J Geophys (1984) 56:47–52

Journal of Geophysics

Increased ionospheric absorption connected with Pc 1 pulsations after geomagnetic storms

F. Märcz

Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences, H-9401 Sopron POB 5, Hungary

Abstract. Short-period magnetic pulsations (Pc 1 and IPDP) recorded during IMS at high latitudes in Finland have been studied around selected geomagnetic storms. As at lower latitudes, Pc 1 pulsations at five Finnish stations are generally missing during the main phase of the storm. However, they frequently occur some days later. Both statistical analyses (by the superposed epoch technique) and the review of individual events have shown that the after-effect in mid-latitude ionospheric absorption is generally significant following storms associated with clear Pc 1 after-effects at each high-latitude station. Using several parameters as indicators, the sequence of processes of importance to the after-effect in ionospheric absorption can be traced in the individual cases presented. The electron precipitation into the lower ionosphere (leading to the enhancement of ionospheric absorption) is usually attributed to resonant pitch angle scattering. The efficiency of this loss process can certainly depend on the occurrence of plasmaspheric whistler mode turbulence which is generally enhanced in the post-storm period. It is also suggested that periodic VLF emissions are involved in the processes generating Pc 1 pulsations. Ground-based Pc 1 observations can help to identify the probable appearance of VLF and/or ELF waves in the plasmasphere.

Key words: Geomagnetic activity – Short-period pulsations – Plasmaspheric waves – Electron precipitation – Lower ionosphere – Absorption after-effect

Introduction

Occurrences of short-period magnetic pulsations (Pc 1 and IPDP) recorded during IMS years at five high-latitude stations (Kevo, Sodankylä, Oulu, Jyväskylä and Nurmijärvi) in Finland have been published in the form of quick-look tables (Pikkarainen et al. 1982). A recent study (Märcz et al. 1984) has reviewed the latitude dependence of these types of pulsations and their association with certain magnetic and ionospheric parameters. Previously, a clear relation of the after-effect in ionospheric absorption to pearl-type (Pc 1) pulsations was shown on the basis of middle latitude data (Märcz and Verö 1977). The above-mentioned quick-look tables made possible the investigation of the dependence of high-latitude Pc 1 and IPDP events on geomagnetic disturbances. The main purpose of this paper is to confirm the connection of the after-effect in mid-latitude ionospheric absorption with Pc 1 pulsations on the basis of pulsation observations along a meridional chain of high-latitude stations. Additionally, it will be shown that the post-storm increase of Pc 1 activity can be regarded as an indicator of the plasmaspheric turbulence and wave-particle interaction generally enhanced during the recovery phase of the magnetospheric storm. This is a signature obtained from ground-based records and might be useful, especially in the case of missing satellite observations. Results derived from statistical analyses and individual case studies are presented.

Data and methods of investigation

The data published in the quick-look tables contain Pc 1 and IPDP events between October 1976 and December 1979 for each station as a function of time (UT). The two types of pulsations have not been separated from each other in the tables. Nevertheless, Pc 1s occur mostly during the morning-day hours and IPDPs during the afternoon-evening hours. In order to yield an appropriate activity measure for both types, the individual occurrences were summarized for each day separately from 0000 to 1200 UT (a.m.) and from 1200 to 2400 UT (p.m.). For a.m. (Pc 1) pulsations a further separation was carried out between 0000 and 0600 UT and between 0600 and 1200 UT respectively, allowing independent analyses with night-time and day-time data.

On the basis of the daily sums of three-hourly *Kp*-indices (ΣKp), days of geomagnetic disturbances were selected and used as key days for superposed epoch analyses. The two combined criteria applied for the selection are as follows: on key days ΣKp must be $\geqq 30$ and in addition, on two out of the three days preceding the key day the actual ΣKp value must not exceed the long-term average determined for the corresponding year. These criteria resulted in the selection of disturbances reaching distinct peak values which were also well separated from each other. Altogether, 46 key days were found for the superposed epoch analyses.

The duration of a.m. and p.m. pulsations has been studied in two independent analyses covering the interval between the third day preceding and the tenth day following the key day. Furthermore, ionospheric absorption has been analysed by separating also the cases of storms with clear Pc 1 events and those without them. The ionospheric night absorption data determined at mid-latitude in Kühlungsborn (GDR) by the A3 method (at 245 kHz) are used (HHI

Geophys. Data, 1976–1979). In the detailed study of an individual event the Průhonice absorption data (at 185 kHz) are also presented for comparison (Ionospheric Data, Praha, 1978).

Results

The occurrence of a.m. (Pc 1) and p.m. (IPDP) pulsations on days around geomagnetic disturbances

The changes in the summarized durations around the 46 key days are shown in Fig. 1 for both a.m. (left) and p.m. (right) pulsations observed at five high-latitude stations. The features of the variations are rather different in the two sections of Fig. 1 hinting at individual responses to the geomagnetic disturbances. This confirms that two, really quite independent types of pulsations have been separated on the basis of their daily occurrence.

The a.m. events actually represent the Pc 1s; this is also indicated by their clear increase for several days following the geomagnetic disturbances (after-effect), as found earlier for the middle latitudes (Märcz and Verö 1977). Another feature indicated by the study of Märcz and Verö (1977), viz. Pc 1 activity is lowest at the time of peak geomagnetic activity (around the 0 day), seems to be common at high latitudes too.

The p.m. occurrences are presented on the right, of Fig. 1. There is only one characteristic change in dependence on increased geomagnetic activity. Short-period p.m. occurrences, accepted as IPDP events, are intensified by the geomagnetic disturbances at certain stations and are generally more frequent in the post-storm interval than before the storm.

Dividing the a.m. occurences into two groups from 0000 to 0600 UT and from 0600 to 1200 UT, the night-time and day-time Pc 1 occurrences can be analysed separately. This has been done in Fig. 2 (left and right) where the variations are generally similar. However, certain peculiarities also appear. At each station, the night-time Pc 1 activity (left) is quite low on days close to the storm (0 day) and a rather broad occurrence maximum can be seen between the days +5 and +9. The latter proves the uniform appearance of the after-effect in night-time Pc 1s at high latitudes.

For day-time Pc 1s (Fig. 2, right), the decrease of the pre-storm activity level towards the storm-day is generally slight. However, it is quite important at the lowest latitude (Nurmijärvi). The occurrence maximum is expressed by a distinct peak on the fifth day following the key day, at all stations except Kevo. In spite of the exceptions mentioned, the after-effect is clearly present in the day-time Pc 1s too. Finally, a comparison of the two sections in Fig. 2 confirms that Pc 1 activity is generally higher during day-time hours (06–12) than at night (00–06), especially at the three stations situated at higher latitudes.

After-effect in ionospheric absorption associated with the appearance of Pc 1 events at high latitudes

Superposed epoch analyses. In Fig. 3 (top), mean values of ΣKp indicate the variation of geomagnetic activity around the 46 days selected as key days for the previous analyses. The horizontal dashed line represents the averaged activity determined for the period between October 1976 and December 1979. It is evident that geomagnetic activity approaches its average level soon after the disturbances. Consequently, the enhanced Pc 1 activity following the storm (Figs. 1 and 2) can be regarded as an after-effect.

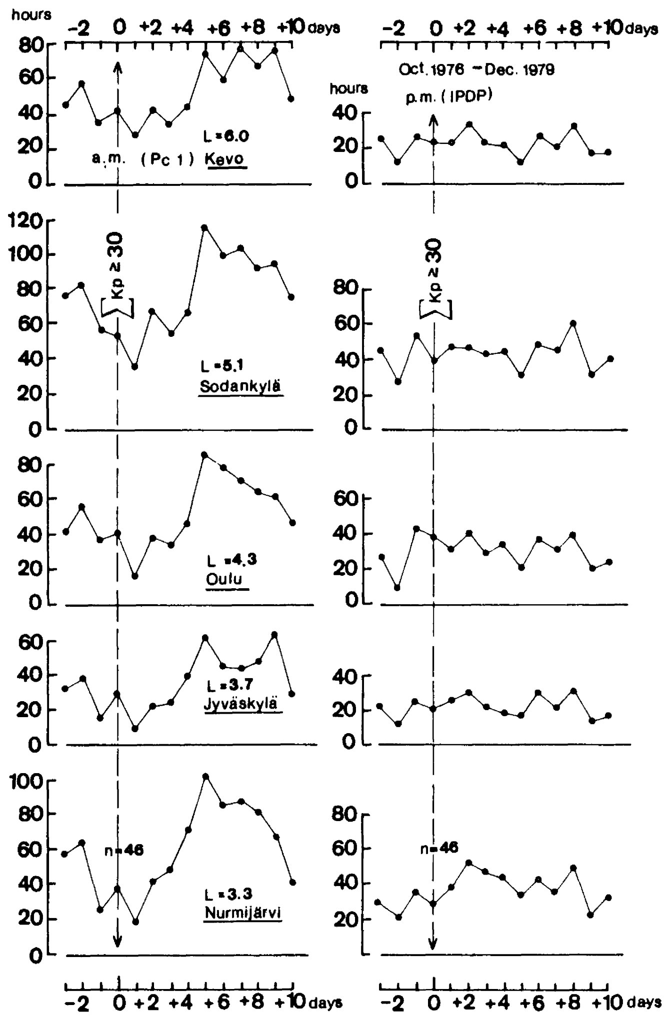

Fig. 1. Changes in the total duration of short-period magnetic pulsations observed at five stations in Finland around the 46 selected geomagnetic storms, between October 1976 and December 1979. *Left*: for a.m. pulsations accepted as Pc 1s. *Right*: for p.m. pulsations accepted as IPDPs

Figure 3 (bottom) shows the mean departure of ionospheric night absorption (determined at 245 kHz at Kühlungsborn, GDR) from the corresponding monthly medians, around the selected 46 geomagnetic disturbances. The highly increased ionospheric absorption on 0 day can be identified as the primary storm effect. There is also a smaller, but rather prolonged absorption enhancement in the interval when the geomagnetic activity has returned to its normal level. This additional increase can be interpreted as an after-effect. On the basis of the error bars indicated in Fig. 3, the significance of the primary storm effect is apparent, but this can hardly be said of the after-effect.

It is known that not every geomagnetic disturbance is followed by enhanced ionospheric absorption (e.g. Lauter and Knuth, 1967). Nevertheless, it was shown that, in the case of a clear after-effect in Pc 1 pulsations, a post-storm enhancement is also most likely to occur in ionospheric absorption (Märcz and Verö, 1977). This connection was

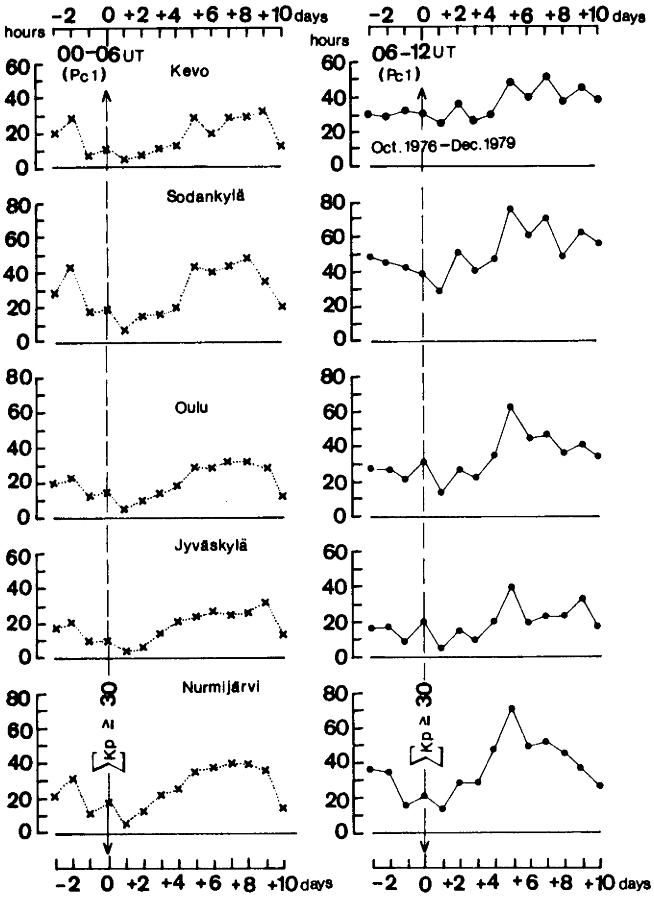

Fig. 2. Changes in the total duration of night-time Pc 1s (*left*) and day-time Pc 1s (*right*) around the same storms as in Fig. 1

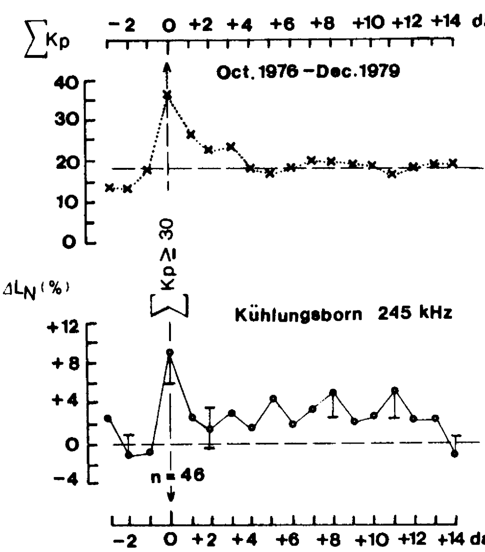

Fig. 3. *Top*: Variations in geomagnetic activity indicated by mean values of the daily *Kp*-sums around the 46 selected storms. (The *horizontal dashed line* indicates the average activity determined for the investigated interval.) *Bottom*: Mean departure of ionospheric night absorption from corresponding monthly medians (ΔL_N given in percent) around the same storms as in the top figure

revealed by means of mid-latitude pulsation observations (at Irkutsk and Nagycenk). Here, Pc 1 pulsation data from five high-latitude stations are used for proving the connection on an extended data base and for introducing some new aspects.

The occurrence of an after-effect in the pearl-type pulsations has been checked by determining a suitable ratio (R) of the Pc 1 durations following and preceding the geomagnetic storm. (In each individual case, the summarized daily durations of the interval between days +5 and +9 were divided by the summarized and appropriately weighted durations of the pre-storm interval between days −3 and −1.) Events with $R > 1$ can be accepted as after-effects. However, for the analysis of rather clearer effects an even stronger criterion ($R \geqq 1.7$) was used. Two independent ratios were determined for each selected storm, one from the night-time (00–06 UT) and another from the day-time (06–12 UT) Pc 1 occurrences. Data from all the stations mentioned were treated in this way. Consequently, both the day-time and the night-time appearance (or lack) of the Pc 1 after-effect could be traced in a wide latitude range and, on this basis, different kinds of events might be distinguished.

Two special groups of events were chosen for testing the relationship between the high-latitude Pc 1 occurrences and the mid-latitude ionospheric absorption enhancements. One group consisted of events when the selected geomagnetic disturbances were followed by Pc 1 after-effects at each of the five stations. The other group of events served as a control. For these geomagnetic storms, the Pc 1 after-effects completely failed to appear at every high-latitude station. Considering both kinds of events, ionospheric night absorption determined at mid-latitude was analysed by the superposed epoch method and the results are presented in Fig. 4.

The night occurrences (00–06 UT) of the Pc 1s indicated clear after-effects for ten storms at all stations. (The mean value determined from the individual ratios of the five stations was higher than 1.7 in each case.) The corresponding increase in the ionospheric night absorption is quite significant (Fig. 4b). For the eight storms chosen without a Pc 1 after-effect at all five stations, no regular absorption variation appears (Fig. 4a). On the basis of day-time (06–12 UT) pulsations, again ten storms were selected when the Pc 1 after-effects occurred at all the stations. (The dates of the storm-days were only partly the same as those of the previous selection on the basis of night-time Pc 1s. However, the mean value of the ratios was at least 1.7 for these cases too.) The corresponding after-effect for ionospheric absorption shown in Fig. 4d is also significant, though its amplitude is somewhat lower than that in Fig. 4b. Storms without any after-effect in day-time Pc 1s (for all the stations) are rather rare and only four events of this kind were selected out of the 46 storms studied. In Fig. 4c the changes in ionospheric absorption for these four events are quite irregular, partly due to the small data set. For the evaluation of the results, error bars are given at main maxima and local minima approaching the average level (Fig. 4b and d). The error bars drawn at the horizontal dashed line (representing the average absorption level) have been determined from data of the pre-storm interval between days −3 and −1 (Fig. 4a–d).

For further analysis, all geomagnetic storms followed by after-effects in Pc 1 pulsations (i.e. the required criterion was fulfilled at each station) were collected into a common

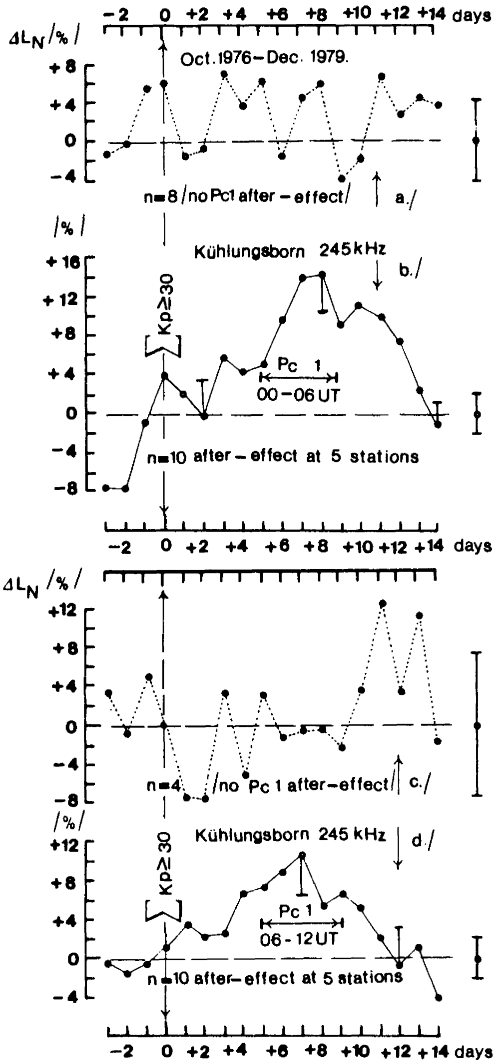

Fig. 4a–d. Mean departure of ionospheric night absorption from corresponding monthly medians for different storm events selected on the basis of Pc 1 pulsations: the after-effect in night-time Pc 1 pulsations **a** is missing **b** is clear and at each investigated station; the after-effect in day-time Pc 1 pulsations **c** is missing **d** is clear and at each investigated station

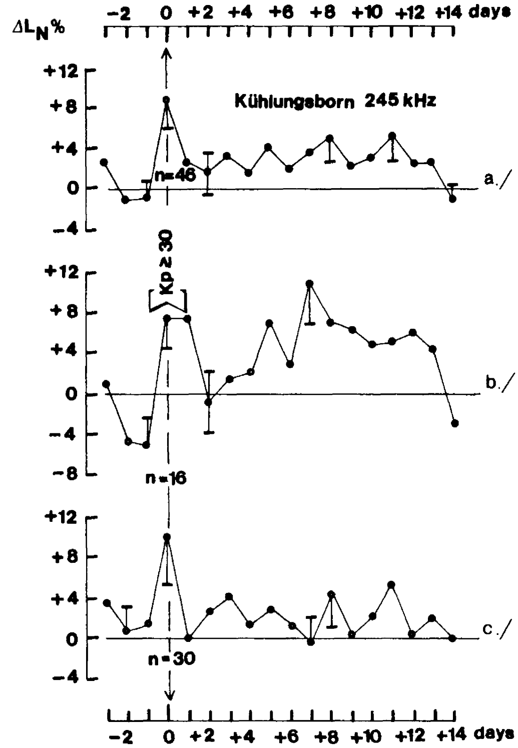

Fig. 5a–c. Mean departure of ionospheric night absorption from corresponding monthly medians for different storms: **a** for the 46 selected stomrs (as in Fig. 3, bottom) **b** for storms followed by clear after-effects in Pc 1 pulsations at all stations (without regard to the time of Pc 1 occurrences) **c** for the rest of the storms

group, whether the after-effect occurred in the night-time (00–06 UT) or the day-time (06–12) pulsations. Altogether 16 events were selected from the original set (46). The changes in ionospheric night absorption around these storms are shown in Fig. 5b. The primary storm effect on the days 0 and +1 is followed by a long-lasting after-effect with a peak on day +7. The enhancements are rather significant, as indicated by the error bars. For comparison, the variations of ionospheric absorption for the total number (46) of geomagnetic storms (Fig. 5a) and for the rest of the events (30) without a clear Pc 1 after-effect (Fig. 5c) are also shown. In both cases, there is an important primary storm effect, but the after-effect is not significant. This indirectly confirms the importance of geomagnetic storms followed by strong Pc 1 activity with regard to the absorption after-effect.

Study of individual events. Figure 6 has been compiled to illustrate, by means of a case study, the following: the absorption after-effect on the basis of A3 measurements at two mid-latitude propagation paths (with different frequencies), the occurrences of Pc 1 pulsations at five high-latitude stations and the changes in geomagnetic activity indicated by ΣKp indices, as well as the equatorial *Dst*-variations. The *Dst*-index can be regarded as a suitable indicator of the hot plasma injections in the main phase and during the recovery phase of the magnetospheric storm (Lauter et al. 1977).

From a detailed analysis of the magnetospheric storm event in September/October 1978, it is clear that the highly increased geomagnetic activity around the 0 day (29 September) is not favourable for the appearance of Pc 1 pulsations. At the same time, the large positive departure (>40%) in ionospheric absorption from the corresponding monthly median, determined for Kühlungsborn (245 kHz), indicates a prominent primary storm effect, but the latter is quite small at a lower latitude (Průhonice, 185 kHz). After one day the *Dst*-field recovers strongly from about −200 nT and, at the start of its slow recovery phase, a peak of enhanced absorption appears at Kühlungsborn as a signature of the after-effect. On 4 October, the recovery phase is interrupted by a minor decrease of *Dst*, thus a new particle injection into the plasmasphere could occur. This is associated with increased Pc 1 activity at each station which can be regarded as a signature of enhanced plasmaspheric turbulence including VLF and/or ELF wave activity. Presumably, these magnetospheric conditions were favourable for effective wave-particle interactions and particle precipitation. As a consequence, ionospheric absorption increased once again at Kühlungsborn and reached its peak value at Průhonice. Similar processes can also be traced

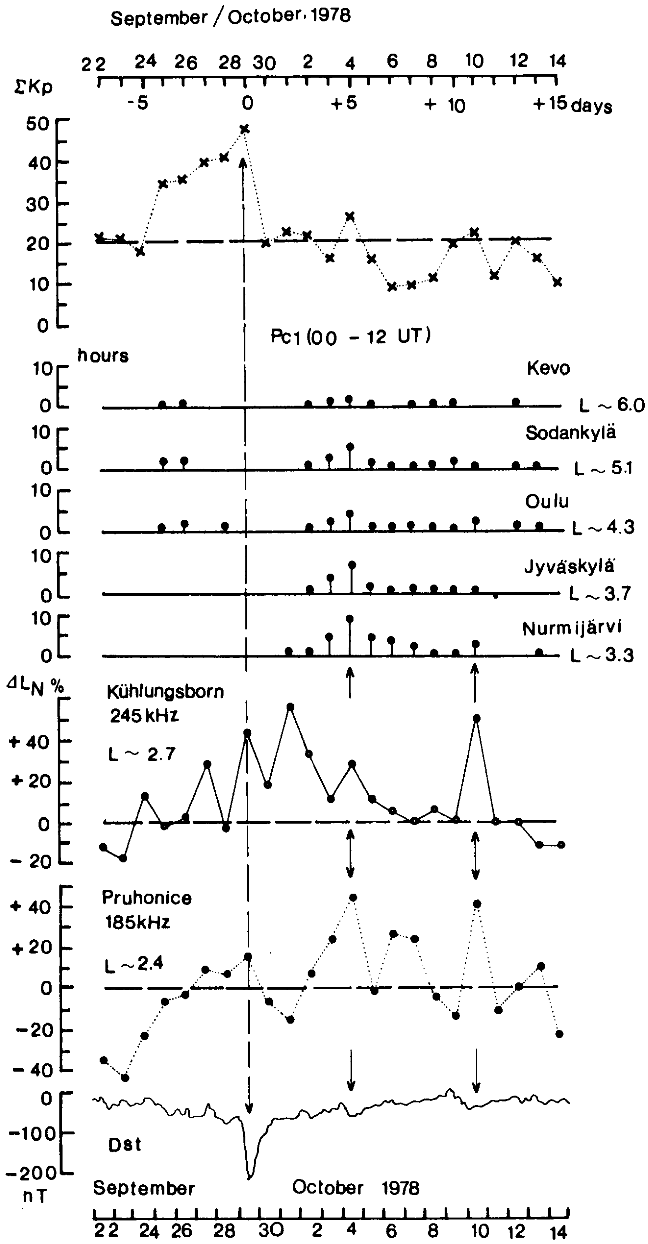

Fig. 6. Variations in several paramters during the September/October, 1978 event. (The parameters shown from *top to bottom* are the daily ΣKp-values, the Pc 1 durations at five high-latitude stations, the ionospheric night absorption at two mid-latitude stations and the *Dst*-index)

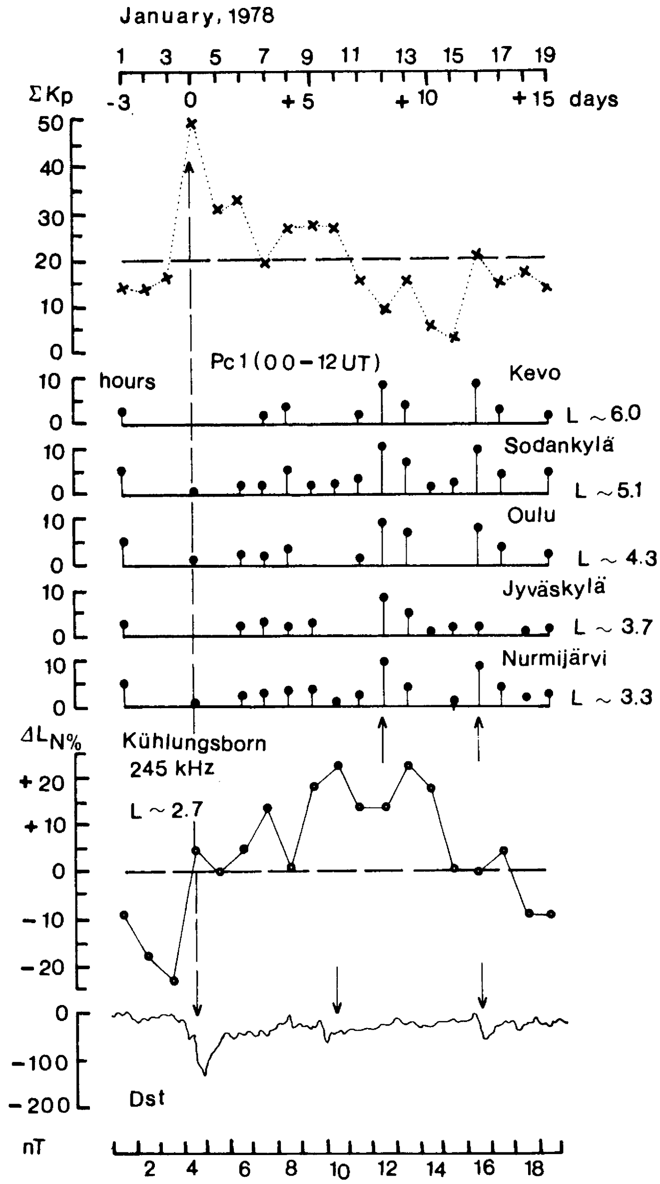

Fig. 7. As Fig. 6 but for the January 1978 event. (Ionospheric absorption is only shown for Kühlungsborn, as Průhonice data are partly missing)

on 10 October, the enhancement in Pc 1 activity being quite moderate, however.

In Fig. 7, the January 1978 event shows, in its initial section, features essentially similar to those in Fig. 6, with the exception of a rather slight primary storm effect in ionospheric absorption. The minor re-enhancement of the *Dst*-field on 10 January should be associated with a particle injection and the simulatneous maximum of increased ionospheric absorption hints at the efficiency of the particle precipitation in spite of the somewhat declining Pc 1 activity. From 12 January the latter becomes reinforced while the *Dst*-filed shows only a slight change, thus an enhanced plasmaspheric wave activity could be responsible for a new particle precipitation indicated by the repeated increase in ionospheric absorption on 13 January. Finally, on 16 January both the *Dst*-field and the Pc 1 activity are strengthened, but the following increase in ionospheric absorption is of no importance. It can be argued that the slot region electrons have been depleted to a high degree by the previous loss processes. Consequently the new particle injection and the probable presence of plasmaspheric waves could only result in a slight electron precipitation. This might be unsatisfactory for influencing the radio wave absorption, but effective for Pc 1 generation. (Processes which are probably responsible for Pc 1 generation will be discussed in the next section.)

Discussion

The excessive ionospheric absorption of radio waves at middle latitudes well after the geomagnetic storm (i.e. the after-effect) is due to increased electron density in the lower ionosphere. The increase in electron density (between about 95 and 75 km) results from enhanced ionization due to high energy electrons (>40 keV) precipitating from the outer radiation belt of the magnetosphere (Lauter and Knuth, 1967). During the main phase of the storm both protons (ions) and electrons are injected into the inner magnetosphere. The increased radial fluxes result in filling up the slot region and the plasmapause moves inwards to lower L values. It has been considered that the interaction between the cold plasma of the plasmasphere and the hot plasma of the plasma-sheet is an important process for particle precipitation (Lauter et al. 1977). From the start of the recovery phase the plasmapause moves outwards and the loss processes become effective. As the trapped electrons are lost to the atmosphere by resonant interaction with whistler mode turbulence (Spjeldwik and Thorne, 1975), the occurrence of VLF and/or ELF waves in the plasmasphere is another vital condition for particle precipitation. Some of these processes are thought to be involved in the generation of Pc 1 pulsations, thus an explanation for the connection of increased ionospheric absorption with Pc 1s should be sought for on this basis.

According to the initial ideas of several authors, Pc 1 pulsations result from bunches of trapped particles bouncing between conjugate points (e.g. Jacobs, 1970). Their generation might be due to ion cylotron resonance and the outer plasmasphere seemed to be the most probable generation region (e.g. Lewis et al., 1977).

Bell (1976) presented a model of artificial pulsation generation which is based on a several-stage process involving pulsed VLF transmissions. According to the Bell (1976) mechanism, Pc 1 pulsations can be stimulated in the following way: from a ground- or satellite-based VLF transmitter, repetitive pulses are injected into the magnetosphere where VLF emissions are triggered and energetic electrons can be precipitated into the ionosphere due to wave-particle interaction; the precipitated flux of electrons modifies the conductivity of the lower ionosphere (D and E regions), inducing periodic changes in the current flow which in turn result in the generation of Pc 1 ULF waves. Consequently, the ULF magnetic field perturbations can be observed directly as pulsations on the ground.

Fraser-Smith and Helliwell (1980) suggested that these processes should also be effective for repetitive VLF activity occurring naturally in the magnetosphere. Recent investigations by Sato (1984) actually yielded experimental evidence for this mechanism. A close correlation between periodic VLF emissions ($T \sim 5.6$ s) and short-period magnetic pulsations was found at Syowa Station ($L \sim 6$) in Antartica.

Conclusions

The connection of increased ionospheric absorption with Pc 1 pulsations, revealed for mid-latitudes by Märcz and Verö (1977) and confirmed in the present study for high latitudes, is not inconsistent with the previously discussed findings. As mentioned, the increase of ionospheric absorption following certain geomagnetic storms is generally attributed to energetic electrons precipitating from the magnetosphere. If the electrons are precipitated by periodic VLF emissions with a repetition time corresponding to the period range of Pc 1s (0.2–5 s), the generation of this type of pulsations can also be expected on the basis of the Bell (1976) mechanism and in accordance with the results of Sato (1984). The latter author (Sato, 1984) has shown that periodic VLF emissions could be observed simultaneously at ISIS 2 satellite level (~1,400 km altitude) in the wide latitude range from $L \sim 3.5$ to $L \sim 14.0$ and on the ground at Syowa. Furthermore, at this station the magnetic pulsations also had the same periods as the repetition time of VLF emissions.

On this basis we have to suggest that both the post-storm increase in ionospheric abosrption at mid-latitudes and the enhanced Pc 1 activity at high latitudes (which generally appear simulateneously, as shown for individual cases in Figs. 6 and 7) might originate from the same sources through processes including the electron precipitation due to VLF emissions in the magnetosphere. Actually, the present study has confirmed that ground-based Pc 1 records can be used as an appropriate tool for selecting geomagnetic storms which are probably followed by plasmaspheric turbulence (in the VLF or ELF band) associated with an effective particle precipitation, which finally results in the increase of radio wave absorption.

References

Bell, T.F.: ULF wave generation through particle precipitation induced by VLF transmitters. J. Geophys. Res. **81**, 3316–3326, 1976

Fraser-Smith, A.C., Helliwell, R.A.: Stimulation of Pc 1 geomagnetic pulsations by naturally occurring repetitive VLF activity. Geophys. Res. Lett. **7**, 851–853, 1980

HHI Geophys. Data, Vol. 27–30, Berlin, 1976–1979

Ionospheric Data, Observatories Průhonice and Panska Ves, Czechoslovak Acad. Sci. Geophys. Inst. Praha, 1978

Jacobs, J.A.: Geomagnetic micropulsations. Berlin. Heidelberg, New York: Springer 1970

Lauter, E.A., Knuth, R.: Precipitation of high energy particles into the upper atmosphere at medium latitudes after magnetic storms. J. Atmos. Terr. Phys. **29**, 411–417, 1967

Lauter, E.A., Bremer, J., Grafe, A., Deters, I., Evers, K.: The post-storm ionisation enhancements in the mid-latitude D-region and related electron precipitation from the magnetosphere. HHI-STP-Report, No 9, Berlin, 1–86, 1977

Lewis, P.B. Jr., Arnoldy, R.L, Cahill, L.J. Jr.: The relation of Pc 1 micropulsations measured at Siple, Antarctica, to the plasmapause. J. Geophys. Res. **82**, 3261–3271, 1977

Märcz, F., Verö, J.: Ionospheric absorption and Pc 1-type micropulsations following enhanced geomagnetic activity. J. Atmos. Terr. Phys. **39**, 295–302, 1977

Märcz, F., Verö, J., Bencze, P.: Short-period pulsations observed in Finland during the IMS and certain associations with magnetic and ionospheric parameters. Acta Geodaet. Geophys. Mont. Hung. **19**, (3–4) 1984 (in press)

Pikkarainen, T., Lukkari, L., Niskanen, J., Kangas, J.: Quick-look tables of Pc 1 and IPDP magnetic pulsatin events recorded in Finland during IMS-years 1976–1979. Department of Physics, University of Oulu, Report No. 92. 1–78, 1982

Sato, N.: Short-period magnetic pulsations associated with periodic VLF emissions ($T \sim 5.6$ s). J. Geophys. Res. **89**, 2781–2787, 1984

Spjeldvik, W.N., Thorne, R.M.: The cause of storm after-effect in the middle latitude D-region. J. Atmos. Terr. Phys. **37**, 777–795, 1975

Received: May 2, 1984; Revised Version: August 25, 1984
Accepted: September 12, 1984