Response of the Midlatitude F2 Layer to Some Strong Geomagnetic Storms during Solar Minimum as Observed at Four Sites of the Globe

Vitaly P. Kim, Valery V. Hegai

Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences, Moscow 142190, Russia

In this study, we documented the midlatitude F2-layer response to five strong geomagnetic storms with minimum Dst < -150 nT that occurred in solar minimum years using hourly values of the F2-layer critical frequency (foF2) from four ionosondes located in different hemispheres. The results were very limited, but they illustrated some peculiarities in the behavior of the F2-layer storm. During equinox, the characteristic ionospheric disturbance patterns over the Japanese station Wakkani in the Northern Hemisphere and the Australian station Mundaring in the Southern Hemisphere were consistent with the well-known scenario by Prölss (1993); however, during a December solstice magnetic storm, both stations did not observe any noticeable positive ionospheric disturbances. Over the “near-pole” European ionosonde, clear positive ionospheric storms were not observed during the events, but the “far-from-pole” Southern Hemisphere station Port Stanley showed prominent enhancements in F2-layer peak electron density in all magnetic storms except one. No event produced noticeable nighttime enhancements in foF2 over all four ionosondes.

Keywords: ionospheric disturbance, midlatitude ionosphere, solar minimum

1. INTRODUCTION

Ionospheric disturbances associated with geomagnetic storms have been reported as long ago as 1928 (Anderson 1928). Since then, a large number of papers devoted to the morphology, physical mechanisms, and prediction of these disturbances have been published. Results of detailed investigations into the topic were provided by Rishbeth (1991), Prölss (1995), Buonsanto (1999), and Mendillo (2006). A magnetic storm-associated increase or decrease in the F region peak plasma density (NmF2) is called a positive or negative ionospheric storm, respectively. Such F region storms have been investigated most extensively at middle latitudes. Matsushita (1959) found that the storm-time midlatitude F2-layer response commonly showed an increase in NmF2 followed by a decrease in NmF2. Storm-induced variations in NmF2 depend on the Universal Time (UT), Local Time (LT), storm time, storm intensity, geographic and magnetic coordinates, season, and solar activity.

The main drivers of ionospheric storms include changes in neutral gas composition and neutral winds, which originate at auroral latitudes as a result of thermospheric heating by storm-time Joule dissipation. Changes in composition take the form of a bulge of increased N2/O density ratio that is transported equatorward by winds at night and that subsequently rotates into the dayside (Fuller-Rowell et al. 1994). The sudden increase in auroral heat input generates a package of large-scale gravity waves that propagate to low latitudes with a mean velocity of ~ 600–700 m/s. This wave package is commonly known as a Travelling Atmospheric Disturbance (TAD). A TAD carries along an equatorward neutral wind with a speed of 100–150 m/s. Behind the TAD, a global-scale disturbed thermospheric circulation is established. The disturbance neutral winds penetrate to middle and low latitudes more efficiently in the night sector and at the longitude of the
magnetic pole (Fuller-Rowell et al. 1994), and can drive ionospheric-disturbance dynamo electric fields at middle and low latitudes (Blanc & Richmond 1980). Magnetic storm-associated variations in electrodynamic drifts and field-aligned plasma fluxes from the plasmasphere can also contribute to the ionospheric storms. The different ionospheric storm drivers can work together or can compete with each other, and their relative importance determines the character of the ionospheric storm.

According to the well-known explanation of mid-latitude F2-layer storm behavior proposed by Prölls (1993), daytime positive ionospheric disturbances are caused by upward transport of ionization due to equatorward-directed winds associated with TADs and subsequent disturbance neutral winds. The TADs are responsible for short-duration enhancements in NmF2 seen soon after the onset of the geomagnetic storm, whereas the large-scale disturbance winds produce large-scale positive ionospheric storms of long duration. Negative ionospheric storms are attributed to changes in the neutral gas composition represented by an increase in the N2/O density ratio.

Another driver of midlatitude positive ionospheric storms may be the electric fields produced by the ionospheric disturbance dynamo (Prölls 2006). It is noteworthy that positive ionospheric storms have been observed at middle latitudes not only during daytime but also during nighttime hours (e.g., Tsagouri et al. 2000; Belehaki & Tsagouri 2002). The nighttime positive ionospheric storms could be attributed to downward plasma fluxes from the plasmasphere.

The ionospheric response to large geomagnetic storms is of particular interest because they produce drastic perturbations in the ionosphere–thermosphere system on a global scale (e.g., Batista et al. 1991; Yeh et al. 1994; Kil et al. 2003; Mansilla 2004; Kane 2005; Abdu et al. 2007). During each intense magnetic storm, the ionosphere reveals an individual pattern of disturbances. The storm-induced ionospheric effects are investigated predominantly for solar maximum because most large magnetic storms occur in solar maximum. The ionospheric response to a strong magnetic storm at solar minimum is less known because storms at solar minimum are rare events. In this work, we examine the midlatitude F2-layer response to the intense geomagnetic storms (minimum Dst < -150 nT) that occurred in solar minimum years beginning from 1965 using the data from four ground-based ionosondes.

2. DATA

We analyzed the hourly values of the F2-layer critical frequency foF2 (NmF2 [m⁻³] = 1.24 × 10⁶ (foF2 [MHz])²) from the four midlatitude ionosondes, the characteristics of which are given in Table 1. The average foF2 values on geomagnetically quiet days were taken as a quiet-time foF2 reference. The geomagnetically quiet days were chosen in the 15-day interval preceding the day of onset of the geomagnetic storm as the days during which none of the 3-h Kp indices exceeded 2 or 2+. The Disturbance storm time (Dst) and the Auroral Electrojet (AE) indices were used as the indicators of geomagnetic activity (Kim & Chang 2014a, b).

We considered the events of intense geomagnetic storms with minimum Dst < -150 nT that occurred in the solar minimum years of 1965–2009, except for the severe storm of 6 February 1986 (the ionospheric response to this storm was studied previously by Cander & Mihajlovic (1998)). The hourly values of the Dst and AE indices were obtained from the GSFC/SPDF OMNIWeb interface at http://omniweb.gsfc.nasa.gov.

| Station       | Geographic Lat (°N) | Geographic Long (°E) | Geomagnetic Lat (°N) |
|---------------|---------------------|----------------------|----------------------|
| Wakkanai      | 45.2                | 141.4 (f)            | 35.6                 |
| Mundaring     | -32.0               | 116.2 (n)            | -43.5                |
| Slough        | 51.5                | 359.4 (n)            | 54.2                 |
| Port Stanley  | -51.7               | 302.2 (f)            | -40.6                |

We analyzed the hourly values of the F2-layer critical frequency foF2 (NmF2 [m⁻³] = 1.24 × 10⁶ (foF2 [MHz])²) from the four midlatitude ionosondes, the characteristics of which are given in Table 1. The average foF2 values on geomagnetically quiet days were taken as a quiet-time foF2 reference. The geomagnetically quiet days were chosen in the 15-day interval preceding the day of onset of the geomagnetic storm as the days during which none of the 3-h Kp indices exceeded 2 or 2+. The Disturbance storm time (Dst) and the Auroral Electrojet (AE) indices were used as the indicators of geomagnetic activity (Kim & Chang 2014a, b).

We considered the events of intense geomagnetic storms with minimum Dst < -150 nT that occurred in the solar minimum years of 1965–2009, except for the severe storm of 6 February 1986 (the ionospheric response to this storm was studied previously by Cander & Mihajlovic (1998)). The hourly values of the Dst and AE indices were obtained from the GSFC/SPDF OMNIWeb interface at http://omniweb.gsfc.nasa.gov.

3. RESULTS

From top to bottom, the panels in Fig. 1 show the variations in the hourly values of the Dst index, the AE index, and the critical frequency foF2 for the four stations from 17 to 22 April 1965. The discontinuities in the curves for foF2 are because of an absence of the corresponding data. The vertical line indicates the time of the minimum Dst. The foF2 data recorded on 2, 3, 8, 11, 14, 15, and 16 April (none of the 3-h Kp indices exceeded 2 on these days) were selected to compute the quiet-time references (thin lines). The monthly mean F10.7 solar flux for April 1965 was 72.4. The relative deviations DfoF2 (%) in the foF2 parameter from its respective quiet values versus time for each station are shown in Fig. 2 along with the Dst and AE indices in the same format used in Fig. 1. The main phase of the magnetic storm began at ~0200 UT on 18 April, and about 6 hr later at ~0800 UT, Dst reached its minimum value of ~162 nT. The AE index began to intensify at ~0200 UT and
reached a peak at ~0600 UT.

The ionospheric response to the magnetic storm demonstrated both positive and negative perturbations in foF2. The prominent feature in storm-time ionospheric behavior at Wakkanai and Mundaring is the significant enhancement of foF2 during almost the entire daytime of 18 April. The peak percentage positive deviations in foF2 at the two stations are ~80%, i.e., NmF2 rose by a factor of more than 3. This feature clearly indicates a dominant role of the equatorward meridional neutral wind triggered by storm intensification of auroral activity. On the following day (19 April), however, ionospheric behavior at Wakkanai and Mundaring was different. While daytime foF2 over Wakkanai exhibited marked depression, perturbation in foF2 over Mundaring was small. During 20 and 21 April, daytime foF2 decreased over Wakkanai but showed no noticeable deviation over Mundaring. The daytime negative storm effect in foF2 over Wakkanai on 19 April can be explained by a prevailing effect of thermospheric composition perturbation, characterized by an increase in the N2/O density ratio.

Over the European station of Slough, after the negative perturbation in foF2 during the daytime and nighttime hours of 18 April, foF2 showed positive disturbance during the daytime of 19 April, which could be attributed to enhancement of the equatorward meridional wind due to changes in the large-scale wind system. The foF2 returned to its quiet-time level after ~2100 LT on 19 April.

Over Port Stanley, the negative perturbation in foF2 started during the night of 18 April at ~2300 LT, when the main phase of the magnetic storm was in progress. This negative phase in foF2 persisted until ~0800 LT on 20 April. The percentage decrease in foF2 was most pronounced during the daytime hours of 19 April, when it reached ~60% (NmF2 reduced by a factor of more than 6). The observed behavior of foF2 indicates that neutral gas with increased...
$N_2/O$ density ratio played a dominant role in the $foF2$ disturbance over Port Stanley.

Figs. 3 and 4 show the same parameters as in Figs. 1 and 2, except for the AE index data, which were not available, for 10 to 14 January 1976. The $foF2$ reference days are 2, 3, and 9 January (none of the 3-h Kp indices exceeded 2 on these days). The monthly mean $F10.7$ was 72.3. As estimated from the Dst values, the magnetic storm began on 10 January with a Dst minimum of $-156$ nT at $-2300$ UT. This corresponds to solstice conditions, whereas all other cases under consideration correspond to equinox conditions.

In the winter (northern) hemisphere, the magnetic storm produced minor disturbances in $foF2$ over Wakkanai and moderate negative disturbances over Slough, where they persisted during nighttime hours from 11–14 January. These negative disturbances in $foF2$ over Slough seen only at nighttime are not easy to explain by neutral composition change. They can probably be attributed to the storm modifications in the ionospheric dynamics.

In the summer (southern) hemisphere, a prominent negative phase in daytime $foF2$ set in over Mundaring on 11 January, soon after the negative Dst peak; the negative phase rotated into the nightside and was then seen during the daytime hours of the next two days. This is a clear indication of an increase in the $N_2/O$ density ratio. Over Port Stanley, a very strong increase in $foF2$ (peak percentage deviation in $foF2$ of $-110\%$) was observed in the late afternoon sector on 10 January during the main phase of the magnetic storm. This feature can be explained readily by the TAD effect. Starting at $0700$ LT on 11 January, a negative storm effect in $foF2$ persisted until $1400$ LT on 13 January during daytime and nighttime hours. This long-lasting depression in $foF2$ may imply that the neutral atmosphere bulge with increased $N_2/O$ density ratio persisted for more than two days over Port Stanley.

Figs. 5 and 6 present the same parameters as in Figs. 3 and 4, but for the interval of 25 March to 5 April 1976, which had two magnetic storms. During the first storm, the Dst index showed two consecutive negative peaks of $-226$ and $-204$ nT at $0800$ and $1500$ UT on 26 March 1976, respectively. In the next magnetic storm, the Dst index reached a minimum value of $-218$ nT at $0800$ UT on 1 April. The days of 22 and 24–25 March were taken as the $foF2$ reference days (none of the 3-h Kp indices exceeded 2+). The monthly mean $F10.7$ values for March and April were 75.9 and 76.8, respectively. This case allows us to examine whether the storm response variations in $foF2$ could be reproduced as the storms have similar characteristics and occurred one after the other in close proximity.

As can be seen in Figs. 5 and 6, the main features of disturbance in $foF2$ over Wakkanai and Mundaring are similar during the two storms. Both storms caused
practically simultaneous positive disturbances in daytime foF2 over the stations during the main phase of the storm, followed by negative deviations in foF2.

Over Slough, the foF2 shows predominantly negative deviations and no TAD effects are observed. At the same time, a clear TAD effect is seen in the daytime ionosphere over Port Stanley, soon after the second negative Dst peak of the first storm when the critical frequency foF2 increased by up to ~120%. In contrast, the second storm caused only a negative disturbance in foF2 over Port Stanley from ~2000 LT of 1 April to ~0800 LT of 2 April. The prominent daytime increase in foF2 on 3 April was likely associated with TAD generated by intensification of auroral activity during multiple small negative deviations in the Dst index on 3
April. Thus, the storm response behavior of the F2 layer for these similar magnetic storms could be reproduced over Wakkanai and Mundaring but not over Slough and Port Stanley.

Figs. 7 and 8 present diurnal variations of the same parameters shown in Figs. 1 and 2 but for the interval of 11–16 September 1986, which included a magnetic storm with a minimum Dst of −170 nT at ~0600 UT on 12 September 1986. The days of 7, 8, and 10 September were taken as the foF2 reference days (none of the 3-h Kp indices exceeded 2). The monthly mean F10.7 for September was 69.4.

Wakkanai and Mundaring showed nearly synchronous large enhancements in foF2 during the daytime hours of 12 September. The positive percentage deviation in foF2 over Wakkanai exceeded 120%. This positive effect was the main storm response feature in foF2 over these stations. It was most likely caused by intensification in the AE index associated with the main storm phase.

Over Slough, the storm produced a long-lasting negative ionospheric disturbance. This disturbance means that the storm-associated increase in the N₂/O density ratio was dominant in the foF2 storm response over Slough. The most prominent depression in foF2 occurred during the daytime hours of 12 September. In contrast, on the same day, Port Stanley showed significant enhancement in daytime values of foF2 without subsequent negative disturbance in foF2. This behavior of foF2 can be explained by an increase in the equatorward neutral wind velocity caused by storm-time intensification of auroral activity.

4. CONCLUSION AND DISCUSSION

We examined midlatitude F2-layer storm behavior during solar minimum as observed by two pairs of ionosondes in different hemispheres during five intense geomagnetic storms (with minimum Dst < −150 nT). Note that such strong storms occur very rarely in solar minimum years. There were only six in the period of 1965–2009. The results were very fragmentary, but they clearly illustrated a complex ionospheric response to the magnetic storms. During equinox, the Northern Hemisphere Japanese station Wakkanai and the Southern Hemisphere Australian station Mundaring showed similar storm responses in foF2, which
were prominent positive disturbances in daytime foF2 as the first phase followed by negative disturbances in foF2 (except for one case over Mundaring) as the next phase. This corresponds to the widely known scenario presented by Prölss (1993), which is based on the assumptions that the dayside enhancements in midlatitude NmF2 soon after the storm-time intensification in auroral activity are attributable to TADs, whereas the subsequent depressions in NmF2 are caused by the changes in the neutral atmosphere composition. During the December solstice magnetic storm, no noticeable positive disturbances in foF2 were seen at Wakkanai and Mundaring.

The European station Slough is at “near-pole” longitude, but it did not show any clear TAD effects in foF2 during any event, i.e., TADs never dominated in the storm-time F2-layer disturbances over Slough, which were mainly negative. However, according to Cander & Mihajlovic (1998), the severe magnetic storm of 6 February 1986 produced a prominent TAD effect in foF2 over Slough. In contrast, the Southern Hemisphere “far-from-pole” station Port Stanley detected clear TAD effects in all storms except the second storm in the period of 25 March to 5 April 1976.

The gross features of the foF2 responses to two very similar consecutive magnetic storms in March and April 1986 were reproduced over Wakkanai and Mundaring, but not over Slough and Mundaring. Belehaki & Tsagouri (2002) reported nighttime enhancements in foF2 at middle latitudes associated with strong geomagnetic storms that occurred during solar maximum, but no such effects were observed in our cases over all four stations.

ACKNOWLEDGMENTS

We are grateful to the World Data Centre (WDC) of IPS Radio and Space Services, Bureau of Meteorology of Australia (http://www.ips.gov.au/World_Data_Centre), for their analysis of the foF2 data. This work was supported by a research grant of the Russian Academy of Sciences.

REFERENCES

Abdu MA, Maruyama T, Batista IS, Saito S, Nakamura M, Ionospheric responses to the October 2003 superstorm: Longitude/local time effects over equatorial low and middle latitudes, J. Geophys. Res. 112, A10306 (2007). http://dx.doi.org/10.1029/2006JA012228

Anderson CN, Correlation of Long Wave Transatlantic Radio Transmission with Other Factors Affected by Solar Activity, Proc. Inst. Radio Eng. 16, 297-347 (1928). http://dx.doi.org/10.1109/TRPRO.1928.221400

Batista IS, de Paula ER, Abdu MA, Trivedi NB, Greenspan ME, Ionospheric Effects of the March 13, 1989, Magnetic Storm at Low and Equatorial Latitudes, J. Geophys. Res. 96, 13943-13952 (1991). http://dx.doi.org/10.1029/91JA01265

Belehaki A, Tsagouri I, On the occurrence of storm-induced nighttime ionization enhancements at ionospheric middle latitudes, J. Geophys. Res. 107, 1209 (2002). http://dx.doi.org/10.1029/2001JA005029

Blanc M, Richmond AD, The ionospheric disturbance dynamo, J. Geophys. Res. 85, 1669-1686 (1980). http://dx.doi.org/10.1029/JA085iA04p01669

Buonsanto MJ, Ionospheric Storms – A Review, Space Sci. Rev. 88, 563-601 (1999). http://dx.doi.org/10.1023/A:1005107532631

Cander LR, Mihajlovic SJ, Forecasting ionospheric structure during the great geomagnetic storms, J. Geophys. Res. 103, 391-398 (1998). http://dx.doi.org/10.1029/97JA02418

Fuller-Rowell TJ, Codrescu MV, Moffett RJ, Quegan S, Response of the thermosphere and ionosphere to geomagnetic storms, J. Geophys. Res. 99, 3893-3914 (1994). http://dx.doi.org/10.1029/93JA02015

Kane RP, Ionospheric foF2 anomalies during some intense geomagnetic storms, Ann. Geophys. 23, 2487-2499 (2005). http://dx.doi.org/10.5194/angeo-23-2487-2005

Kil H, Paxton LJ, Pi X, Hairston MR, Zhang Y, Case study of the 15 July 2000 magnetic storm effects on the ionosphere-driver of the positive ionospheric storm in the winter hemisphere, J. Geophys. Res. 108, 1391 (2003). http://dx.doi.org/10.1029/2002JA009782

Kim JH, Chang HY, Statistical Properties of Geomagnetic Activity Indices and Solar Wind Parameters, J. Astron. Space Sci. 31, 149-157 (2014a). http://dx.doi.org/10.5140/JASS.2014.31.2.149

Kim JH, Chang HY, Spectral Analysis of Geomagnetic Activity Indices and Solar Wind Parameters, J. Astron. Space Sci. 31, 159-167 (2014b). http://dx.doi.org/10.5140/JASS.2014.31.2.159

Mansilla GA, Mid-latitude ionospheric effects of a great geomagnetic storm, J. Atmos. Sol.-Terr. Phys. 66, 1085-1091 (2004). http://dx.doi.org/10.1016/j.jastp.2004.04.003

Matsushita S, A study of the morphology of ionospheric storms, J. Geophys. Res. 64, 305-321 (1959). http://dx.doi.org/10.1029/JZ064i003p00305

Mendillo M, Storms in the ionosphere: Patterns and processes for total electron content, Rev. Geophys. 44, RG4001 (2006). http://dx.doi.org/10.1029/2005RG000193

Prölss GW, On explaining the local time variation of ionospheric storm effects, Ann. Geophys. 11, 1-9 (1993).
Prölss GW, Ionospheric F-region storms, in Handbook of Atmospheric Electrodynamics, vol. 2, ed. Volland H (CRC Press, Boca Raton, 1995), 195-248.

Prölss GW, Ionospheric F-region storms: unsolved problems, In Characterising the Ionosphere, Proceedings of RTO-MP-IST-056, Paper 10 (2006).

Rishbeth H, F-Region Storms and Thermospheric Dynamics, J. Geomag. Geoelectr. 43, 513-524 (1991). http://doi.org/10.5636/jgg.43.Supplement1_513

Tsagouri I, Belehaki A, Moraitis G, Mavromichalaki H, Positive and negative ionospheric disturbances at middle latitudes during geomagnetic storms, Geophys. Res. Lett. 27, 3579-3582 (2000). http://dx.doi.org/10.1029/2000GL003743

Yeh KC, Ma SY, Lin KH, Conkright RO, Global ionospheric effects of the October 1989 geomagnetic storm, J. Geophys. Res. 99, 6201-6218 (1994). http://dx.doi.org/10.1029/93JA02543