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Positive and negative ionospheric disturbances at middle latitudes during geomagnetic storms

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Abstract. The morphology of middle latitude ionospheric disturbances in response to geomagnetic storms has been investigated to determine the phenomenological differences between positive and negative ionospheric storm effects, using foF2 observations from azimuthal chain of stations. To better organize the disturbance signatures, two ionospheric indices were introduced to describe the maximum positive (Dfu-index) and negative (Dfl-index) deviation observed during an ionospheric storm. A systematic appearance of nighttime positive effects was determined with a 24-hour recurrence. The thermospheric-ionospheric view associated with positive and negative storm effects proposed by Prolss (1993) was extended to encompass our observations. This test clearly demonstrates that such a model can capture most of the basic aspects of ionospheric storms, nevertheless the prominent feature of large nighttime enhancements in the ionization density have yet to be explained.

Introduction

Positive and negative ionospheric storm effects are following the dissipation of solar wind energy to the upper atmosphere showing a strong dependence on local time (Prolss, 1995; Rishbeth, 1998). Negative storm effects are attributed to composition changes (Prolss et al., 1988; Field and Rishbeth, 1997; Rishbeth, 1998) and are the dominant characteristic in ionospheric response to geomagnetic activity enhancements (Cander, 1993; Cander and Mihajlovic, 1998; Szuszczewicz, 1998). It has been suggested that positive ionospheric storm effects are also caused by composition changes (Rishbeth, 1991; Fuller-Rowell et al., 1996; Field and Rishbeth, 1997; Field et al., 1998). There is a conflicting aspect that positive storm effects are caused by the transport of ionization (Prolss, 1995) either by electric fields (Reddy et al., 1990; Reddy and Nishida, 1992) or by thermospheric winds (Prolss, 1991; Prolss, 1993). A possible scenario for time sequence ionospheric-thermospheric storm effects was suggested by Prolss (1993) based on the assumptions that positive storms are attributed to meridional winds and negative ionospheric storms may be caused by changes in the neutral gas composition. According to this solar wind energy input injection to the polar upper atmosphere launches a so-called traveling atmospheric disturbance (TAD) causing at middle latitudes daytime positive storm effects of short duration by an uplifting of the F2 layer. On the other hand, the dissipation of solar wind energy input generates a permanent composition disturbance zone at polar latitudes. During disturbed conditions this zone expands toward middle latitudes in the post-midnight sector due to winds of moderate magnitude, designated as midnight surge (Killeen and Roble, 1986). At the recovery of the geomagnetic activity the composition disturbance region is simply rotated to the forenoon sector following the Earth's rotation and although is partially recovered the perturbations are still large enough to produce daytime negative ionospheric storm effects.

The aim of this contribution is a) to further distinguish between the phenomenological differences of positive and negative ionospheric storm effects and b) to compare the consistency of real observations with the Prolss model.

Data presentation and analysis

An experimental investigation on mid-latitude characteristics of the F region peak densities during two intense storms is presented. Simultaneous hourly foF2 observations from several mid-latitude stations globally distributed in longitude were analyzed for each event. A list of the stations is given in Table 1. The AE and Dst indices of hourly resolution were chosen as diagnostic tools of geomagnetic activity. The first event occurred on September 17, 1979 and the second one on December 19, 1980. Both are classified as intense geomagnetic storms having values of Dst < −100 nT (Kamide and Joselyn, 1991). A main distinction between the two events is the two-step main phase development characterizing the first event, which may be considered as the result of two closely spaced moderate storms (Kamide et al., 1998).

The relative deviations Df% in foF2 from their respective monthly median value, evaluated for the observatories LAN, DOU, MOS, TAS, ALM, IRK, WAK, PAR, BOU, and WAL, are given in Figure 1 together with the AE and Dst indices during the 17-19 September 1979 disturbance period. The event consists of two successive storms whose onsets are indicated by the two vertical lines. The storm onset occurred at 2200 UT on September 17, 1979, is followed by weak positive ionospheric storm effects observed at LAN, WAK, PAR, BOU and WAL, by weak negative ionospheric storm effects at ALM and TAS and by symmetric disturbance signatures at MOS and DOU. The effect of the second storm onset occurred

Table 1. A list of ionospheric stations (arranged by local time).

Name and	Code	Geomagnetic Lat(° N)	Local Time
Dourbes	DOU	51.6	UT
Lannion	LAN	51.8	UT
Poitier	POI	49.4	UT
Rome	ROM	42.2	UT+2
Moscow	MOS	50.7	UT+2.5
Alma Ata	ALM	33.5	UT+5
Tashkent	TAS	32.3	UT+5
Irkutsk	IRK	41.3	UT+7
Kokubunji	KOK	25.9	UT+9
Wakkanai	WAK	35.6	UT+9
Point Arguello	PAR	42.3	UT+16
Boulder	BOU	48.9	UT+17
Wallops Is	WAL	48.9	UT+19

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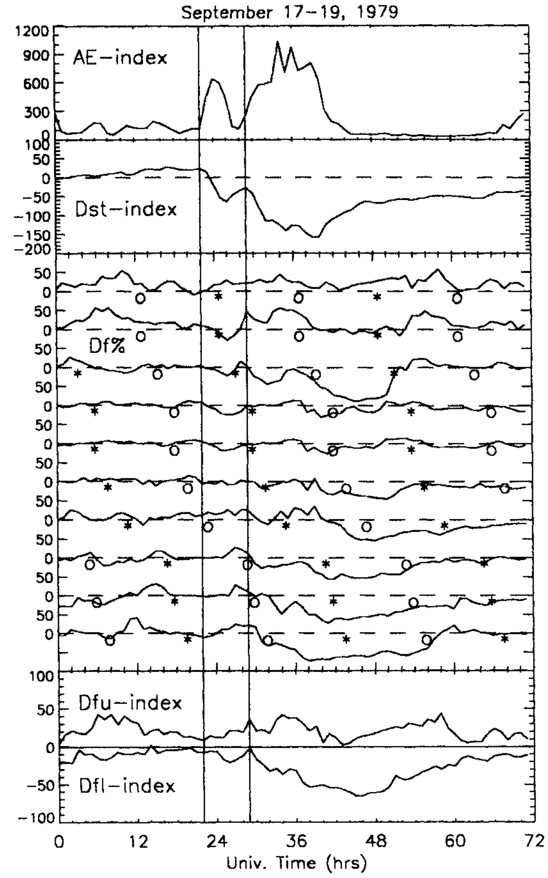

Figure 1. From top to bottom: hourly distributions of AE and Dst indices during the 17-19 September 1979 storm, the relative deviation, Df%, in foF2 from their respective monthly median values calculated on an hourly basis and finally the hourly values of the Dfu and Dfl ionospheric indices. The local noon and midnight is noted by the symbol (o) and (*) for each station respectively.

at 0500UT on the next day, is evident first in the three stations located in the American sector, PAR, BOU and WAL, that responded with a negative deviation in foF2, which lasted 24 hours. Going toward the east, typical daytime positive effects are observed at LAN and DOU, while MOS recorded a large negative storm with 6h time delay while rotated toward the night sector. Nighttime positive sharp effects are observed at WAK in the pre-midnight sector, followed by negative storm effects in the next day. Similar variations although weaker in intensity are seen at IRK, ALM and TAS.

In an attempt to correlate the ionospheric activity with global magnetospheric indices, two new indices were introduced to monitor the ionospheric disturbances at mid-latitudes worldwide. To define the two indices, Df% measurements from an azimuthal chain of mid-latitudes stations arranged by universal time, were superposed. The two indices Dfu and Dfl correspond to the upper and lower envelopes between which all curves lie. Consequently, Dfu-index records positive ionospheric disturbances, while Dfl-index refers to negative deviations. The inspection of these indices could lead to results concerning the maximum ionospheric perturbation at mid-latitudes during a storm. For the case study of September 1979, data from the above listed ten stations were used to derive the indices. The results are given in the last panel of Figure 1. Due to the inhomogeneous and sparse distribution of stations, the Dfl and Dfu indices do not contain full information on the maximum ionospheric deviation observed worldwide. They give though a rough global picture of the storm effect at mid-latitudes. In this case a good correlation between Dst and Dfl indices is obvious. Another interesting remark is the systematic occurrence of positive perturbations through the main and the recovery phase of the storm.

The second case study occurred on December 18-21, 1980. The hourly Df% variations evaluated for POI, ROM, KOK, WAK, PAR and BOU are given in Figure 2 together with the hourly AE and Dst indices. The two ionospheric indices Dfu and Dfl, are also presented in Figure 2. Prior to the geomagnetic storm onset, indicated by the vertical line in Figure 2, the magnetosphere was in a disturbed condition; at least three magnetospheric substorms were recorded by AE index from 0200UT of December 19, to 1200UT of next day. The mid-latitude ionosphere responded to this magnetospheric disturbance with a series of positive effects observed in all the stations of the chain. The Dfu-index shows also the dominance of positive effects during this period. The expansion of the geomagnetic storm produced strong ionospheric disturbances, as can be seen by the isolated stations and the ionospheric indices as well. As an immediate response, strong negative storm effects are clearly seen at BOU, followed by large nighttime enhancement in the ionization density. Similar effects but of weaker intensity are recorded at PAR. In the European sector, large enhancements – lasted for about 10 hours - in the ionization density are recorded around local midnight at POI and ROM. Weaker positive disturbances recorded before local noon at WAK and KOK followed by negative storm effects appeared about 20

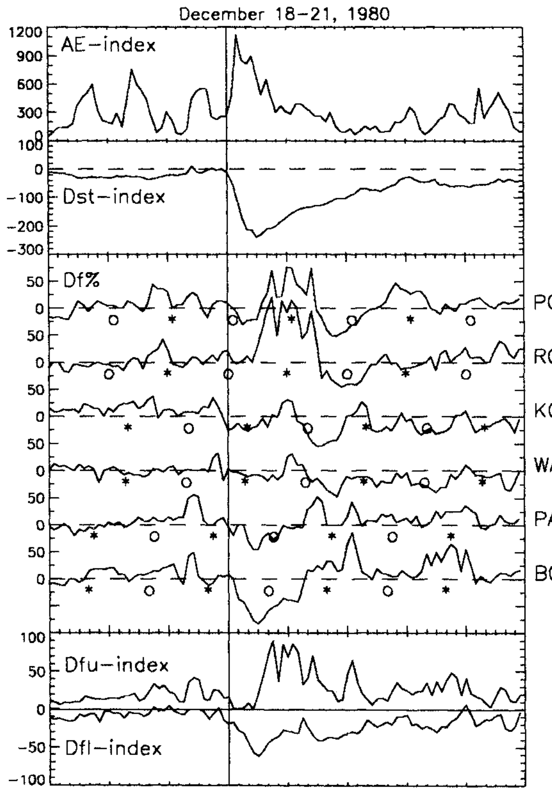

Figure 2. Same as Figure 2 for the geomagnetic storm occurred on December 18-21, 1980.

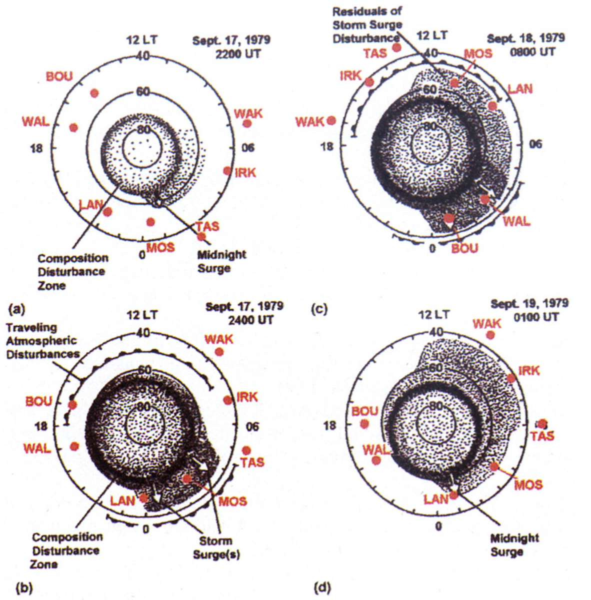

Figure 3. The time sequence of thermospheric-ionospheric storm effects caused by the geomagnetic storm occurred on September 17-19, 1979.

hours after the storm onset. It should be also noticed that nighttime enhancements recorded at BOU, PAR and POI present a clear 24 hours recurrence.

In summary, positive storm effects present a spiky structure, following with a certain time delay the AE enhancements. Positive storm characteristics are more often observed at nighttime than during daytime, in both events. Nighttime enhancements last much longer than daytime do and are generated in the dusk sector. Another noticeable difference between nighttime and daytime enhancements is that the former present a clear tendency for 24 hours recurrence, which is obvious from the inspection of Dfu-index time plots.

Negative storm effects are smooth in nature and last up to 24 hours. They follow geomagnetic storms only. They correlate reasonably well with the Dst index during the whole development of the geomagnetic storm, as can be seen from the Dfl index general shape. They appeared as the dominant ionospheric response, in some cases though, as in the first event, positive storm effects are the only type of response throughout the whole event recorded by two stations (DOU and LAN). Stations located in the post-midnight sector are the first to be affected by negative effects. All remaining stations will record negative effects with a time delay increasing from midnight sector in the clockwise direction.

Local time variations of the ionospheric storm effects

The time sequence of thermospheric-ionospheric storm effects presented here was based on Prolss (1993) model. This model presents an ionospheric storm scenario caused by an isolated geomagnetic storm with well-defined phases. To encompass real conditions of disturbed magnetosphere preceding the storm onset, an additional sequence was considered in its original view. A detailed presentation of the modified model is given for each event in Figures 3 and 4. The distribution of stations in local time frame from above onto the northern hemisphere is also included. Three concentric circles indicate the location of 80, 60, 40° magnetic latitude.

17-19 September 1979, event: Figure 3a illustrates pre-storm conditions. A neutral composition disturbance zone indicated by the dotted area due to moderate geomagnetic activity is restricted in general to the higher latitudes. Indeed, no significant disturbance effects during this interval are recorded at mid-latitudes. Figure 3b represents the ionospheric state 2h after the first storm onset. A TAD is moving toward lower latitudes and expansion of composition disturbance zone to mid-latitudes is observed. Positive storm effects recorded at the WAK station may be attributed to TAD since this station was located in the forenoon sector. On the other hand, positive storm effects at LAN, PAR, BOU and WAL recorded in the pre-midnight sector cannot be justified in the frame of this model. Figure 3c is referred to the ionospheric state 3 h after second storm onset. The composition disturbance zone generated in the post-midnight sector is now rotated in the forenoon sector but the new burst of activity generates a new disturbance zone in the post-midnight sector. The ionospheric stations of BOU and WAL record intense negative storm effects that may be associated to composition changes since the two stations were embedded in this newly generated disturbance region. Any new burst of activity may generate another TAD and a further positive storm effect but this could not be the explanation for the positive storm effects recorded at WAK and probably IRK during this phase since they were located in post-midnight sector. Combined study of Figures 1 and 3 results in that nighttime enhancements become clearer and intense as closer a station is located to the pre-midnight sector when the geomagnetic storm initiates. Figure 3d covers the storm recovery phase. The disturbance region generated in the post-midnight sector due to last storm activity has simply rotated into the forenoon sector. WAK, IRK and TAS are very close to the equatorward boundary of the disturbance zone and record weak negative ionospheric storm effects.

18-21 December event: Figure 4a illustrates again pre-storm conditions. Figure 4b is representative for the substorm expansion phase. Weak positive storm effects observed at POI and ROM may be explained in terms of TADs. Figure 4c is referred to the ionospheric state during the storm main phase.

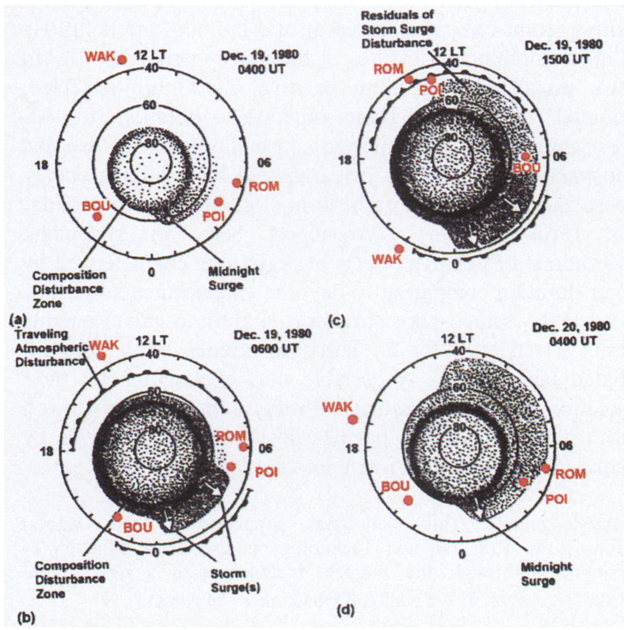

Figure 4. The time sequence of thermospheric-ionospheric storm effects caused by the geomagnetic storm occurred on December 18-21, 1980.

In the meantime interval BOU rotated towards the disturbance zone previously generated in the post-midnight sector, which is now located in the forenoon sector and records intense negative storm effects. Later during this phase, positive storm effects appeared at POI and ROM locations around midnight. Consequently, they cannot be attributed to TADs generated by new burst of activity, which is probably the case for observed positive storm effects recorded at WAK prior to local noon. Figure 4d refers to the storm recovery phase. The composition disturbance region has simply rotated into the forenoon sector including POI and ROM, which now record negative storm effects less intense than those recorded previously at BOU. The other two stations are away from the disturbance zone.

Discussion and Conclusions

A strong dependence of negative storm effects occurrence at mid-latitudes on geomagnetic activity level was detected, since these effects were observed as response to geomagnetic storms and not during a substorm lifetime. Since Dst index is resulted from a number of contributing sources acting either serially or concurrently to compose a geomagnetic storm it is expected that negative storm effects and Dst development are connected -probably indirectly-through a fundamental process that governs the geomagnetic storm phenomenon. The above is supported by the visual correlation of negative storm effects and Dst index shape. Negative storm effects are triggered and driven by the solar wind energy deposition to the auroral ionosphere but they are furthermore modified by a number of contributing mechanisms. According to Prolss scenario, negative storm effects are attributed to composition changes and this explanation fits reasonably well to our observations and to determined characteristics of these effects. An interesting point resulted from the above analysis is that any new burst of storm activity denoted by a new Dst reduction is associated to a new generated disturbance zone. The two disturbance zones, the previous and the new generated, are superimposed and co-exist as the first is moving into the forenoon sector making possible the simultaneous recording of negative effects from stations located in the post-midnight and forenoon sectors.

Positive storm effects observed at mid-latitudes are definitely the most unpredicted features of the ionospheric response. In Prolss model only daytime positive effects are expected, attributed to TADs. Their obvious correlation to AE enhancement may be expected since TADs are pulse-like atmospheric perturbations just triggered by a sudden energy release and then moving in the form of global and circumpolar front (Prolss, 1995). We report here on systematic observations of positive effects at nighttime, characterized by longer duration comparing to daytime enhancements but they all have the same spiky structure. Nighttime enhancements present a tendency for 24 hours recurrence while they all initiated before dusk. A possible thus explanation for their generation may be consistent with the point of Fuller-Rowell et al. (1994) suggesting that if a positive phase is driven by winds before dusk it will rotate into the night side.

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