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The low latitude ionospheric effects of the April 2000 magnetic storm near the longitude 120°E

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In this paper, we report the responses of the low latitude ionosphere near the longitude 120°E to the April 2000 geomagnetic storm using Digisonde data measured at Chungli (25.0°N, 121.2°E, Mag. 13.8°N), Wuhan (30.6°N, 114.4°E, Mag. 19.3°N), and Kokubunji (35.7°N, 139.5°E, Mag. 25.7°N). At these three stations, the significant ionospheric responses are near-simultaneous height disturbances after the sudden storm commencement (SSC) on April 6, 2000 and wave-like disturbances in the daytime on April 7. The ionospheric height disturbances in the nighttime after the SSC at these stations are suggested to be caused by the storm related perturbed electric fields, and the followed wave-like disturbances may be caused by storm induced atmospheric gravity waves. The vertical effective winds derived from Digisonde measurements imply the existence of significantly large vertical drifts during this storm, which are in agreement with the perturbed zonal electric fields predicted by the model of Fejer and Scherliess (1997) and Scherliess and Fejer (1997). Finally, the storm time derivations of foF2 from its monthly median level at these stations are used to validate the predication ability of the empirical model of Araujo-Pradere *et al.* (2002), which has included in the International Reference Ionosphere model IRI2000.
Key words: Geomagnetic storm, ionospheric storm, F-layer, low latitude, perturbed electric field, International Reference Ionosphere.

1. Introduction

As we know, during active solar activities, the solar energy and momentum injected into the earth may induce such complex phenomena as geomagnetic storms, substorms, and ionospheric and thermospheric disturbances. Many past studies revealed that the storm-time ionosphere changes in rather complicated ways. Due to their complexity, the ionospheric storms and the underlying physical processes are still far beyond being fully understood, in spite of many case studies and statistical ones (e.g. Prölss, 1995; Buonsanto, 1999; Danilov and Lastovička, 2001).

A series of solar events and geomagnetic storms occurred in the 23rd solar cycle. Among those events, a halo-CME induced interplanetary shock wave that passed the Earth around 1640 UT on April 6, 2000 triggered a severe geomagnetic storm with a minimum value of about −288 nT in Dst index. In this paper, we report the ionospheric responses during the April 2000 storm using Digisonde data measured at Chungli (25.0°N, 121.2°E, Mag. 13.8°N), Wuhan (30.6°N, 114.4°E, Mag. 19.3°N), and Kokubunji (35.7°N, 139.5°E, Mag. 25.7°N).

2. Ionosonde Data

The solar and geomagnetic conditions during the April 2000 storm are depicted in Fig. 1. The solar 10.7 cm flux index, F107, was downloaded from the American National Geophysical Data Center (NGDC-NOAA) database, and the geomagnetic indices Dst, ap and AE were from the web site of World Data Center C2.

Ionospheric data were measured at Chungli with a DPS-1, at Wuhan with a DGS-256, and at Kokunbuji with a DGS-256. The Digisondes were operated quarter hourly during this period. The critical frequency, foF2, and the peak height of F layer, hmF2, over Chungli, Wuhan, and Kokubunji during April 4–10, 2000 are illustrated in Fig. 2 with thick lines. The average values of foF2 and hmF2 on April 3–5 are served as the reference level (thin lines in Fig. 2). The onset moment of the sudden storm commencement (SSC) of the April 2000 storm is indicated with a short vertical line in each panel of Fig. 2 and other figures. The values of hmF2 are calculated from ionograms with the UMLCAR SAO-Explorer.

The effective drifts, which are a joint contribution of the meridional neutral winds and the north perpendicular $E \times B$ drifts, near the F-layer peak can be estimated from ionosonde measurements based on the nature that neutral winds and electric fields strongly control the evolution of the ionosphere near and above the F-layer peak (e.g., Titheridge, 1995; Liu *et al.*, 2003). In this paper, the vertical component of effective drifts is estimated from ionospheric data with the method of Liu *et al.* (2003). Figure 2 also depicted the vertical effective drifts derived from hmF2 and foF2 at these three stations.

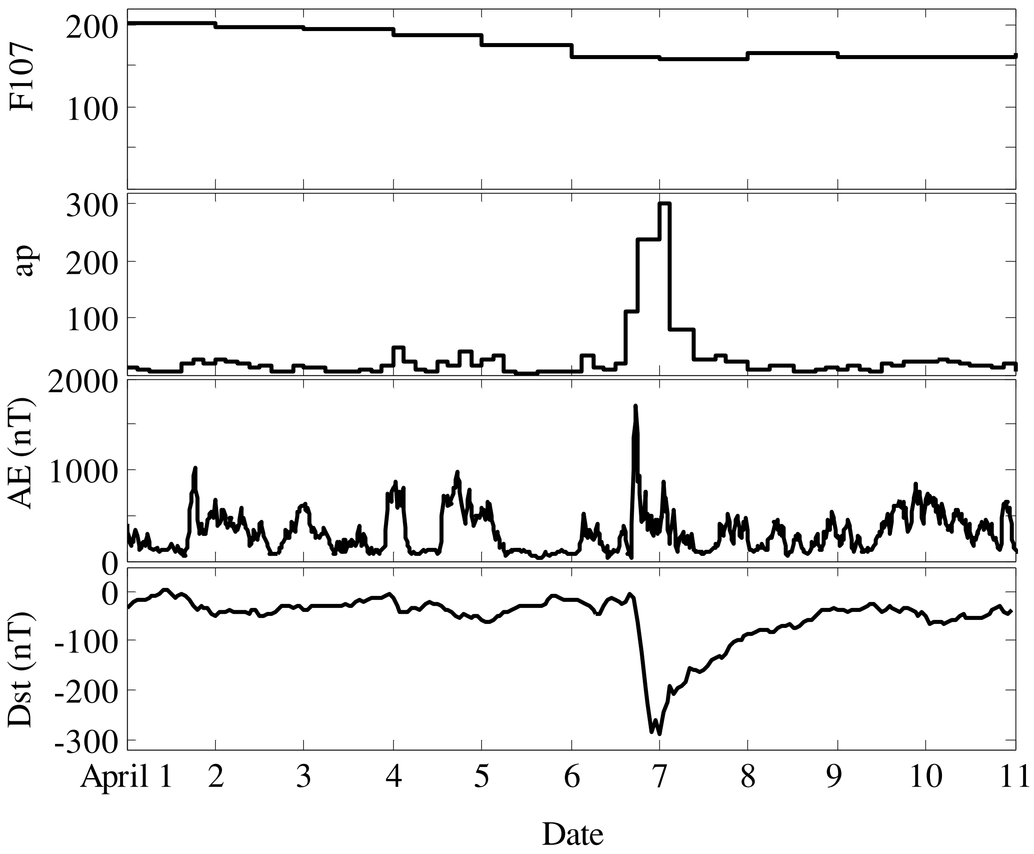

Fig. 1. The solar 10.7 cm flux index, F107, and the geomagnetic indices Dst, ap and AE during April 1–10, 2000. The geomagnetic indices are downloaded from the web site of World Data Center C2 and F107 from the American National Geophysical Data Center (NGDC-NOAA) database.

3. Ionospheric Responses

Figure 3 shows the deviation of foF2 and hmF2 on April 6–10 from the reference level at these three stations. Shortly after the SSC onset on April 6, 2000, the ionosphere was characterized by significant height disturbances. These height disturbances were frequently occurred in the night time during storms (e.g., Reddy and Nishida, 1992). Compared with the reference levels, the peak height of the F-layer is near simultaneously decreasingly deviated and then rapid and large lift at these stations (Fig. 3). The similar feature can also be clearly found in the minimum virtual height of the F-layer, h′F, at these three stations. (Figure does not present here.)

The low latitude ionosphere is very sensitive to zonal electric fields. Ionospheric electrodynamics studies have identified the occurrence of large scale disturbed electric fields during and after geomagnetically perturbed times. There are two kinds of large scale disturbed electric fields (Fejer and Scherliess, 1997; Scherliess and Fejer, 1997; Fejer, 2002) at the equatorial region and low latitudes. Disturbed electric fields at high latitude can promptly penetrate to equatorial and low latitudes with timescales of about an hour (Scherliess and Fejer, 1997; Richmond and Lu, 2000), and the corresponding drifts are called as the prompt-penetration drifts. In addition to these perturbations, another kind of electric field perturbations is associated with ionospheric disturbance dynamo effects, which appear later and last longer.

Figure 4 illustrates the total equatorial perturbed drifts and the component due to the prompt penetration effect on April 6–8, which were predicted by the model of Fejer and Scherliess (1997) and Scherliess and Fejer (1997) using AE index shown in Fig. 1. At equatorial region and low latitudes near the longitude 120°E, the model predicted drifts exhibit large perturbations shortly after the SSC, which are mainly contributed from the prompt penetration effect (Fig. 4). The predicted disturbed drifts are downward first and then gradually turn upwards. It should be pointed out that, the condition of electric fields penetrate from high latitudes to lower latitudes is met, because an IMF Bz southward turning during this time was detected by the WIND satellite (CDAWeb). In addition to these perturbations, due to enhanced energy and momentum deposition into the high latitude ionosphere, the disturbance dynamo will significantly contribute the perturbed electric fields some hours after the SSC, and take effect again about twenty hours later (Fejer, 2002). Those features are also consistent with the derived vertical effective winds at these low latitude stations (Fig. 2). Thus it also reflects the ability to capture the physics of the April 2000 storm by the model of Fejer and Scherliess (1997) and Scherliess and Fejer (1997). Thus, it may suggest that, after the SSC onset of the April 2000 storm, the $E \times B$ plasma drifts of storm origin are the cause of the near simultaneity of height disturbances at these stations.

Figure 5 illustrates the ratio of foF2 (daily values to their monthly median ones) measured and predicted by the STORM model (Araujo-Pradere *et al.*, 2002) using ap index.

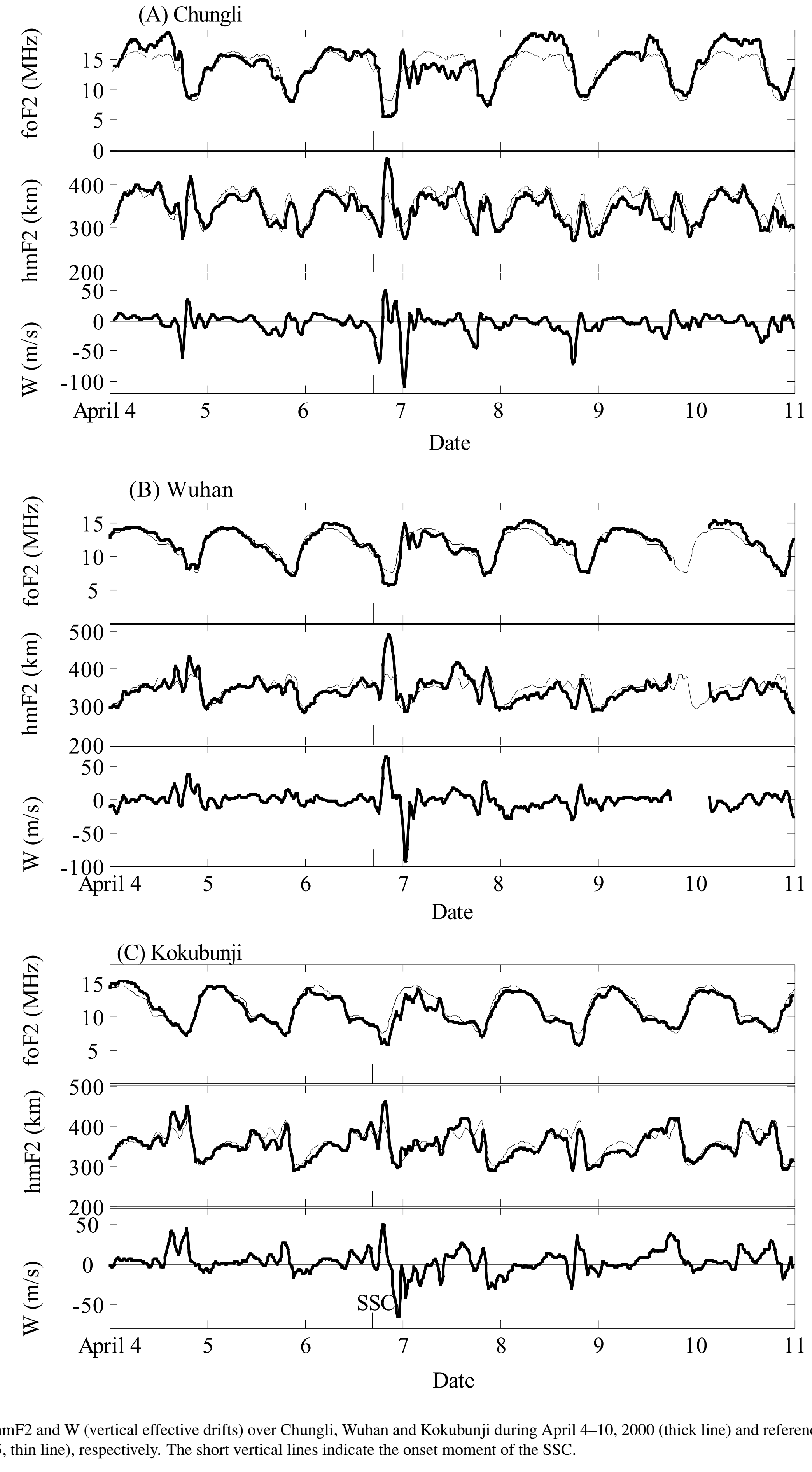

Fig. 2. foF2, hmF2 and W (vertical effective drifts) over Chungli, Wuhan and Kokubunji during April 4–10, 2000 (thick line) and reference level (average of April 3–5, thin line), respectively. The short vertical lines indicate the onset moment of the SSC.

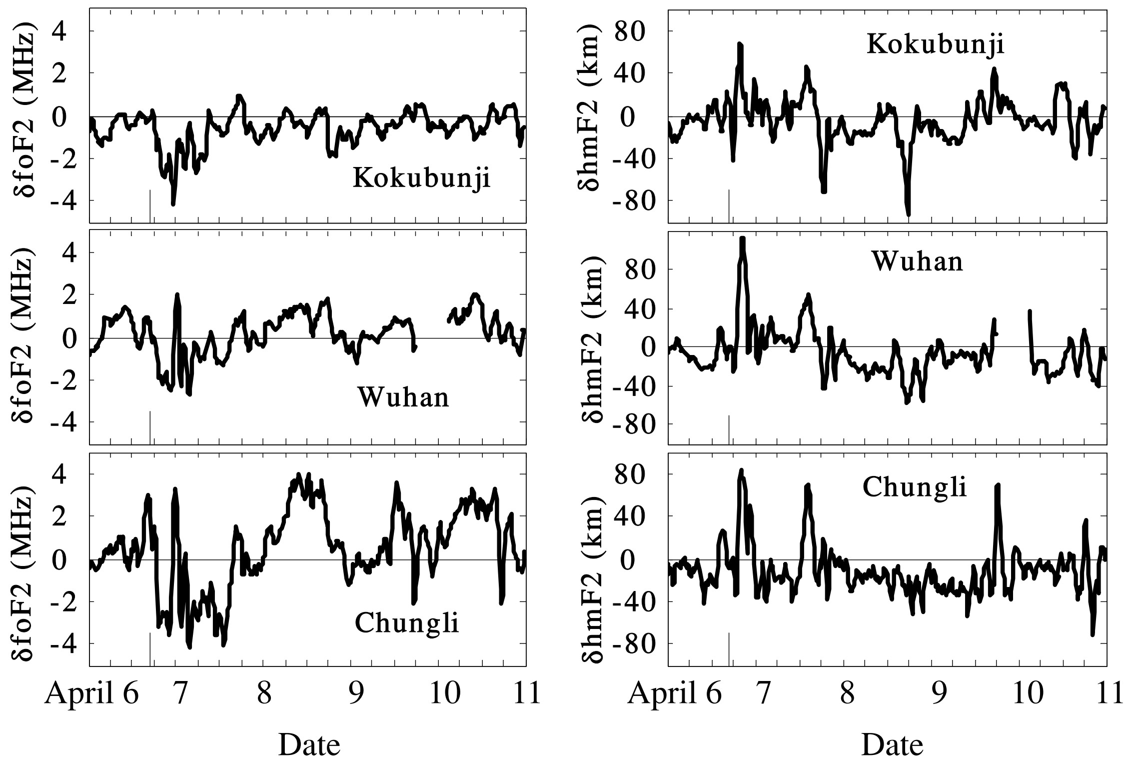

Fig. 3. The deviation of foF2 (left) and hmF2 (right) from a reference level (average of April 3–5) at Kokubunji, Wuhan and Chungli during April 6–10, 2000. The short vertical lines indicate the onset moment of the SSC.

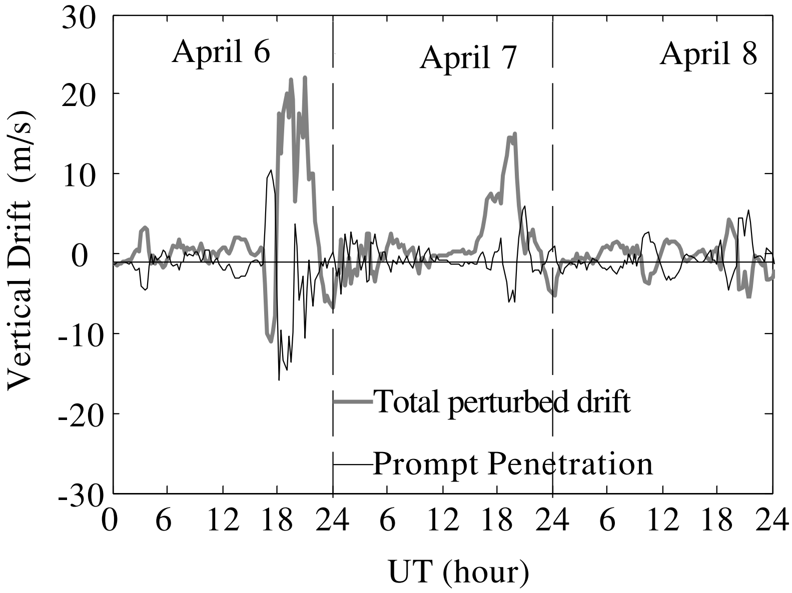

Fig. 4. The total perturbed vertical drifts and prompt penetration drifts during April 6–8, 2000. These are predicted by the storm-time drift model of Fejer and Scherliess (1997) and Scherliess and Fejer (1997) using the AE indexes shown in Fig. 1.

Positive deviations from the reference level are already occurred in foF2 at Wuhan and Chungli several hours before the SSC, but it is not observed at Kokubunji. After the SSC, the deviations of foF2 are negative at Kokubunji, and it also gradually turn to negative at Wuhan and Chungli. In the daytime of April 7, the most significant feature is depleted foF2 with wave-like disturbances (Fig. 2) at these stations. foF2 depletes about −2 to −4 MHz throughout the day at those stations, besides an enhancement (about 2–3 MHz) peaked at 00:00–00:30 UT over Wuhan and Chungli for about one hour or two.

On April 7, after the anomalous height lift, the peak height of F layer also oscillates and becomes lower gradually than the reference level at Chungli, but hmF2 still remains high level at Wuhan and Kokubunji. On April 8–9, an interesting feature is the F2 layer moves to a much lower level, especially at Wuhan and Kokubunji. In contrast, the ionosphere is generally at its positive phase at Wuhan and Chungli and

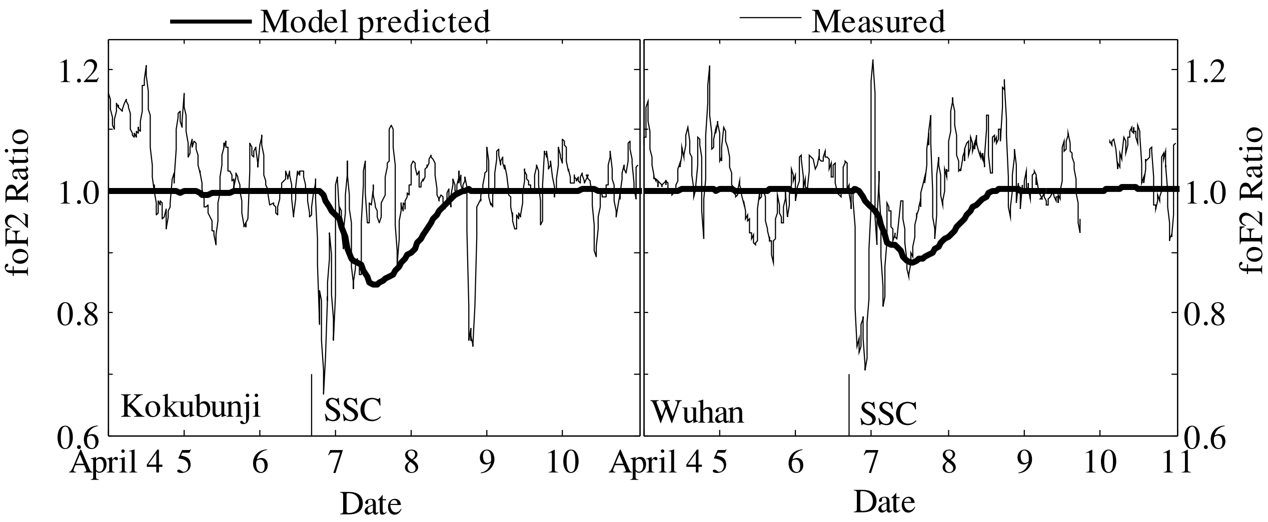

Fig. 5. The foF2 ratio (the ratio of foF2 to their monthly median ones) during April 4–10, 2000 observed at Wuhan and Kokubunji and predicted by the STORM model (Araujo-Pradere *et al.*, 2002) using ap index shown in Fig. 1.

negative phase at Kokubunji, and the deviations of foF2 are largest at Chungli. An anomalous enhancement of equatorial anomaly on April 8 can also be found in the GPS-TEC observed with a GPS network near this longitude (Wan *et al.*, Very intense ionospheric storms observed with a GPS network, manuscript submitted to Adv. Space Res., 2002).

4. Discussion and Summary

In this work, Digisonde data at three stations near the longitude 120°E illustrates that the responses of low latitude ionosphere to the April 2000 severe storm are rather complicated. The responses to this storm at these stations are summarized as follows:

After the SSC onset, near simultaneous, significant height disturbances are observed at these stations. The significant height disturbances lasted for about 2 hours or longer. During the height lift, there is a foF2 depression as compared to the median or the pre-storm levels. After the anomalous height lift, the most significant feature of foF2 and hmF2 is wave-like disturbances. At Kokubunji, foF2 is a negative storm in general. At Wuhan and Chungli, the temporal behavior of foF2 consists of positive and negative phases, and the deviations are larger at Chungli. At Wuhan and Chungli, besides a positive phase peak at 00:00–00:30 UT, the change of foF2 on April 7 is generally negative. It should be noted that the equatorial anomaly tends to be more pronounced on April 8 and later days, and the ionosphere was at its positive phase.

The initial short positive phase before the SSC and the negative phase after the SSC on April 6 seem to be dynamically controlled, because the composition disturbances should propagate to these stations much later (Prölss, 1995). A very important factor influencing the F2 layer (Danilov and Lastovička, 2001) is the vertical plasma drift, which is caused by horizontal thermospheric circulation and electric fields. The effective drifts from ionospheric measurements and the behavior of hmF2 at these stations are well consistent with those predicted by the model of Fejer and Scherliess (1997) and Scherliess and Fejer (1997), which suggests that the penetration drifts and followed disturbed dynamo drifts may be the cause of the near simultaneous height disturbances. The followed wave-like disturbances have been investigated by Lee *et al.* (2002) and attributed to the effect of TADs propagation which originates in the energy and momentum deposition at high latitudes.

At middle latitudes, a possible explanation often assumes that positive ionospheric storms are caused by TADs and meridional winds, and negative ionospheric storms by changes in the neutral gas composition (Prölss, 1995). Mechanisms responsible for the disturbances on April 8 should explain the negative deviation in hmF2 and enhanced foF2 at Wuhan and Chungli. One possibility is the ceasing of meridional wind-induced perturbations or enhanced poleward winds. Equatorward winds will oppose the poleward transport of ionization along the magnetic fields lines. Opposite situation can well explain the ionospheric changes on April 8. But a confirmation of what causes enhanced equatorial fountain effects and height decrease during this storm is still lacking.

This storm also provides a good opportunity to verify the ability of empirical models. For this storm, the perturbed electric fields, or vertical drifts (Fig. 4), predicted by the model of Fejer and Scherliess (1997) and Scherliess and Fejer (1997), are well consistent with the behavior of hmF2 at low latitudes near 120°E. As for the STORM model (Araujo-Pradere *et al.*, 2001), it captures the general direction of foF2 negative change, but the TID-like disturbances on April 7 and positive phases on April 8 are not found from its predictions. And the negative phase after the SSC is also missed by the model. It should be mentioned that the low latitude ionosphere exists large day-to-day variations. So it is naturally hard to predict its behavior during storms, and there is also large ambiguity in choosing the reference level to determine the storm time variations. As the authors mentioned, the model predicts better at middle latitudes and in summer. The assumption of the model to the cause of the storm is the composition changes propagate from high latitudes to lower latitudes, which may be too simple and depart far away from the observations, especially to the low latitudes and for positive storms. Now, this empirical model has been included in the International Reference Ionosphere model as an option for the storm time prediction, so its current limitations should be realized when using it.

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