than the northeastern part at this local time and latitudinal sector. To determine the gradient of the background TEC, the absolute values of TEC were estimated with the GPS data at 2330 JST on May 22, 1998. The average values of TEC in the southern part and northern part of Japan, which are divided by 34.5° latitude, are 12.0 TEC unit and 12.3 TEC unit, respectively. Considering the amplitude of the TIDs and the ambiguity of the estimation of biases contained in the GPS data, we conclude that there was no significant gradient of the background TEC over Japan at that time. Therefore, the intensification of TIDs is not only in ΔTEC but also in the ratio, ΔTEC/TEC. An unknown mechanism seems to intensify the amplitude of TIDs as they travel to the southwest. The Perkins instability is one of the candidates to grow the structure. The growth rate of the Perkins instability calculated by *Garcia et al.* [2000] under the average condition of the electric field and the neutral wind is 7×10^4/s and adequate to explain the observed intensification of TIDs over Japan. It should be, however, noted that *Garcia et al.,* [2000] also specified that under the average condition the Perkins instability is expected to enhance the waves that travel to the northeast, not to the southwest.

The relationship between the TID and the F-region field-aligned irregularities is evident in the FRONT-1 campaign. As shown in Figure 4, the occurrence of the FAI has clear relation with the TID activity. The gradient of electron density at the wall of TID could generate the small scale irregularities through the gradient drift instability process. The anti-correlation of occurrence rate of the F-region FAI with the solar activity is known [*Fukao et al.,* 1991]. There is no FAI observed on May 21 and May 24, 1998, when the TID activity is comparably high as that on May 20. And no FAI was observed in the FRONT-2 campaign period in 1999 in spite of the appearance of TID. Thus, the activity of TID is only one of the factors controlling the occurrence of the F-region FAI. Other factors, such as the amplitude and direction of the electric field and the neural wind and the vertical structure of the ionosphere would also contribute to the occurrence rate. No sufficient physical explanation including both of TID and FAI in the mid-latitude ionosphere has been proposed yet. Further theoretical and observational studies are needed to explain this relationship between them.

The coordinated observation of optical and radio instruments with wide field-of-view revealed new features of the nighttime traveling ionospheric disturbance at midlatitudes. Their morphology has been clarified with various techniques, but the essential mechanism for its generation and intensification have not yet been determined. To clarify the mechanism of this phenomenon, further studies including the numerical simulation and the high resolution neutral wind observations are necessary.

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