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Storm-time Pc1 activity at high and middle latitudes

R. Kerttula, K. Mursula, and T. Pikkarainen
Department of Physical Sciences, University of Oulu, Oulu, Finland

J. Kangas
Sodankylä Geophysical Observatory, Sodankylä, Finland

Abstract. We study structured and unstructured Pc1 pulsations observed at a high-latitude station (Sodankylä; $L = 5.1$) and a midlatitude station (Nurmijärvi; $L = 3.3$) during 18 storms occurring in low solar activity years (1976-1978 and 1984-1988). Pc1 activity was studied from the day of storm sudden commencement (denoted by day 0) onward during six consecutive days. While unstructured pulsations are only weakly affected, structured pulsations are greatly dependent on storm evolution. During the storm main phase they nearly vanish on the ground, despite strong wave activity in space. Structured Pc1 activity increases from day 0 to day 4 by a factor of about 4-5, reaching maximum occurrence on day 4 at both stations. Also, the average daily frequency of structured Pc1s increases from day 0 to a maximum on day 3 at Nurmijärvi or day 4 at Sodankylä. The diurnal distribution of structured Pc1s suffers a dramatic change during the storm. On days 1 and 2, structured pulsations are strongly concentrated in the evening sector, but during the later recovery (days 3-5) the activity shifts to the morning sector. The latitudinal similarity of structured Pc1 occurrence and the daily evolution of wave frequency argue against the model according to which the outward expansion of plasmapause causes the maximum wave occurrence on the ground on day 4. We also note that the strong maximum of structured Pc1s during the late storm recovery phase is not supported by the model calculations of the magnetospheric wave source or by direct observations of waves in space. Instead, we argue that the ionospheric resonator and propagation conditions which strongly affect wave observations on the ground are deteriorated during the storm main and early recovery phases, impeding wave propagation to the ground. The subsequent recovery of the ionospheric conditions leads to the maximum occurrence of structured Pc1s on the ground during the late storm recovery phase.

1. Introduction

Pc1 pulsations are electromagnetic ion cyclotron (EMIC) waves with frequencies of 0.2–5.0 Hz observed on the ground. EMIC waves are generated in the equatorial magnetosphere in ion cyclotron instability with energetic ions of sufficient thermal anisotropy [*Cornwall*, 1965; *Kennel and Petschek*, 1966]. At high latitudes, Pc1 amplitudes are of the order of 0.1–1.0 nT, while at low latitudes they are typically one order of magnitude smaller. Using their appearance in dynamic spectra, Pc1s can roughly be divided into two main morphological groups. The first group, structured or "pearl" pulsations, contains events with periodically modulated amplitude. The large majority of all other events forms the second group, called unstructured pulsations. Examples of a typical structured pulsation event and a typical unstructured pulsation event are presented in Figure 1.

Pearl pulsations are the most common Pc1 type at low latitudes and midlatitudes [*Benioff*, 1960; *Fraser-Smith*, 1970; *Kawamura*, 1970; *Kuwashima et al.*, 1981]. They are fairly frequent even at high latitudes [*Fukunishi et al.*, 1981; *Mursula et al.*, 1994a]. The diurnal occurrence of pearls is concentrated in morning hours. Both ground-based [*Roth and Orr*, 1975; *Lewis et al.*, 1977; *Webster and Fraser*, 1985] and satellite measurements [*Taylor and Lyons*, 1976; *Fraser et al.*, 1989; *Erlandson et al.*, 1990, 1992, 1996; *Mursula et al.*, 1994b] indicate that pearls are generated fairly close to the plasmapause, where density gradients of cold plasma can enhance wave growth and help waves to remain guided [*Mazur and Potapov*, 1983; *Thorne and Horne*, 1992]. According to the traditional model, the repetitive structure is due to a wave packet bouncing back and forth between the opposite hemispheres [*Ja-*

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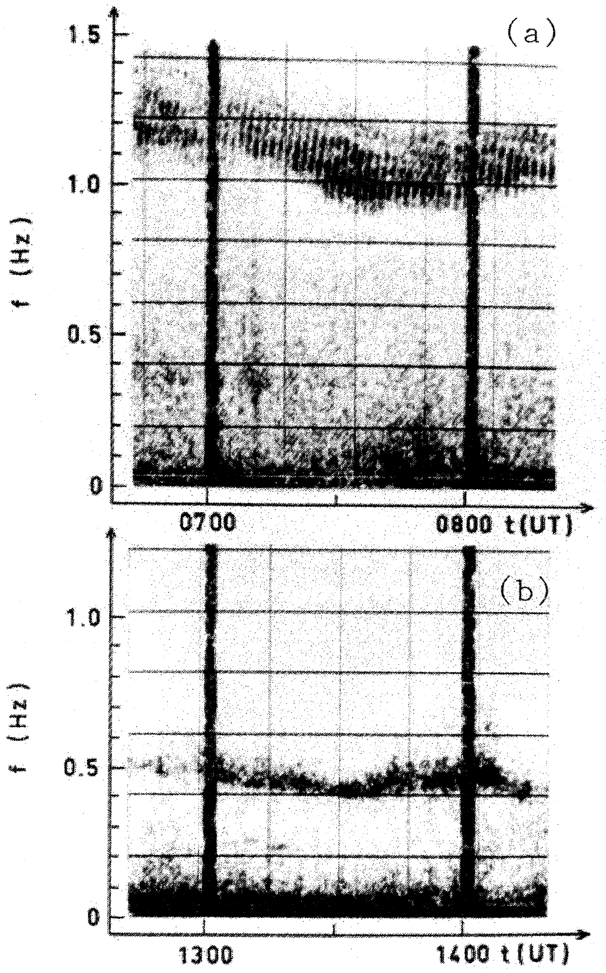

Figure 1. Dynamic spectra for typical (a) structured and (b) unstructured Pc1 events registered at SOD on March 27, 1975, and March 6, 1976, respectively.

cobs and Watanabe, 1964; *Obayashi*, 1965]. Recently, new evidence has been given [e.g., *Plyasova-Bakounina et al.*, 1996; *Rasinkangas and Mursula*, 1998; *Mursula et al.*, 1999] in favor of an alternative model where a long-period ULF wave modulates the Pc1 growth rate, causing repetitive enhancements of Pc1 intensity. Unstructured Pc1 pulsations dominate at high latitudes. The diurnal occurrence maximum at auroral latitudes is in the noon-afternoon sector [*Troitskaya and Guglielmi*, 1970; *Kuwashima et al.*, 1981; *Mursula et al.*, 1994a]. Satellite measurements have shown that the activity of EMIC waves in the Pc1-2 frequency range is concentrated in the noon-afternoon sector and increases with equatorial distance at least up to $L \approx 8$ [*Anderson et al.*, 1992]. On the ground, unstructured Pc1s have lower average frequencies than structured Pc1s, reflecting their source being at higher latitudes, i.e., at lower magnetic field intensities.

Ground-based observations of Pc1 pulsations during magnetic storms have been studied by several authors. *Wentworth* [1964] analyzed low-latitude Pc1 activity during 25 magnetic storms and found that it is increased during the week following the storm main phase. Enhanced Pc1 activity after the storm main phase has been observed also at midlatitudes [*Plyasova-Bakounina and Matveyeva*, 1968; *Gupta*, 1983] and at high latitudes [*Heacock and Kivinen*, 1972]. *Kuwashima et al.* [1981] found that the occurrence maximum of structured Pc1s is seen at a low-latitude station 2–3 days after the storm main phase but at high latitudes only after 4–5 days. They also reported that the occurrence rate of unstructured pulsations does not depend on storm evolution.

Satellite observations of storm-time Pc1 pulsations are few. Recently, *Bräysy et al.* [1998] studied the evolution of Pc1 activity during a great magnetic storm in April 1993 by using electric field data from the Freja satellite. In the initial (compression) phase of the storm they found Pc1 events particularly in the postnoon sector at high latitudes, whereas during the main phase the occurrence was concentrated at lower latitudes and in the late evening hours. Wave amplitudes were found to increase dramatically during the decrease of the *Dst* index. Moreover, events with frequencies less than the local equatorial O^+ gyrofrequency were observed in the main and early recovery phase of the storm. *Erlandson et al.* [1994] found strong Pc1 activity with a wave source at $L \approx 4$, extending on the ground over a wide magnetic local time (MLT) range in the morning sector during the recovery phase of an intense storm. Earlier, *Bossen et al.* [1976] used data from the ATS 1 satellite and found enhanced EMIC wave activity during a storm main phase.

Charge exchange and Coulomb scattering are traditionally expected to be the two main loss processes leading to ring current decay. However, numerical simulations including these two processes have shown [*Fok et al.*, 1995, 1996] that they cannot be the only factors controlling the decay. As compared to observations, the model resulted in too flat ion pitch angle distributions and too high ion fluxes above a few tens of keV during the storm recovery phase. *Fok et al.* [1996] suggested that an additional loss process associated with ion cyclotron resonance, leading to enhanced pitch angle scattering of resonant ions and a faster decrease of ring current intensity, would give a better consistency between the model calculations and observations. Moreover, *Jordanova et al.* [1997] and *Kozyra et al.* [1997] used a model to study effects of wave-particle interactions on the ring current decay. They showed a dramatic (more than two orders of magnitude) enhancement in the proton precipitation in association with wave activity just inside and at the plasmapause in the postnoon sector and concluded this loss type to be important to the global energy balance of the ring current. Satellite observations of enhanced EMIC wave activity in this sector during the storm main and early recovery phase have confirmed the importance of this loss type in the ring current decay [*Bräysy et al.*, 1998].

In this paper we study Pc1 pulsations observed at high latitudes and midlatitudes during 18 magnetic storms. The two main Pc1 types, structured and unstructured pulsations, are studied separately. In section 2 we present the data and methods used in the study. Section 3 contains the storm-time Pc1 observations, concentrating on the daily evolution as well as the diurnal distributions of Pc1 activity and frequency during the storm process. In section 4 we discuss the main observations and compare them with earlier results. Finally, section 5 presents our conclusions.

2. Data and Method

We selected a total of 18 magnetic storms by means of the *Dst* index. This selection was based on the following requirements. First, only storms of low solar activity years (1976-1978 and 1984-1988) were included in the study because of the great changes in Pc1 activity over the solar cycle [e.g., *Benioff*, 1960; *Fraser-Smith*, 1970, 1981; *Matveyeva et al.*, 1972; *Kawamura et al.*, 1983; *Matveyeva*, 1987; *Mursula et al.*, 1991, 1994a]. Second, the storms had to be triggered by a verified storm sudden commencement (SSC) signal. Third, the storms had to develop systematically so that the different storm phases (initial, main, and recovery phase) were clearly recognizable in the *Dst* index. (For example, the recovery phase was not allowed to contain very large additional intensifications.) Fourth, the storms had to be of a suitable intensity, not too intense or too weak. Very intense storms were rejected since their *Dst* often does not return close to the prestorm value during the 6 days included in this study. The storm days included in this study, the SSC times, as well as the values of *Dst* minima are presented in Table 1. The *Dst* minimum of the strongest (weakest) storm is −226 nT (−77 nT). The mean (median) *Dst* value is −133 nT (−110 nT).

Table 1. Analyzed Storm-Time Periods, Occurrence Times of SSCs, and *Dst* Minimum Values[a]

Storm Interval			SSC		Dst Minimum,
Year	Month	Day	Day	UT	nT
1976	Jan	10–15	10	1004	−156
1976	March	26–31	25	2339	−226
1976	April	1–6	1	0251	−218
1977	July-Aug.	29–3	29	0027	−94
1978	Feb.	15–20	14	2147	−108
1978	March	8–13	8	1439	−99
1978	Aug.-Sep.	27–1	27	0247	−226
1984	July-Aug.	31–5	31	1451	−112
1985	June	9–14	9	1715	−77
1986	Jan.	6–11	6	1312	−79
1986	Sep.	11–16	11	1836	−170
1986	Oct.	13–18	13	1454	−101
1986	Nov.	4–9	3	2354	−100
1987	July-Aug.	28–2	28	0849	−100
1987	Aug.	24–29	24	0939	−97
1988	Jan.	14–19	13	2330	−147
1988	Feb.	21–26	21	0156	−130
1988	May	6–11	6	0427	−160

[a]SSC, storm sudden commencement.

We have used the superposed epoch method when studying the storm-time Pc1 activity. The zero time is set at 0000 UT on the day of SSC occurrence (denoted by day 0). In order to keep the total measurement time equal to 24 hours even for day 0, Pc1 data has been collected for the whole day of SSC occurrence; that is Pc1 events appearing even before SSC have been included. In four storms (March 1976, February 1978, November 1986, and January 1988) the SSC time was very late (prior to midnight), and day 0 for these storms was taken to be the day after SSC. With this change the *Dst* minimum occurred on day 0 (1) in the case of 11 (7) storms. The interpretation of results for day 0 is somewhat limited because the storms can be in different phases (initial, main, or early recovery) during this day. However, we note that other choices of defining the zero day (e.g., as the minimum *Dst* day) would have led to results essentially similar to those obtained.

We use Pc1 data from two search-coil magnetometers situated at the high-latitude Sodankylä station (SOD, geographic coordinates 67.4° latitude, 26.6° longitude, corrected geomagnetic coordinates (CGM) 63.9° latitude, 109° longitude, $L = 5.1$) and at the midlatitude Nurmijärvi station (NUR, geographic coordinates 60.5° latitude, 24.7° longitude, 57.0° CGM latitude, 103° CGM longitude, $L = 3.3$). The observed Pc1 events were divided into three groups: structured, unstructured (mainly the Pc1-2 band and hydromagnetic chorus; see the classification by *Fukunishi et al.* [1981]), and the rest (e.g., Intervals of Pulsations of Diminishing Period (IPDP) and unclear events). The first two groups are the two main Pc1 types observed at SOD and NUR, the rest forming just a small fraction of all Pc1 events observed. The type, start time, intensity, and duration of each Pc1 event (which may last from a few minutes to several hours) were registered for each hour separately. We registered the type, start time, intensity, and duration of each such UT sample. Moreover, for each sample we noted the highest and lowest frequency as well as the average frequency at the time of maximum intensity. Possible simultaneous bands (multiband events) were analyzed as separate events.

3. Observations

3.1. Overall Pc1 Properties

During the 18 storms we observed altogether 511 Pc1 events at SOD and 567 events at NUR, with a total Pc1 active time of more than 26 days (24.5% of the time) at SOD and over 22 days (20.6%) at NUR. The occurrence frequency (in percentage of time), number of events, average duration, and average frequency are given in Table 2 for the three Pc1 categories separately. Structured pulsations dominated at both stations: at SOD (NUR), more than 63% (70%) of Pc1 activity was classified to be structured, and 31% (23%) of the activity was un-

Table 2. Pc1 Occurrence Frequencies and Percentages of the Total Pc1 Occurrence for the Three Pc1 Categories[a]

	Occurrence Frequency %	Percentage of Total Occurrence	Number of Events	Average Duration, min	Average Frequency, Hz
			SOD		
S	15.5	63.3	313	77	0.96
U	7.7	31.4	162	74	0.47
O	1.3	5.3	36	57	0.67
All	24.5	100	511	69	0.7
			NUR		
S	14.5	70.5	379	59	1.14
U	4.8	23.3	137	55	0.37
O	1.3	6.2	51	39	0.83
All	20.6	100	567	55	0.7

[a] S, structured; U, unstructured; O, other.

structured. We note that structured Pc1s dominated even at SOD, contrary to long-term high-latitude Pc1 observations without a reference to storm evolution or geomagnetic activity [*Mursula et al.*, 1994a]. The absolute level of structured Pc1 activity is only slightly lower at NUR than at SOD, but unstructured Pc1s are much less frequent at NUR. Note also that both Pc1 types seem to last somewhat longer at SOD than at NUR. In Table 2 and elsewhere, the Pc1 average frequency corresponds to the average frequency calculated from the intensity maximum. The average frequency of structured pulsations is higher at NUR, implying that NUR (SOD) better observes the structured Pc1 events generated at low (high) latitudes.

3.2. Daily Pc1 Activity

The above mentioned zero time problem affects the study of the fairly brief storm main phase. However, we analyzed the Pc1 activity during the main phase of each storm separately in order to avoid this timing problem. We found that structured or unstructured Pc1 pulsations are seldom observed on the ground during the main descent of the *Dst* index. Figures 2a and 2b present the daily activity of structured and unstructured pulsations at SOD and NUR, respectively. Almost each day there are more structured than unstructured Pc1s at both stations. The structured Pc1 activity increases from day 0 to day 4 by a factor of about 4 (from 6.8 to 26.3% of the time) at SOD and about 5 (from 4.5 to 24.6% of the time) at NUR. The maximum of structured Pc1 activity is attained at both stations on day 4. On days 1-3 the absolute level of structured Pc1 activity is almost the same at the two stations, but on days 0, 4, and 5 it is higher at SOD. On the other hand, unstructured pulsations are not affected by the storm evolution as dramatically as structured Pc1s.

3.3. Overall Diurnal Distributions of Pc1 Activity

Figures 3a and 3b show the overall diurnal (UT; LT is 2-3 hours ahead of UT at these stations) distribution of structured and unstructured pulsations at SOD and NUR. Structured pulsations are fairly evenly distributed throughout the day but have a maximum in the late morning sector and a minimum in the afternoon at both stations. This roughly corresponds to the diurnal distribution observed earlier in long-term observations of structured Pc1s [*Fukunishi et al.*, 1981; *Kuwashima et al.*, 1981; *Mursula et al.*, 1994a]. Unstructured pulsations are strongly concentrated around noon at both stations, in accordance with earlier results [*Fukunishi et al.*, 1981; *Kuwashima et al.*, 1981; *Mursula et al.*, 1994a]. Only in this diurnal sector there is more unstructured than structured Pc1 activity. As already seen in Table 2, unstructured Pc1 activity at NUR is weaker than at SOD.

3.4. Development of Diurnal Distributions

Figures 4a and 4b depict the hourly duration of structured and unstructured pulsations at SOD for each day of the storm. On day 0 the diurnal distribution of structured Pc1s is reminiscent of their quiet-time form [e.g., *Mursula et al.*, 1994a] except that the morning maximum is slightly later. A dramatic change in the distribution of structured pulsations is seen from day 0 to day 1. On day 1, structured pulsations are strongly concentrated in the afternoon-dusk sector with no events in the morning hours. On day 2 some structured pulsations appeared in the morning sector, but the main activity is still in the dusk sector. Transition to earlier local times continues on day 3, and from day 4 onward the shape of the distribution only slightly deviates from

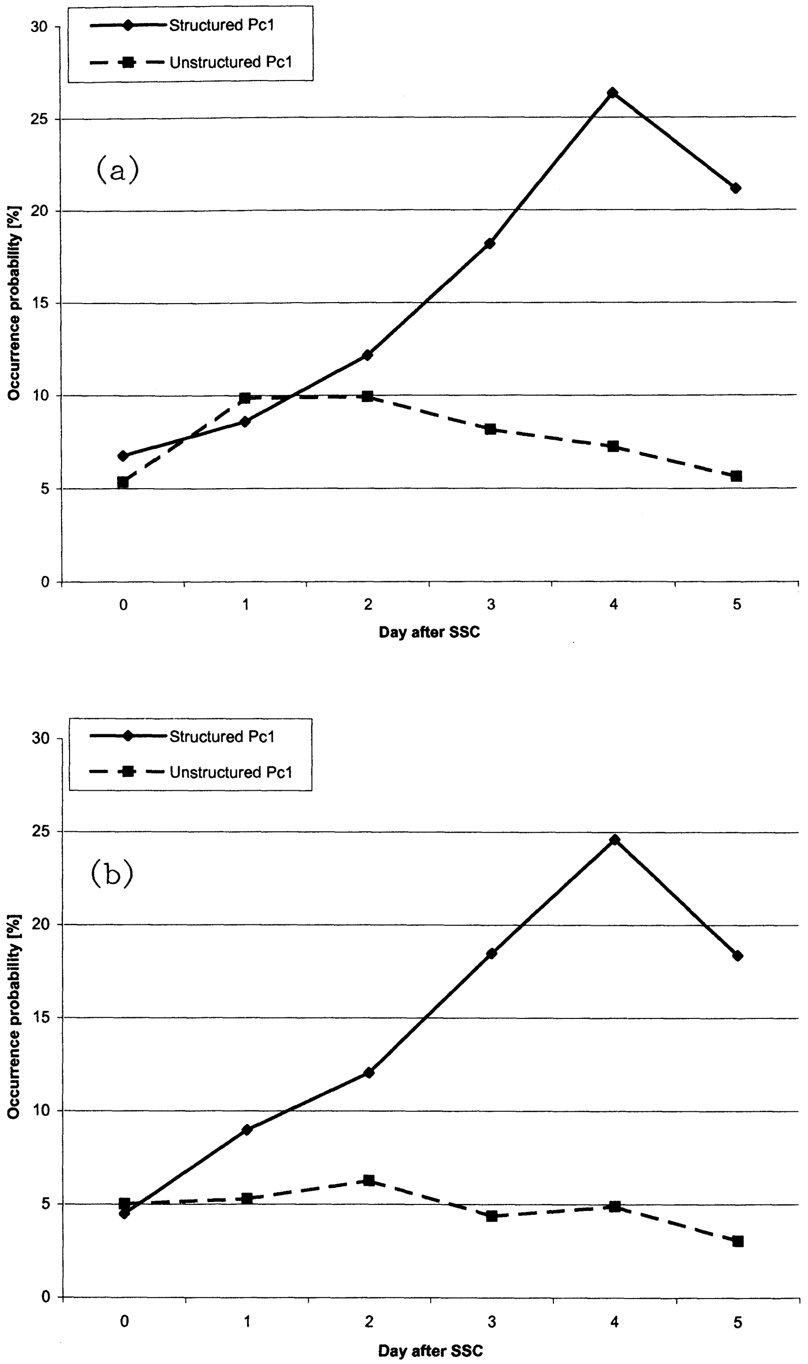

Figure 2. The daily activity of structured and unstructured pulsations at (a) SOD and (b) NUR. Day 0 corresponds to the day of SSC occurrence.

the average distribution with morning maximum. On the other hand, there are no dramatic changes in the diurnal distribution of unstructured pulsations (see Figure 4b). The activity is fairly well concentrated around noon on each day studied. The later maximum on day 0 is due to SSCs which enhance unstructured Pcl activity [e.g., *Anderson and Hamilton*, 1993]. As noted earlier, unstructured Pcls are slightly more frequent at SOD on days 1 and 2, but the increased activity seems to follow the regular diurnal distribution.

The diurnal distributions at NUR (not shown) are fairly similar to those at SOD for both Pcl types. However, the activity of structured Pcls on day 1 extends to somewhat earlier hours (0700–1100 UT) at NUR than at SOD. On days 3-5 the distributions of structured Pcls are very similar at the two stations, both in shape and in overall activity (see also Figure 2). The additional activity of structured Pcls at SOD on days 4 and 5 seems to be concentrated in the premidnight to early morning sector. On the other hand, despite the

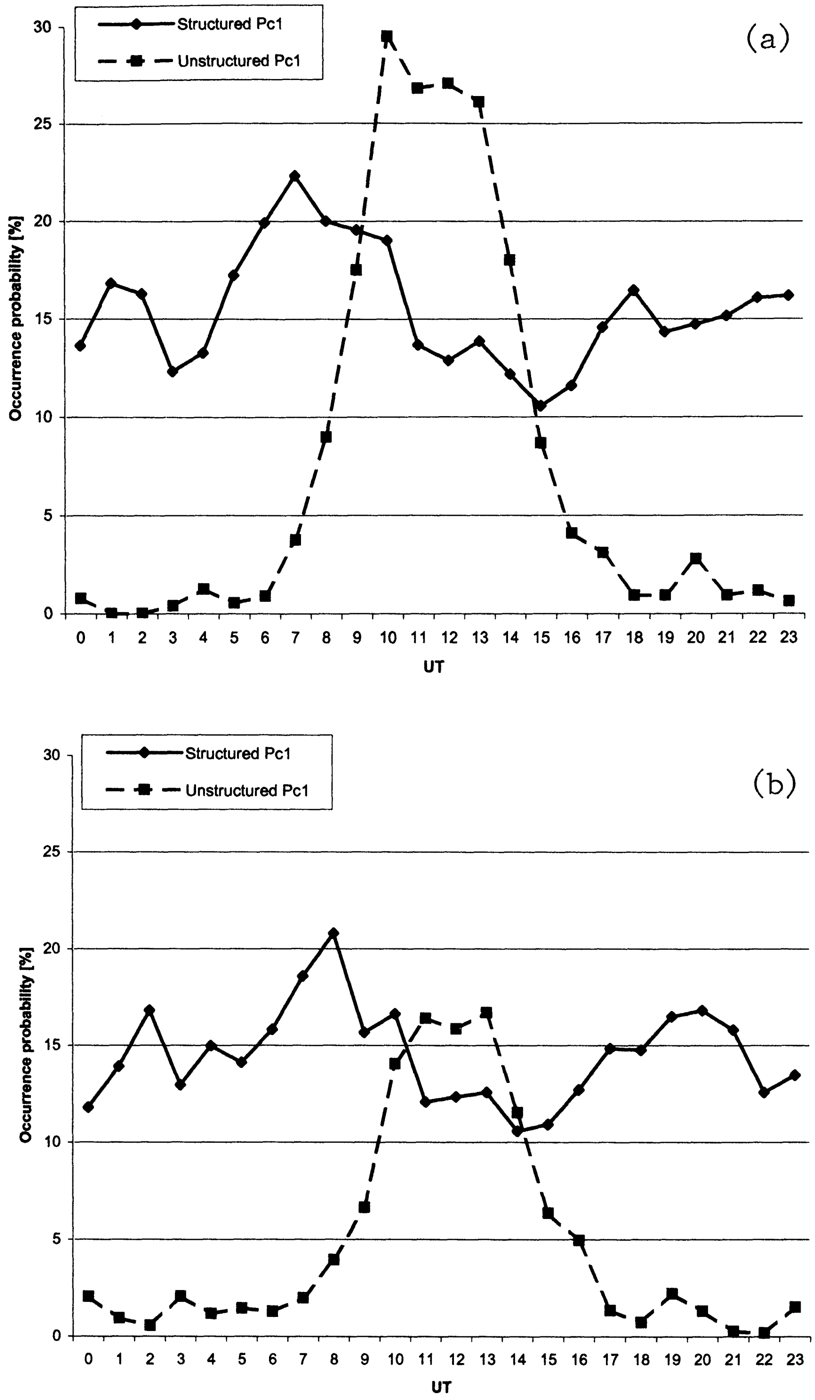

Figure 3. The overall diurnal distribution of structured and unstructured pulsations at (a) SOD and (b) NUR.

smaller activity of unstructured pulsations at NUR, the shape of UT distributions is fairly similar at the two stations.

3.5. Daily Average Frequency

Figure 5 presents the average daily frequencies of structured and unstructured pulsations observed at SOD and at NUR. At both stations the average frequency of structured Pc1s is consistently higher than that of unstructured Pc1s throughout the storm. At SOD the frequency of structured Pc1s increases by more than 50% from day 0 (0.7 Hz) to its maximum on day 4 (1.1 Hz), while the frequency of unstructured pulsations depicts only a small increase during days 1–3. Throughout the storm process the average frequency of structured pulsations is higher at NUR than at SOD. The increase at NUR is more than 65% from 0.75 Hz on day 0 to 1.25 Hz on day 3. The average frequency remains high, at

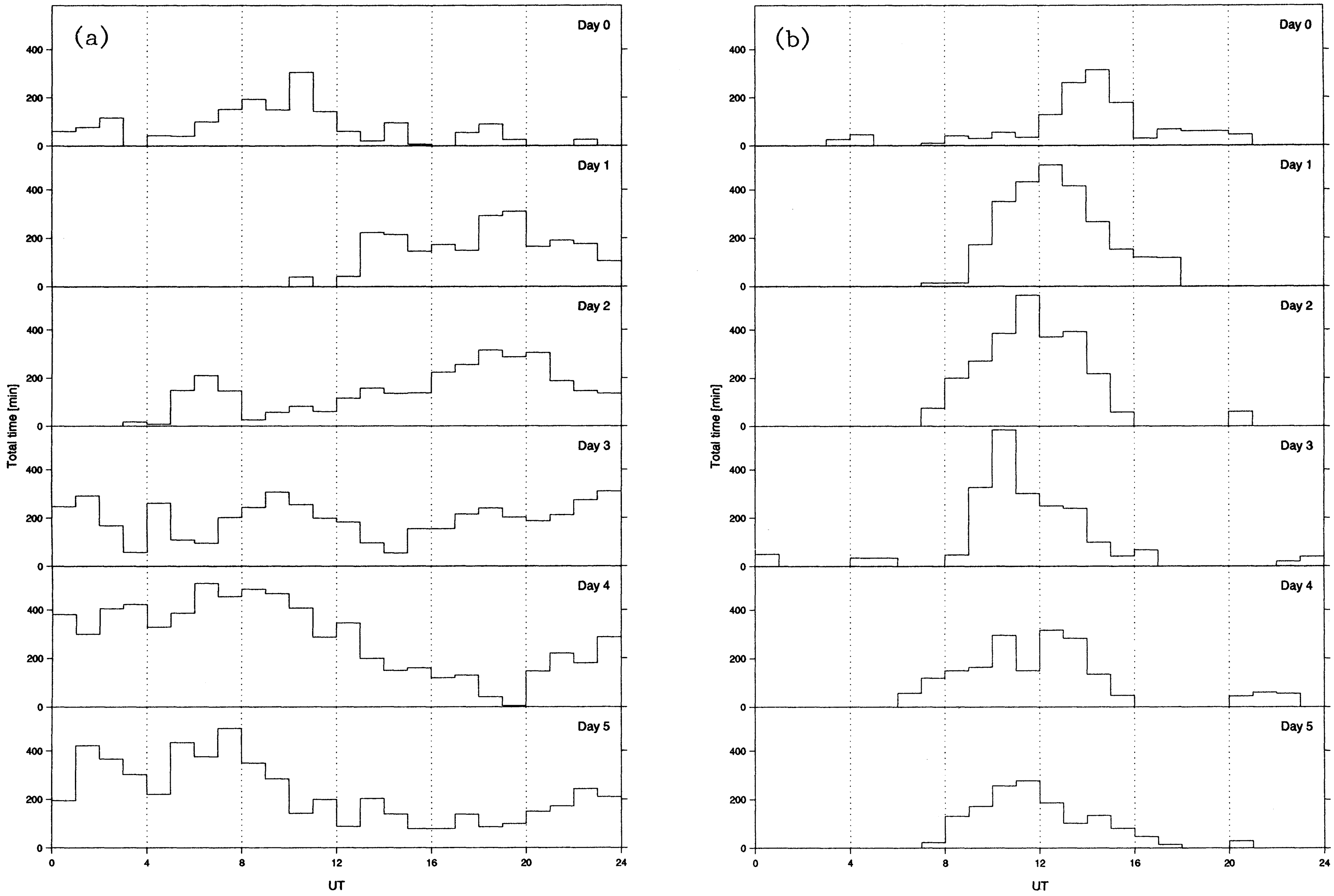

Figure 4. Daily evolution of the diurnal distributions of (a) structured and (b) unstructured pulsations at SOD.

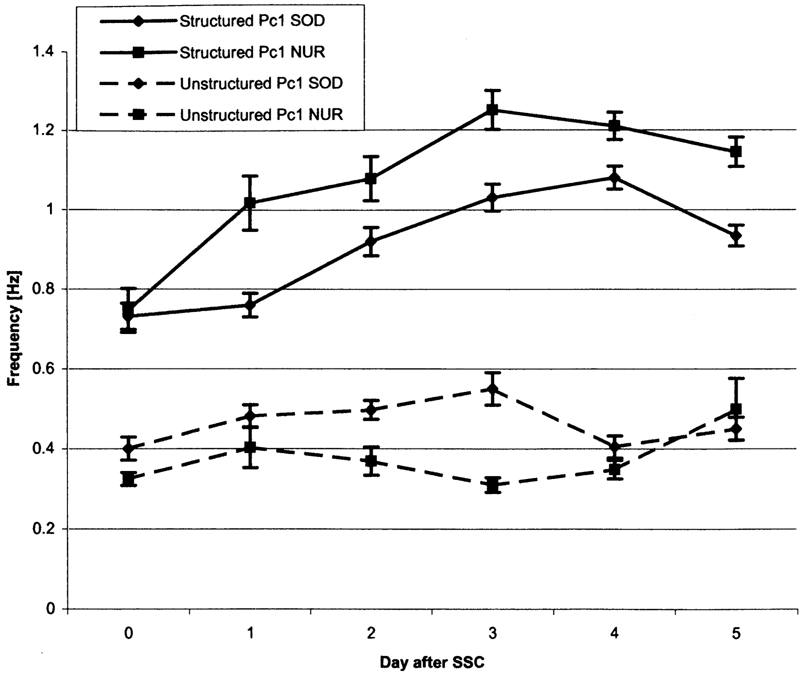

Figure 5. The daily average frequencies of structured and unstructured pulsations at SOD and NUR. The standard errors on the daily average frequency are noted by vertical bars.

around 1.2 Hz, even on days 4 and 5. The frequency of unstructured Pc1s at NUR remains slightly below that seen at SOD on days 0–4.

3.6. Diurnal Variation of Frequency of Structured Pc1s

Figures 6a and 6b show remarkable changes in the diurnal occurrence and frequency distributions for structured Pc1s at SOD and NUR during storm development. In addition to the diurnal occurrence distributions discussed above, Figure 6 depicts remarkable changes in the diurnal frequency distribution of structured pulsations during the storm development. At SOD (Figure 6a) most Pc1s are concentrated in a rather narrow frequency band from 0.5 to 1.0 Hz on day 0, and the diurnal variation of frequency is quite small. The lowest frequencies of ~0.5 Hz are found around local noon. As previously noted (Figure 4a), structured Pc1 activity at SOD on day 1 is restricted to the evening sector. The diurnal variation of frequency is somewhat larger than on day 0, rising from ~0.5 Hz in the afternoon to ~1 Hz in the late evening. During the morning hours of day 2 the frequency decreases from ~1.5 Hz to around 0.5 Hz at noon. In the evening hours, where the activity is still mostly concentrated, the average frequency and the scatter of frequencies increase as on day 1. On day 3 the activity extends over a very broad frequency range, about 0.5–2.0 Hz throughout the day, even around noon, so that no clear frequency minimum is found there, contrary to the previous days. On day 4, when the total occurrence maximum of structured Pc1s at SOD is attained, the pulsations still have a wide range of frequencies, especially in the morning, where most events are found. There is a diurnal minimum frequency in the afternoon sector, somewhat later than on days 0–2. Also, on day 5, pulsations have a relatively wide range of frequencies and a diurnal frequency minimum close to noon.

The diurnal frequency distributions of structured pulsations at NUR (Figure 6b) largely reproduce the above observations at SOD. However, some differences are seen. On day 0 a more clear diurnal variation is seen at NUR than at SOD. On day 1 the evening activity at NUR is spread over a significantly broader frequency range than at SOD. Contrary to SOD, there is a population of events at NUR on day 1 before noon with frequency decreasing with increasing LT. This behavior is similar to the distribution one day later at both stations. On subsequent days the frequency spread at NUR extends clearly higher than at SOD.

4. Discussion

4.1. Total Pc1 Occurrence

At both stations, Pc1 activity was dominated by structured Pc1s, forming 15.5% (14.5%) of the total measurement time at SOD (NUR). Without observations of non-storm-time wave activity for the years studied here, we cannot reliably estimate the effect of storms on the quiet-time level of structured Pc1 activity. Although the main aim of the present paper is to study the changes in wave activity during the storm, some comparison between storm-time and non-storm-time activity can be made. As seen in Figure 2, structured Pc1

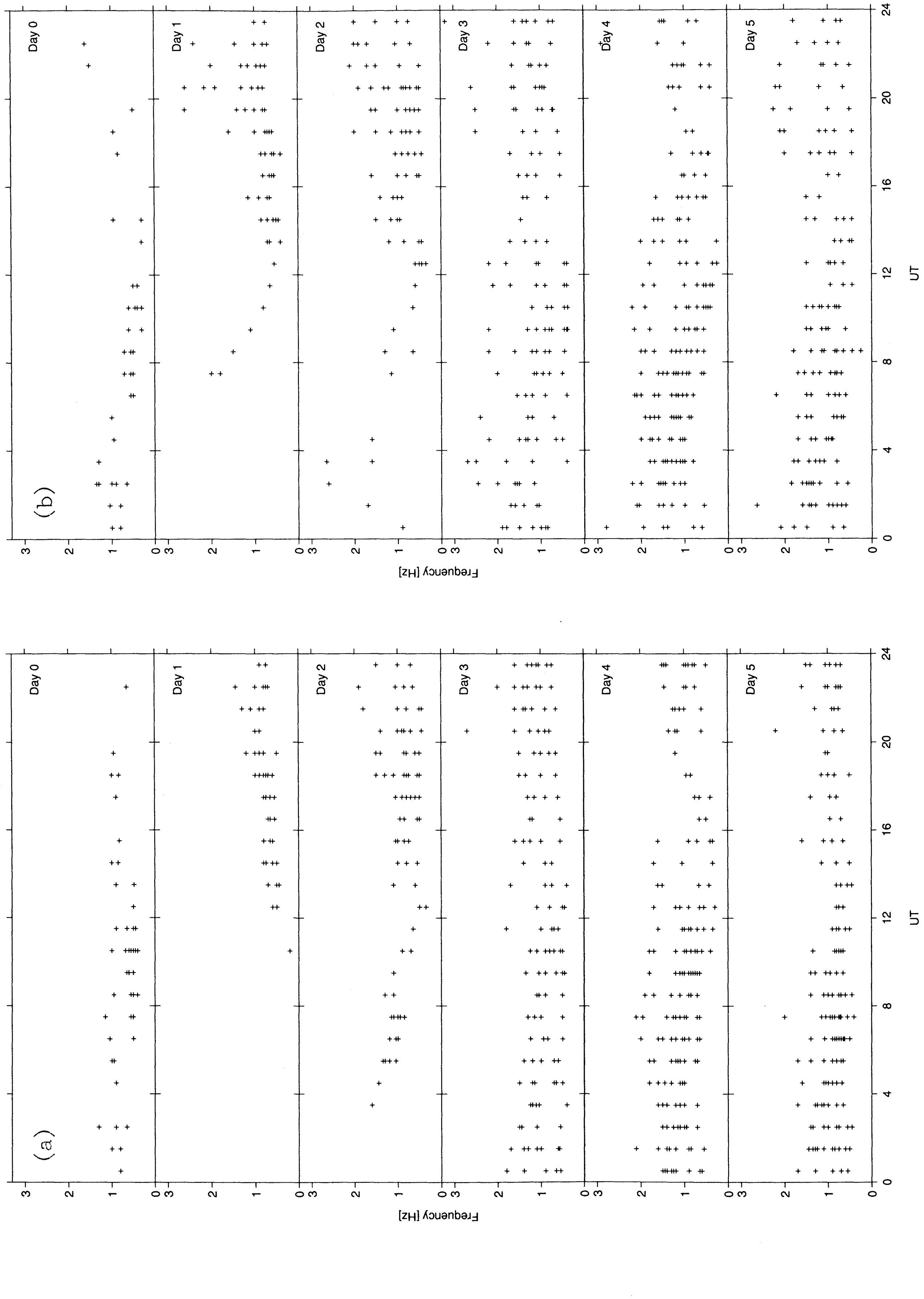

Figure 6. Daily evolution of the frequency of structured Pc1 samples at (a) SOD and (b) NUR.

activity increased at SOD (NUR) from 6.8% (4.5%) to 26.3% (24.6%) from day 0 to the maximum on day 4, i.e., by nearly a factor 4 (by more than 5, respectively). This increase cannot straightforwardly be used to estimate the difference of structured Pc1 activity during quiet times and storms because the activity on day 0 is affected, for example, by the depletion of waves during the storm main phase. Accordingly, we expect that structured Pc1 activity on day 0 is somewhat below the overall activity level. This is supported by *Mursula et al.* [1994a], who studied Pc1s at SOD in equinox months during sunspot minimum years, finding that structured Pc1s occurred ~11.7% of the time. Taken at face value, this would imply an overall increase of wave activity of ~40% from quiet-time level to average storm level and of a factor of 2–2.5 from quiet-time level to the storm maximum on day 4. However, since the interval studied by *Mursula et al.* [1994a] contained a number of magnetic storms as well, these estimates are lower limits to actual values. Moreover, an accurate comparison between the two studies is also complicated by solar cycle and seasonal changes. For a more reliable estimate a separate, long-term study of the difference between structured Pc1 activity during quiet times and storms is needed.

4.2. Daily Pc1 Activity

Storm main phase is associated with ring current intensification due to an increase of the ion energy content, particularly at $L < 4$ [*Smith and Hoffman*, 1973; *Lui et al.*, 1987; *Hamilton et al.*, 1988]. Particle transport to these low L shells is caused by enhanced convection [*Lyons and Williams*, 1976; *Kamide et al.*, 1997] or by the fluctuations in the convection electric field [*Wolf et al.*, 1997 ; *Chen et al.*, 1997]. A high fraction (96%) of the quiet-time ring current near $L = 5$ is carried by protons and only 2% of O^+ ions [*Gloeckler and Hamilton*, 1987]. However, during the storm main phase, ionospheric feeding of O^+ ions is enhanced, and the inner ring current ($L = 3$–5) consisted of 77% protons and 17% O^+ ions [*Gloeckler and Hamilton*, 1987]. Also, the outer ring current ($L = 5$–7) measurements show that the O^+ content increases with geomagnetic (storm) activity. During a storm main phase with a minimum *Dst* of –180 nT, the energy flux fraction of these ions exceeded even 60% [*Daglis*, 1997]. During a storm with *Dst* minimum of about –140 nT (–300 nT), the energy density maximum was located at $L = 3.5$ ($L = 2.5$) [*Korth and Friedel*, 1997; *Hamilton et al.*, 1988].

In accordance with earlier ground-based studies, structured pulsations were practically not seen on the ground in this study during the main phase and the first few hours after *Dst* minimum. However, *Bräysy et al.* [1998] found a significant amount of strong EMIC waves in space (but not on the ground) during the storm main and early recovery phase. These waves were seen mainly at latitudes between 50° and 60° CGM latitude with frequencies less than the local equatorial He^+ gyrofrequency. Note that the location of the waves observed by *Bräysy et al.* [1998] corresponds very well to the L shell of the above mentioned energy maximum of the ring current for an average storm. The reason for the lack of waves at higher latitudes was suggested to be due to stop bands generated by outflowing heavy ions from the polar ionosphere [*Cladis and Francis*, 1985] or complete quenching of waves by resonant absorption [*Thorne and Horne*, 1997]. Since waves were not seen in space at high latitudes at this time, it was well understandable that they were not seen on the ground at these latitudes (SOD) either. It is interesting that structured Pc1 events are not seen during the storm main phase at NUR either, even though this station is at a considerably lower latitude than SOD and therefore in a better position to observe the wave activity existing in space at low latitudes. Since NUR is very close to the latitude of the storm-time waves observed by *Bräysy et al.* [1998], the nearly complete absence of structured Pc1s at NUR is hardly due to the deterioration of the horizontal waveguide properties. Rather, it seems that it is very difficult for the waves to find their way from space to the ground at all. Since *Bräysy et al.* [1998] observed the waves just above the ionosphere, the waves are not cancelled during their magnetospheric path from the equator to the low altitudes but rather inside the ionosphere. Such a dramatic effect of the ionosphere on waves can be understood in terms of the idea of the ionospheric Alfvén resonator [*Polyakov and Rapoport*, 1981]. Using model calculations based on this idea, it was recently shown [*Mursula et al.*, 2000] that the frequency of structured Pc1s on the ground corresponds to the frequency of the maximum transmission coefficient for waves incident from above upon the ionosphere, i.e., to the eigenfrequency of the ionosphere for Alfvén waves. This emphasizes the role of the ionosphere for wave observations on the ground. Therefore, taking the exceptional conditions during the storm main phase into account, it is quite possible that the resonator conditions are so strongly disturbed that no coherent wave signal is obtained on the ground.

Fraser-Smith [1970] suggested that structured Pc1 activity increases during the recovery phase because of an outward expansion of plasmapause, leading to a maximum a few days earlier at low than at high latitudes. *Heacock and Kivinen* [1972] and *Heacock and Akasofu* [1973] assumed that the observed increase of structured Pc1 activity during late recovery phase is due to the slowly refilling plasmasphere which destabilizes ring current ions and enhances EMIC wave growth. *Kuwashima et al.* [1981] found the occurrence maximum of structured Pc1s at a low-latitude station ($L = 1.5$) 2–3 days and at a high-latitude station ($L = 6.1$) 4–5 days after the *Dst* minimum, explaining this difference with plasmapause expansion. In this study, we did not detect such a latitudinal timing difference. Instead, we found that the daily evolution of structured Pc1 activity (see Figure 2) is quite similar at high latitudes and midlatitudes. This agrees with *Wentworth* [1964], who found the occurrence maximum on day 4 at low latitudes, in direct contradiction to the low-latitude observation by *Kuwashima et al.* [1981]. Also, the wave activity in space was not increased during storm recovery [*Bräysy et al.*, 1998], contrary to the expectations based on the plasmapause expansion model. Accordingly, we conclude that there is no support from the daily evolution of structured Pc1s on the ground for the plasmapause outward expansion being the main cause of the great enhancement of structured Pc1 activity in the late recovery phase. This topic will be further discussed in section 4.4.

It is interesting that the occurrence maximum of structured Pc1s on the ground is seen only on the fourth day after the storm main phase. On the other hand, satellite observations have shown that EMIC wave activity has its maximum much earlier, already around the storm main phase [*Bräysy et al.*, 1998]. This indicates that the magnetospheric wave source is most active during days 0 and 1, weakening rather than strengthening during later storm recovery. The different daily evolution of wave activity in space just above the ionosphere and on the ground can only be due to the crucial effect of the ionosphere on the incident EMIC waves and the change of this effect with storm evolution. As already discussed, the ionospheric resonator and ducting properties can significantly affect Pc1 activity on the ground. These properties are seriously deteriorated during the storm main and early recovery phase. Later, the improved ionospheric conditions allow a dramatically larger number of waves to be detected on the ground despite the weakening magnetospheric wave source (weaker ring current). These two counteracting developments produce the maximum of ground-based observed waves on day 4. Thereafter, the ring current soon approaches its quiet-time intensity.

4.3. Development of Diurnal Distributions

At both stations the diurnal distribution of structured Pc1 pulsations suffers dramatic changes during the storm process (see Figure 4a for SOD). On day 0, structured Pc1 events have a maximum in the late morning sector, in rough agreement with long-term statistics. Soon after the main phase (day 1) the structured Pc1 activity is almost completely in the evening sector. The storm-time ring current evolution was recently modeled by *Jordanova et al.* [1997] and *Kozyra et al.* [1997] by including ion losses associated with charge exchange, Coulomb collisions, and wave-particle interactions. These model calculations show that in the main phase, EMIC waves are preferentially excited in a localized region in the afternoon-evening sector of the magnetosphere, which agrees well with the present observations. Moreover, *Bräysy et al.* [1998] verified the late evening maximum of EMIC waves during the main phase using satellite observations. These waves were also the strongest of all waves observed during the storm.

On day 2 a small population of structured Pc1 events appears in the morning sector, but the occurrence is still concentrated in the evening sector. From day 3 onward, the main activity is in the morning sector. The model calculations [*Kozyra et al.*, 1997] show that the afternoon-eveningside source slowly weakens in a few days. This is in agreement with the present ground-based observations and with the low-altitude Freja measurements of EMIC waves [*Bräysy et al.*, 1998]. However, it is important to note that the model calculations did not find a shift of wave occurrence to the morning sector, but rather the modeled wave source remained in the eveningside. This is in agreement with the above presented idea that the observed increase in morningside structured Pc1 activity (see Figure 4a), which is significantly higher during the late recovery (days 3–5) than the eveningside activity during the early recovery (days 1–2), is not due to an exceptionally intense source region appearing in the morning sector. This again emphasizes the role of the ionosphere for ground-based Pc1 activity since even quite a weak source (as compared to the eveningside source at storm main phase) can produce a much larger amount of structured Pc1 pulsations on the ground if the ionospheric properties are favorable.

4.4. Frequency Characteristics

The average daily frequencies of the structured Pc1s (Figure 5) are significantly higher since day 1 at NUR than at SOD, implying that NUR (SOD) better observes waves generated at lower (higher) L shells. The average daily frequency of structured Pc1s increases during the storm recovery at SOD from 0.7 to 1.1 Hz on days 0–4 and at NUR from 0.75 to 1.25 Hz on days 0–3. Since this increase was observed in all LT sectors, including the dusk sector, the increase of the daily average frequency cannot be due to only the shift of activity to the dawn sector. It is impossible to explain these changes by assuming that the wave generation region is closely connected to the plasmapause position, moving slowly outward during the storm recovery. Therefore the view [*Fraser-Smith*, 1970; *Kuwashima et al.*, 1981] of wave generation being strictly connected with a simple expanding plasmapause is erroneous. Interestingly, Figure 6 depicts a very large scatter of wave frequencies, in particular at NUR. The new high-frequency waves appear at NUR from day 1 onward, first in the premidnight sector (day 1), then early morning (day 2), and, finally, in most LT sectors. This development is the main reason for the increase of daily average frequencies at the two stations.

Jordanova et al. [1997] discussed two mechanisms which may account for the observed increase in wave frequency. As one possible mechanism, they found that the eveningside ring current ion precipitation zone, associated with EMIC wave instability, moved to lower L shells (from L = 4–5.5 to L = 3–4). However, if the dominant reason of wave frequency increase is the movement of the wave source to lower latitude, this would imply a relatively larger fraction of waves at NUR compared to SOD in the late recovery phase. However, the contrary is observed: wave activity at NUR decays slightly earlier than at SOD. Also, *Bräysy et al.* [1998] found that the wave activity region stayed at a rather constant latitude at around 60° CGM latitude soon after the main phase during days 2–4. These observations imply that the frequency increase on the ground is not mainly due to the movement of the wave source region to lower latitudes. As a second, more important mechanism for frequency increase, *Jordanova et al.* [1997] found the decrease of ring current ion energy. Such a decrease is indeed expected during the ring current decay. However, the results by *Jordanova et al.* [1997] apply only to the evening sector, where the main model wave source was located during all storm phases. They do not apply in the morning sector, where the maximum of structured Pc1s was observed on day 4. Moreover, the relative decrease of ion energy is much higher in the evening sector soon after the main phase than in the morning sector in the late recovery phase. Accordingly, it is not probable that the decrease of ion energy would sizably contribute to the frequency increase during the late recovery phase in the morning sector. Certainly, it does not explain the simultaenous increase of wave occurrence and wave frequency during the late recovery phase, as observed here.

There are also other factors which may, at least in principle, affect the frequency of Pc1 waves. Growth rate calculations by *Kozyra et al.* [1984] show that an increase in the anisotropy of energetic ions, keeping all other plasma parameters fixed, results in a shift of peak growth rates to higher frequencies. However, both model calculations [*Jordanova et al.*, 1997] and space observations [*Chen et al.*, 1999] indicate that the anisotropy decreases rather than increases during a storm recovery phase. Thus the observed increase of structured Pc1 frequency cannot be explained in terms of changes in resonant ion anisotropy. Cold plasma density is expected to increase during storm recovery phase as a result of plasmasphere refilling. However, an increase in plasma density shifts the growth rate peak to a lower frequency [*Kozyra et al.*, 1984], excluding the change in cold plasma density as an explanation for the observed increase of structured Pc1 frequency.

The simultaneous occurrence of structured Pc1s with a wide range of frequencies from day 3 onward (see Figure 6) suggests that the source region extends over a wide L shell range. However, on days 1 and 2 the morningside activity at both stations is restricted to a very narrow frequency band which closely follows the diurnal variation of frequency. This band is missing on day 1 from SOD, and the bands on day 2 have somewhat different frequencies in the two stations. The fact that the waves are first restricted to a very narrow frequency range and then spread to cover a large frequency range cannot be understood in terms of changes in the source since the source is decreasing rather than increasing in intensity. However, this evolution can be explained in terms of the above discussed idea that the ionospheric conditions largely determine the appearance of waves on the ground. We suggest that the spatial extent around each station from where the waves are observed (the "propagation oval" introduced by *Mursula et al.* [1994a]) is changing with storm development. Soon after the main phase on days 1–2, the stations can only register waves having their footpoint close to the station, because the horizontal propagation conditions are still very limited. Later in the storm recovery, the stations observe waves produced at a variety of L shells (larger propagation oval), leading to a larger scatter of simultaneous frequencies observed.

The fact that the NUR station sees the morning waves already on day 1 is probably due to the fact the ionosphere at lower latitudes is less severely affected by the storm and recovers more rapidly after the main phase. This latitudinal asymmetry in ionospheric conditions would also contribute to the change of the daily average frequency of structured Pc1s (see Figure 5). If the ionospheric conditions are improved earlier at lower latitudes, the corresponding higher-frequency waves are detected increasingly with time at each station. (The propagation oval expands more rapidly equatorward.) This continues until day 3, when the maximum average frequency at NUR is observed. Since the inner ring current decreases more rapidly because of higher plasmaspheric density, the low-latitude wave source weakens earlier, leading to a decrease of frequency at NUR after day 3. However, the propagation properties still improve, and the maximum wave occurrence is found at both stations only on day 4. Since SOD station is at a higher latitude than the EMIC wave source region [*Bräysy et al.*, 1998], the improved propagation conditions raise rather than lower the average frequency even from day 3 to day 4.

5. Conclusions

Magnetic storms are known to have a strong effect on EMIC wave activity in space and on Pc1 pulsations on the ground. We have studied the structured and unstructured Pc1 activity in low solar activity years at high latitudes and midlatitudes during 18 magnetic storms. The structured Pc1 activity was found to increase from day 0 to a maximum on day 4 by a factor of 4 at high latitudes and 5 at midlatitudes. During the storm main phase, little structured or unstructured Pc1 activity was found at high latitudes or midlatitudes, although the midlatitude station was fairly close to the latitude of storm-time EMIC waves observed by *Bräysy et al.* [1998] above the ionosphere. We argued that the disturbed ionospheric conditions dramatically limit wave observations on the ground during this time despite a very strong magnetospheric wave source. Such an effect can be understood in terms of the ionospheric Alfvén resonator, and we propose that the changes in the resonator properties during the storm main phase lead to the depletion of waves on ground.

The maximum of structured Pc1s was found on day 4 at both high latitudes and midlatitudes, in agreement with low-latitude observations by *Wentworth* [1964]. Accordingly, no significant latitudinal delay is observed, contrary to *Kuwashima et al.* [1981]. The daily average frequencies were found to increase from day 0 to a maximum on day 3 at midlatitudes and on day 4 at high latitudes. These facts oppose the simple model [*Fraser-Smith*, 1970] that the uniform expansion of plasmapause is the main cause for increased Pc1 activity on the ground in the late recovery phase. Moreover, the expanding plasmapause model predicts increasing wave growth in space, contrary to the observations by *Bräysy et al.* [1998]. As an alternative explanation, we argue that the improved ionospheric conditions lead to the maximum occurrence of structured Pc1s on day 4. This mechanism also allows us to explain the increase of the daily average frequency as well as the great increase of scatter of frequencies during the later recovery phase.

We note that in the storm main and early recovery phase, structured Pc1s were concentrated in the afternoon-evening sector, in agreement with space observations of EMIC waves [*Bräysy et al.*, 1998] and theoretical modeling [*Jordanova et al.*, 1997; *Kozyra et al.*, 1997]. However, the increased concentration of structured Pc1s in the morning sector in the course of storm recovery is not reproduced in these models. Instead, the models predict that the dominant wave source will remain in the afternoon-evening sector, weakening with time. Also, space observations [*Bräysy et al.*, 1998] show no increase in wave activity in the late recovery phase. These results further support the above idea that the maximum of structured Pc1 occurrence on day 4 is not due to an enhancement of the wave source but rather due to ionospheric changes. Finally, we note that in order to verify the observed differences between in situ and ground observations of waves, a larger number of storms should be studied by both satellite and simultaneous ground-based observations.

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J. Kangas, Sodankylä Geophysical Observatory, University of Oulu, FIN-99600 Sodankylä, Finland. (Jorma.Kangas@sgo.fi)

R. Kerttula, K. Mursula, and T. Pikkarainen, Department of Physical Sciences, University of Oulu, P.O. Box 3000, FIN-90014 University of Oulu, Finland. (email: Raine.Kerttula@oulu.fi, Kalevi.Mursula@oulu.fi)

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