GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 24, PAGES 4037-4040, DECEMBER 15, 2000

# Traveling ionospheric disturbances observed in the OI 630-nm nightglow images over Japan by using a multi-point imager network during the FRONT campaign

M. Kubota

Communications Research Laboratory, Koganei, Tokyo, Japan.

K. Shiokawa, M. K. Ejiri, Y. Otsuka, and T. Ogawa

Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Japan.

T. Sakanoi, and H. Fukunishi

Graduate school of Science, Tohoku University, Sendai, Japan.

M. Yamamoto, and S. Fukao

Radio Science Center for Space and Atmosphere, Kyoto University, Uji, Japan

A. Saito[1]

Department of Geophysics, Kyoto University, Kyoto, Japan.

**Abstract.** Pilot observations using a network of five all-sky imagers (ASIs) were conducted during the new moon period of May 19-22, 1998 as part of the $F$-region Radio and Optical measurement of Nighttime TID (FRONT) campaign. The network observation enabled us to track propagation of medium-scale traveling ionospheric disturbances (TIDs) in the OI 630-nm nightglow over a distance of more than 2500 km. The TIDs were observed every night during the campaign period, but occurrence was limited from evening to midnight. They have horizontal wavelengths of 200-600 km, travel a horizontal distance of more than 1000 km, and last for more than three hours. In every case, the TIDs moved southwestward with a velocity of 83-137 m/s. Using dual-site TID images, the altitude of the TID structures in the 630-nm nightglow was calculated to be ~260 km, which corresponds to the bottom side of the mid-latitude ionospheric $F$ layer.

## Introduction

The OI 630-nm nightglow can be an important indicator of thermospheric and ionospheric processes because its intensity at mid-latitudes is effectively controlled by the altitude and the density of the ionospheric plasma [*Barbier*, 1959; *Barbier and Glaume*, 1962]. Therefore, observations of this emission have been made by many investigators to determine if it is connected with traveling ionospheric disturbance (TID) [e.g., *Porter et al.*, 1974; *Sobral et al.*, 1978].

The application of CCD detectors to airglow measurements enable us to observe two-dimensional distributions of the 630-nm emission intensity. This technique revealed new phenomena in the mid-latitude region. *Mendillo et al.* [1997] conducted 630-nm imaging observations at Arecibo, Puerto Rico, using an all-sky, image-intensified CCD camera system. They observed wave-like structures moving slowly ($v \leq 100$ m/s) toward the southwest, which are the dominant patterns of the 630-nm airglow activity on clear nights in January. *Taylor et al.* [1998] observed medium-scale TIDs with a wavelength of ~280 km in the OI 630-nm thermospheric nightglow over Kyushu, Japan using a monochromatic cooled-CCD imager. The TID structures appeared on five of eight observation nights. In the recent observations mentioned above, distinctive wave-like structures in the OI 630-nm nightglows have often appeared in mid- and low-latitudes. Their horizontal separation and speed were a few hundred kilometers and about 100 m/s, respectively, and they mostly move towards the southwest. However, these previous observations used single imager, and imaging observations of TIDs using spatially-separated ground-based network stations have not been done yet.

In this paper, we report results from multi-point network observations of mid-latitude TIDs using five all-sky imagers (ASIs) over Japan for May 19-22, 1998. The observations were made as a part of the $F$-region radio and optical measurement of nighttime TID (FRONT) campaign [*Saito et al.*, 2000]. Prominent TID structures were observed in the OI 630-nm nightglow images for most of the observation intervals. Characteristics of the observed TIDs including their spatial extent and duration, are discussed.

## Observations and results

During the FRONT campaign period, ASIs were installed at the following five sites in Japan: Moshiri (44.37°N, 142.27°E); Zao (38.10°N, 140.53°E); Kiso (35.80°N, 137.63°E); Shigaraki (34.85°N, 136.11°E); and Bisei (34.67°N, 133.55°E). Figure 1 shows the location of these observatories and field-

---

[1] Now at School of Electrical and Computer Engineering, Cornell University, Ithaca, NY.

Paper number 2000GL011858.
0094-8276/00/2000GL011858$05.00

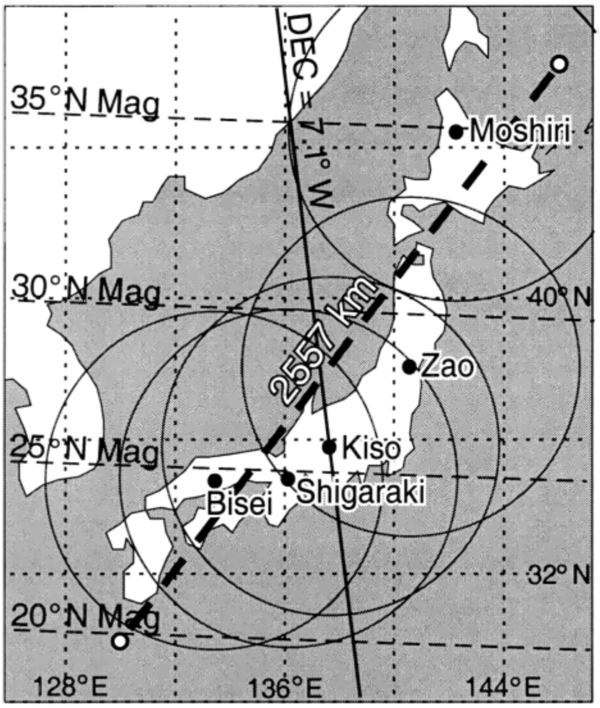


**Figure 1.** Map of Japan with the field-of-view (FOV) of the ASI network. Moshiri, Zao, Kiso, Shigaraki, and Bisei are the observatories at which imaging observations are conducted. Circles with a radius of 740 km indicate FOVs of 150° for an assumed OI 630-nm emission height of 250 km. The orientation of the geomagnetic meridian at Kiso is indicated by the solid line (declination angle is about 7° W). To produce Figure 4a, the 630-nm intensity was sliced along the thick dashed line.

of-view (FOV) of the ASIs. Although the ASI covers a FOV of 180°, the view at low elevation angles is obstructed by trees, buildings, and mountains. The practical FOV is therefore limited to about 150°.

OI 630-nm emission and OH Meinel band emission were observed at all the observatories with a time resolution of 3-3.5 minutes. The OH observation is necessary in order to confirm that the structures seen in the 630-nm images are not caused by contamination of the OH emissions, since the OH band has some weak emission lines near 630 nm. In addition, background emission at 573 nm was observed at Moshiri, Shigaraki, and Bisei. The all-sky imagers at these three sites were constructed at STEL, and their absolute sensitivities were fully calibrated [*Shiokawa et al.*, 1999; 2000]. Therefore, we can calculate absolute intensity of the OI 630-nm emission at these three sites.

Figure 2 summarizes the seeing conditions during the FRONT campaign. The appearance of wave-like TID structures in the 630-nm nightglow images is also indicated. The TID structures were the dominant pattern of activity before local midnight at 0 JST (Japanese Standard Time; JST = UT + 9 hr) on clear nights during the campaign period.

Figure 3 shows perturbations of OI 630-nm emission from 2201 JST to 2340 on May 22, 1998. These images, a 20-min sequence of 630-nm emission maps over Japan, are made by the following procedures using all-sky image data observed at the five sites.

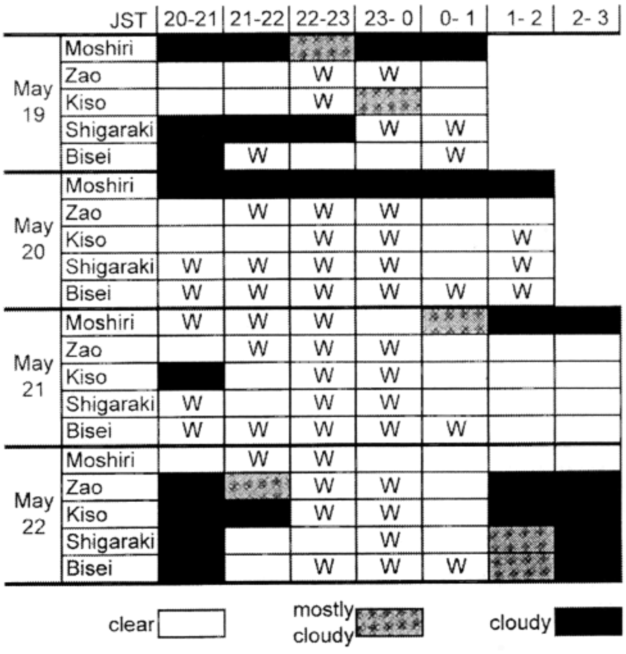
1) Deviations from a mean image are calculated for each site in order to extract spatial structures that move temporary. The mean image is made by superposing the 630-nm images taken over 3 hours. The van Rhijn effect, the atmospheric extinction, and the non-uniform sensitivity of the imager are corrected by this procedure.

2) The fish-eye lens images are transformed into images in the geographic coordinates by assuming an emission height of 260 km.

3) The five images from the five sites are combined to make a 630-nm emission map over Japan.

In Figure 3, wave-like structures progressing towards the SW are clearly seen. These wave-like structures are probably correspond to the medium-scale TIDs. The structures (bands) change their shapes as they propagate. Some bands seem to extend much longer than imager's FOV in the direction from NW to SE, and separation between the bands (wavelength) is about 500 km. There are also some small bands between the big ones in the southern part of Japan.

To illustrate the movements of these TID structures more clearly, a time series of the intensity distribution (keogram) along a NE-SW line indicated in Figure 1, is constructed from the 630-nm emission maps over Japan on the night of May 22, 1998. The result is shown in Figure 4a. The vertical axis of this figure represents time (20 JST at bottom to 3 JST on the next 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. This figure shows that several crests corresponding to the propagation of the band structures in Figure 3 clearly move southwestward. Until 23 JST, bright crests appear in the NE part of Japan at the distance of 1200-2500 km, and the NE-SW separation between two crests is about 500 km. After 23 JST, the disturbed area shifts to the SW part of Japan at the distance of 0-1500 km, and weak crests appear between the bright



|  | JST | 20-21 | 21-22 | 22-23 | 23- 0 | 0- 1 | 1- 2 | 2- 3 |
|---|---|---|---|---|---|---|---|---|
| May 19 | Moshiri | ■ | ■ | ▨ | ■ | ■ |  |  |
|  | Zao |  |  | W | W |  |  |  |
|  | Kiso |  |  | W | ▨ |  |  |  |
|  | Shigaraki | ■ | ■ | ■ | W | W |  |  |
|  | Bisei | ■ | W |  |  | W |  |  |
| May 20 | Moshiri | ■ | ■ | ■ | ■ | ■ | ■ |  |
|  | Zao |  | W | W | W |  |  |  |
|  | Kiso |  |  | W | W |  | W |  |
|  | Shigaraki | W | W | W | W |  | W |  |
|  | Bisei | W | W | W | W | W | W |  |
| May 21 | Moshiri | W | W | W |  | ▨ | ■ | ■ |
|  | Zao |  | W | W | W |  |  |  |
|  | Kiso | ■ |  | W | W |  |  |  |
|  | Shigaraki | W |  | W | W |  |  |  |
|  | Bisei | W | W | W | W | W |  |  |
| May 22 | Moshiri |  | W | W |  |  |  |  |
|  | Zao | ■ | ▨ | W | W |  | ■ | ■ |
|  | Kiso | ■ | ■ | W | W |  | ■ | ■ |
|  | Shigaraki | ■ |  |  | W |  | ▨ | ■ |
|  | Bisei | ■ |  | W | W | W | ▨ | ■ |

clear □ mostly cloudy ▨ cloudy ■

**Figure 2.** Summary of seeing conditions during the FRONT campaign of May 19-22, 1998. Conditions labeled "mostly cloudy" refer to clouds somewhere in the all-sky field of view. Hours marked with "W" refer to periods of wave-like structures in the 630-nm images.

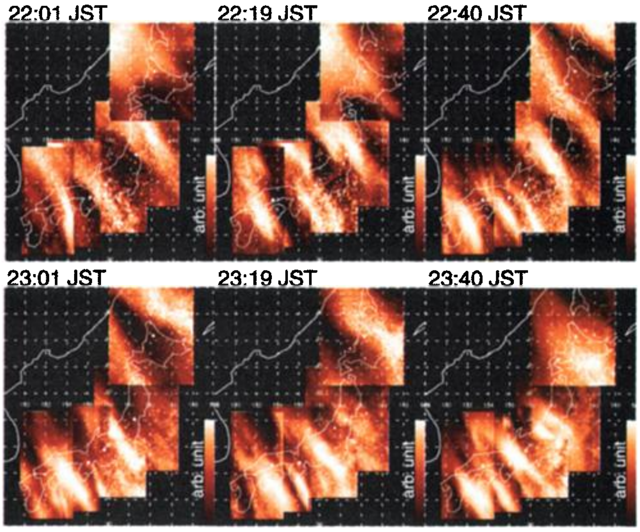


**Figure 3.** A 20-min sequence of images which exhibits the motion of the TID structures in the OI 630-nm emissions over Japan.

crests. After the midnight, the 630-nm emission intensity decreases, and the structures disappear. The slope of the solid line of maximum brightness gives an effective NE-SW wave speed of 133 m/s. It is noteworthy that the speed is almost constant throughout the motion. After 01 JST in the NE part of Japan at the distance of 0-1000 km, the keogram is contaminated by clouds.

Figure 4b shows an intensity profile along the NE-SW line at 2320 JST in Figure 4a. There is a general gradient of the 630-nm nightglow intensity from SW (high) to NE (low). This gradient possibly correspond to the latitudinal gradient of electron densities in the mid-latitude ionosphere. The average intensity indicated by a red line is about 95 Rayleigh. The difference between the local intensity peak at 1100 km and the local depletion at 1250 km is 50 Rayleigh. Thus the amplitude of the 630-nm variation associated with the TID structure is $\sim$26% of the average intensity. The amplitude is more intense in the SW part than in the NE part.

Wave-like structures in the OI 630-nm emission were also observed on three other nights during the campaign period. Typical propagation speeds were 92, 83, and 137 m/s on the nights of 19, 20, and 21 May, 1998, respectively. The direction of propagation was southwestward for all cases.

## Discussion

The OI 630-nm nightglow emits in an altitude range of 200-350 km in the low- and mid-latitude regions [*Takahashi et al.*, 1990; *Mendillo et al.*, 1997]. The altitude of the airglow structures can be determined from two images obtained at two neighboring sites using a triangulation technique [*Kubota et al.*, 1999]. Using this technique, we calculated the 630-nm structure altitude from image data obtained at Shigaraki and Bisei. The horizontal distance between the two sites is 235 km. The derived altitude was 260±10 km above the southwest part of Japan at 2320 JST on May 22, 1998. It should be noted that the structure altitude does not have to equal the peak altitude of the nightglow emission. It is the altitude where the nightglow emission is most effectively fluctuated by wave disturbances. However, the 630-nm structure altitude of 260 km on this night was apparently near the peak altitude of the 630-nm nightglow emission. Normally, the 630-nm emission peak is located about one scale height below the *F*-region maximum [*Takahashi et al.*, 1990]. The wave-dominant altitude of 260 km corresponds to the bottom side of the ionospheric *F* layer.

What is the source of these disturbances? Geomagnetic activity was quiet and Kp index ranged from 1 to 3$_+$ on May 22, 1998. Therefore, it is not likely that the observed ionospheric disturbances are caused by the higher latitude (auroral) energy source. The TIDs appear simultaneously over Japan with a spatial extent of more than 2500 km. The airglow structures of TIDs travel a horizontal distance of more than 1000 km and last for more than three hours. If these disturbances are caused by the upward propagating gravity waves (GWs), this result is the largest horizontal coverage of GW trains ever observed.

*Taylor et al.* [1998] observed medium-scale TIDs in the OI 630-nm thermospheric nightglow over Kyushu, Japan in August 1996. The TID structures appeared on five of eight observation nights. The horizontal separation of the crests was 182-292 km and their average speed was 95 m/s. A strong tendency for wave progression towards the SW was found. *Saito et al.* [1998] reported similar TIDs traveling to the SW with phase speeds up to 150 m/s, and wavelengths up to 300 km using the Geographical Survey Institute GPS network in Japan. Similar 630-nm structures have also been observed at Arecibo (18.3°N, 66.75°W, approx. 30° magnetic lat.) [*Mendillo et al.*, 1997]. Arecibo is located in the magnetic mid-latitude region as is Japan. The observed structures propagated toward the SW with phase speed of $\sim$100 m/s.

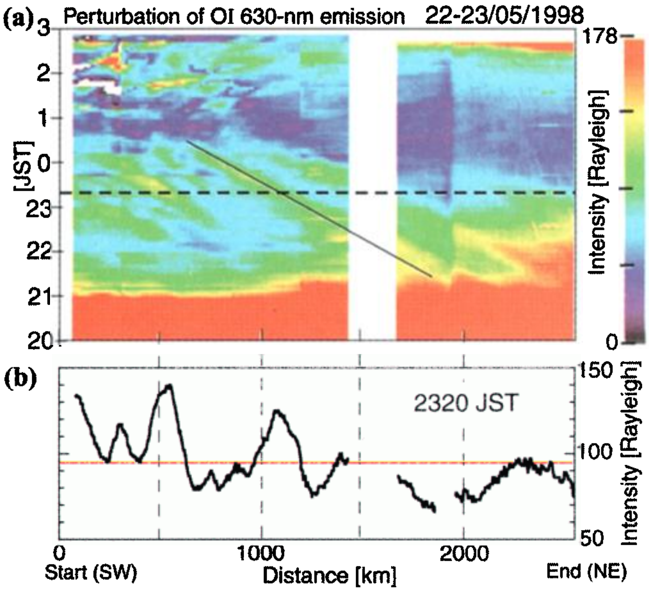


**Figure 4.** (a) 630-nm wave morphology using NE-SW scans of images versus time on the night of May 22, 1998 over Japan. The color code corresponds to the absolute intensity (Rayleigh). The 630-nm intensity values are assigned the horizontal distances indicated in Figure 1. The slope of the solid line of maximum brightness gives an effective NE-SW wave speed of 133 m/s. (b) 630-nm intensity profiles along the dashed line (2320 JST) in (a). The red line indicates the average intensity.

Our observational results and these recent results have the following characters in common: 1) The propagation direction is toward the SW. 2) The phase speed is around 100m/s. 3) The wavelength is several hundred kilometers. 4) Occurrence is limited from evening to midnight. To explain these common features, some wave filtering and raising mechanisms commonly existing in the mid-latitude region would be necessary.

*Kelley and Miller* [1997] conducted a two-dimensional simulation of the time evolution of the Perkins plasma instability, which amplifies the electric field and conductivity perturbations associated with a gravity wave. They predicted that the medium-scale ionospheric disturbances generated by the electrodynamic process would have a strong preference for southwest propagation, and they simulated two-dimensional maps of wave-like disturbances in the ionosphere. The simulated ionospheric disturbances closely resemble our observational results. To confirm the actual existence of the Perkins plasma instability as a cause of the observed TIDs, neutral wind data will be essentially needed.

## Summary

In the recent observations mentioned above, distinctive wave-like structures in the OI 630-nm nightglows have often appeared over Japan. Their horizontal separation is a few hundred kilometers and their speed is about 100 m/s, and they move towards the southwest for almost all cases. For closer investigation of this phenomenon, we conducted wide area observations using an all-sky imager (ASI) network over Japan during May 19-22, 1998, as a part of the FRONT campaign. Wave-like structures in the OI 630-nm emission were observed at every night during the campaign period. The features of these structures are summarized as follows. 1) Propagation speed, wavelength, and period and were 83-137 m/s, 200-600 km and 25-103 min, respectively. 2) The direction of propagation was southwestward in every case. 3) The airglow structures of TIDs traveled a horizontal distance of more than 1000 km and lasted for more than three hours. 4) The TIDs appeared simultaneously over a large spatial extent of more than 2500 km. 5) Occurrence was limited from evening to midnight. 6) Amplitude of the intensity variation was ~20-30 %. 7) Altitude at which the nightglow emission is most effectively fluctuated by the wave disturbances was estimated to be about 260 km, which corresponds to the bottom side of the ionospheric *F* layer.

**Acknowledgments.** This work was carried out by the joint research program of the Solar-Terrestrial Environment Laboratory (STEL), Nagoya University. The observation at Moshiri was supported by Y. Ikegami and M. Sera of STEL. The observation at Zao was carried out in collaboration with the Upper Atmosphere and Space Research Laboratory, Tohoku University. The observation at Kiso was carried out in collaboration with Y. Kiyama, and the Institute of Astronomy, University of Tokyo. The observation at Shigaraki was carried out by M. Ishii of Communications Research Laboratory, in cooperation with T. Tsuda and T. Nakamura of the Radio Science Center for Space and Atmosphere (RASC), Kyoto University. The all-sky imagers at Bisei was operated with a support by students of RASC, at the Bisei Astronomical Observatory of the Bisei Town.

## References

Barbier, D., Recherches sur la raie 6300 de la luminescence atmosphérique nocturne, *Ann. Géophys.*, *15*, 179-217, 1959.

Barbier, D. and J. Glaume, La couche ionosphérique nocturne F dans la zone intertropicale et ses relations avec l'émission de la raie 6300 Ådu ciel nocturne, *Planet. Space Sci.*, *9*, 133-149, 1962.

Kelley, M. C. and C. A. Miller, Electrodynamics of midlatitude spread *F* 3. Electrohydrodynamic waves? A new look at the role of electric fields in thermospheric wave dynamics, *J. Geophys. Res.*, *102*, 11539-11547, 1997.

Mendillo, M., J. Baumgardner, D. Nottingham, J. Aarons, B. Reinisch, J. Scali, and M Kelley, Investigations of thermospheric-ionospheric dynamics with 6300-Å images from the Arecibo Observatory, *J. Geophys. Res.*, *102*, 7331-7343, 1997.

Kubota, M., M. Ishii, K. Shiokawa, M. K. Ejiri, and T. Ogawa, Height measurements of nightglow structures observed by all-sky imagers, *Adv. Space Res.*, *24*, No. 5, 593-596, 1999.

Porter, H. S., S. M. Silverman and T. F. Tuan, On the behavior of airglow under the influence of gravity waves, *J. Geophys. Res.*, *79*, 3827-3833, 1974.

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

Saito, A., M. Nishimura, M. Yamamoto, M. Kubota, K. Shiokawa, Y. Otsuka, T. Tsugawa, S. Fukao, T. Ogawa, M. Ishii, T. Sakanoi, and S. Miyazaki, Traveling ionospheric disturbances detected in the FRONT campaign, *Geophys. Res. Lett.*, *this issue*, 2000.

Shiokawa, K., Y. Katoh, M. Satoh, M. K. Ejiri, T. Ogawa, T. Nakamura, T. Tsuda, and R. H. Wiens, Development of optical mesosphere thermosphere imagers (OMTI), *Earth, Planets and Space*, *51*, 887-896, 1999.

Shiokawa, K., Y. Katoh, M. Satoh, M. K. Ejiri, and T. Ogawa, Integrating-sphere calibration of all-sky cameras for nightglow measurements, *Adv. Space Res.*, *26*, 1025-1028, 2000.

Sobral, J. H. A., H. C. Carlson, D. T. Farley and W. E. Swartz, Nighttime dynamics of the F region near Arecibo as mapped by airglow features, *J. Geophys. Res.*, *83*, 2561-2566, 1978.

Takahashi, H., B. R. Clemesha, P. P. Batista, Y. Sahai, M. A. Abdu, and P. Muralikrishna, Equatorial *F*-region OI 6300 Å and OI 5577 Å emission profiles observed by rocket-borne airglow photometers, *Planet. Space Sci.*, *38*, 547-554, 1990.

Taylor, M. J., J. -M. Jahn, S. Fukao, and A. Saito, Possible evidence of gravity wave coupling into the mid-latitude F region ionosphere during the SEEK campaign, *Geophys. Res. Lett.*, *25*, 1,801-1,804, 1998.

---

M. Kubota, Communications Research Laboratory, 4-2-1 Nukuikita-machi, Koganei-shi, Tokyo 184-8795, Japan. (e-mail: mkubota@crl.go.jp)

(Received June 9, 2000; accepted September 8, 2000.)