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Estimation of Storm-Time Level of Day-Side Wave Geomagnetic Activity Using a New *ULF* Index

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Abstract—The level of wave geomagnetic activity in the morning and daytime sectors of auroral latitudes during strong magnetic storms with $Dst_{\min}$ varying from –100 to –150 nT in 1995–2002 have been studied using a new *ULF* index of wave activity proposed in [Kozyreva et al., 2007]. It has been detected that daytime Pc5 pulsations (2–6 mHz) are most intense during the main phase of a magnetic storm rather than during the recovery phase as was considered previously. It has been indicated that morning geomagnetic pulsations during the substorm recovery phase mainly contribute to daytime wave activity. The appearance of individual intervals with the southward IMF B_z component during the magnetic storm recovery phase results in increases in the *ULF* index values.

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1. INTRODUCTION

It is known that Pc5 pulsations in the frequency range 2–6 mHz are most typical morning and daytime geomagnetic pulsations in the magnetosphere. Numerous satellite observations in the Earth's magnetosphere also indicated that Pc5 geomagnetic pulsations at distances of $R \geq 6$–$8\ R_E$ are typical daytime phenomenon. As a rule, these oscillations have the aligned and transverse components of the same order. Numerous publications are devoted to studying the morphological characteristics and physical origin of generation of Pc5 pulsations.

Generation of pulsations is of prime importance in the processes of energy transfer in the solar wind–Earth's magnetosphere system. Many works (see, e.g. [Antonova, 2000; Borovsky and Funsten, 2003]) indicated that these processes are nonstationary and turbulent. Energy is transferred most effectively during magnetic storms. Different magnetic storms are characterized by different levels of wave geomagnetic activity. However, none of the geomagnetic index used in geophysics (*Kp*, *Ap*, *AE*, *AL*, *Dst*, *SYM-H*, *PC*) reflects the level of wave activity. A special index should be used to estimate wave intensity.

The first attempts to create the activity index of Pc5 geomagnetic pulsations were made at the end of the past century. Thus, Glassmeier [1995] proposed to use the ratio of the pulsation energy in a relatively narrow band to the energy in a wide band. This index was useful in studying narrowband quasi-monochromatic Pc5 pulsations. A similar parameter, defined as a ratio of the pulsation power in the band 2–10 mHz to such a power at 0.2–10 mHz, was used by Posch et al. [2003] in order to study Pc5 pulsations during five magnetic storms. This allowed the researchers to suggest that the storm initial phase is characterized by an excitation of broadband geomagnetic pulsations during all intervals of local time, and the recovery phase is characterized by a generation of morning narrowband pulsations; i.e., the results of the previous works (see, e.g. [Troitskaya et al., 1965]) were confirmed. However, Posch et al. [2003] analyzed observations at stations located in one longitudinal sector, which could not completely reflect wave activity on the global scale.

O'Brien et al. [2001] used the observations at 11 stations of the INTERMAGNET network, located at $L = 3.5$–7.0, in order to calculate wave activity. They calculated the Fourier spectrum of the total field vector for each station (all three components were taken into account) in a 2-h sliding window in the 150–600 s range of periods. Then, the station where the oscillation power was maximal was selected, but the station local time was not taken into account in this case. As a result, nighttime oscillations in this range, which belong to the class of irregular Pi3 pulsations, participated in the estimation of wave activity. In addition, it is insufficiently correct to use the total field vector since the *Z* field component is very sensitive to local geoelectric inhomogeneities.

Since an analysis of ground-based observations at one selected observatory or at any one meridian does not give information about the level of wave activity on the global scale, a new index was developed in order to estimate global wave activity in the daytime (0300–1800 MLT) sector of the magnetosphere [Kozyreva et al., 2007]. In the English literature, it is accepted to

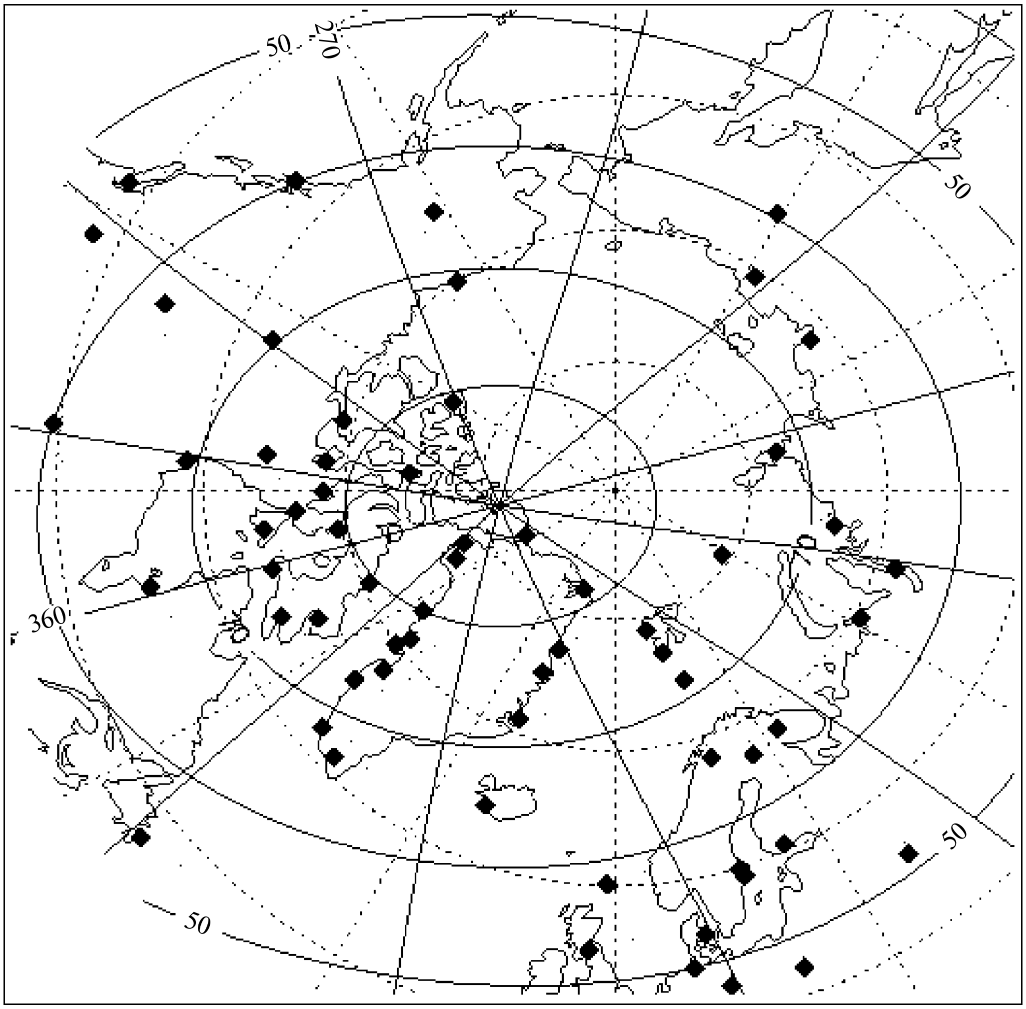

Fig. 1. The location of the observatories in the Northern Hemisphere, which were used to calculate the *ULF* index; solid and dashed lines show geomagnetic and geographic coordinates, respectively.

call the frequency band 1–10 mHz ULF (ultralow frequency) band; therefore, the proposed index was called the *ULF* index. Romanova et al. [2007] used the *ULF* index to study acceleration of energetic electrons in the Earth's magnetosphere. The aim of the present work is to estimate the level of daytime wave geomagnetic activity during different phases of strong magnetic storms using the *ULF* index.

2. BRIEF DESCRIPTION OF THE *ULF* INDEX

To calculate the surface *ULF* index, one uses 1-min data of observations at the global ground-based network of magnetometers in the Northern Hemisphere, including more than 60 stations (INTERMAGNET, MACCS, 210 MM, and Greenland and Russian Arctic coast). Figure 1 presents the map of location of the observatories used to calculate the *ULF* index. The stations are automatically selected for each hour of day, depending on the specified range of geomagnetic latitudes, in order to calculate the hourly values of the *ULF* index. The Fourier spectra are first calculated for these stations in a 1-h window for two horizontal components of the geomagnetic field. Only the stations with the highest signal level exceeding the $K^*\max\{Tj\}$ level, where Tj is the calculated amplitude of the ith station horizontal component, and $K = 0.5$–1.0 (at $K = 1$, only one station with the maximal value of the spectral maximum in the specified frequency range is used) are finally used to calculate the global *ULF* index (the logarithm of the maximal oscillation amplitude during the selected hour). The technique for calculating the *ULF* index is considered in more detail in [Kozyreva et al., 2007].

The *ULF* index for the near-Earth space is considered in a similar way. The data of the GOES geostationary satellites are used in this case. The data of the WIND, ACE, IMP-8, or 1-min OMNI data (ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/

high_res_omni/monthly_1min/) are used to calculate the *ULF* index in order to estimate IMF wave activity.

The database of the *ULF* index hourly values can easily be obtained from the Internet site ftp://space.augsburg.edu/MACCS/ULF_index. The data for each month of a year are presented as tables and figures. The *ULF* index values on the Earth's surface and in the near-Earth and interplanetary space are completed with the data on the solar wind velocity (*V*) and density (*N*), IMF B_z component, and *Dst* index. The initial magnetograms (of the ground-based magnetometers and geostationary and removed satellites), used to calculate the *ULF* index, are additionally presented for each day in the special directory. By the present, the *ULF* index has been calculated for the period 1991–2003, but this base is still widened and becomes more exact.

3. ANALYSIS OF DAYTIME WAVE ACTIVITY

To analyze geomagnetic pulsations of the Pc5 type at frequencies of 2–6 mHz, we calculated the *ULF* wave index for the morning–daytime sector (0300–1500 MLT) of auroral latitudes ($\Phi = 60°–70°$).

First, the background level of wave turbulence (i.e., the level of daytime *ULF* activity during the magnetically quiet period) was determined. The days with $|Dst| < 20$ nT and $Kp < 2$ were selected for 1995–2001 (605 days, including 207 days in winter, 253 days in summer, and 145 days during the periods of vernal and autumnal equinoxes). The average value of the *ULF* index under quiet conditions was 0.29 ± 18. In this case the *ULF* index value in summer (0.32) was larger than in winter (0.26) and in the equinox (0.27). This is apparently the result of the ionospheric effect on the level of wave turbulence on the Earth's surface (see [Kozyreva et al., 2006]).

To study the level of morning–daytime *ULF* activity during different phases of a magnetic storm, we selected 19 strong storms with the *Dst* index varying from –100 to –150 nT at a maximum of the storm main phase and with a duration of not more than a day from the storm commencement to the main phase maximum. We did not consider the so-called "double storms" [Kamide et al., 1998; Tsurutani et al., 1999], when the storm main phase is composed of two minimums following each other at an interval of several hours. We continued studying using the superposed epoch method. The universal time of the minimal *Dst* index value during the magnetic storm main phase was taken as a reference point. The time interval of 48 h (i.e., a day before and after the *Dst* minimum) was analyzed for each storm. The results of an analysis are shown in Fig. 2, where the plots of the *Dst* index hourly values (the upper panel) and the *ULF* index (surface, magnetospheric, and interplanetary) are presented for all studied storms, and thick lines show the average hourly value and rms deviation ($\pm\sigma$).

We now consider the features of the surface *ULF* index (Fig. 2b). It is clear that the intensity of the daytime geomagnetic pulsations in the Pc5 range increases and considerably exceeds the background values at the beginning of a magnetic storm. It was indicated [Kozyreva et al., 2004; Kozyreva and Kleimenova, 2007] that, during the storm initial phase, most intense geomagnetic pulsation in the range 1–6 mHz are observed in the polar cap daytime sector and apparently result from a direct penetration of hydromagnetic waves from the interplanetary space. Part of such oscillations probably penetrates to auroral latitudes.

The performed studies indicated (Fig. 2) that daytime wave activity is maximal during the storm main phase rather than during the recovery phase as was considered previously. The scatter of the surface *ULF* index values is also minimal during the storm main phase. The amplitude of the daytime oscillations rapidly decreases at the early stage of the magnetic storm recovery phase. At the late stage of this phase, average activity of *ULF* waves remains almost unchanged for a long time. However, the rms deviation (σ) considerably increases in this case as compared to the storm main phase. Note that the oscillation amplitude becomes not larger than the background values in some cases and, on the contrary, abruptly increases and can even be larger than the amplitude values during the storm main phase in several other cases (Fig. 2).

The variations in the *ULF* index during four magnetic storms are presented in detail in Fig. 3, where the variations in the *Dst* index, IMF B_z component, solar wind density (*N*) and velocity (*V*), and surface *ULF* index are shown. Sudden commencement of magnetic storms (Figs. 3a–3d) was characterized by a considerable jump of the solar wind density and velocity and was accompanied by an abrupt increase in the *ULF* index (the pulsation amplitude increased by more than an order of magnitude in this case). It has long been known that geomagnetic pulsations are generated during storm sudden commencement (SC) (see, e.g. [Gogatishvili, 1976]). Note that all three considered storms developed at very large (to ~40 cm^{-3}) and average (~400–450 km s^{-1}) values of the solar wind density and velocity, respectively.

The southward turning of the IMF B_z component and the development of the magnetic storm main phase were accompanied by a gradual increase in the *ULF* index in all considered cases in spite of an abrupt decrease in the solar wind density to the background values during isolated storms (Figs. 3a, 3b). During the main phase of the magnetic storms shown in Figs. 3c and 3d, the values of the solar wind velocity remained large; however, the value of the *ULF* index was approximately identical during the main phase of all four considered storms. The value of the *ULF* index started decreasing when the IMF B_z component turned northward and the storm recovery phase developed. However, the appearance of individual intervals with

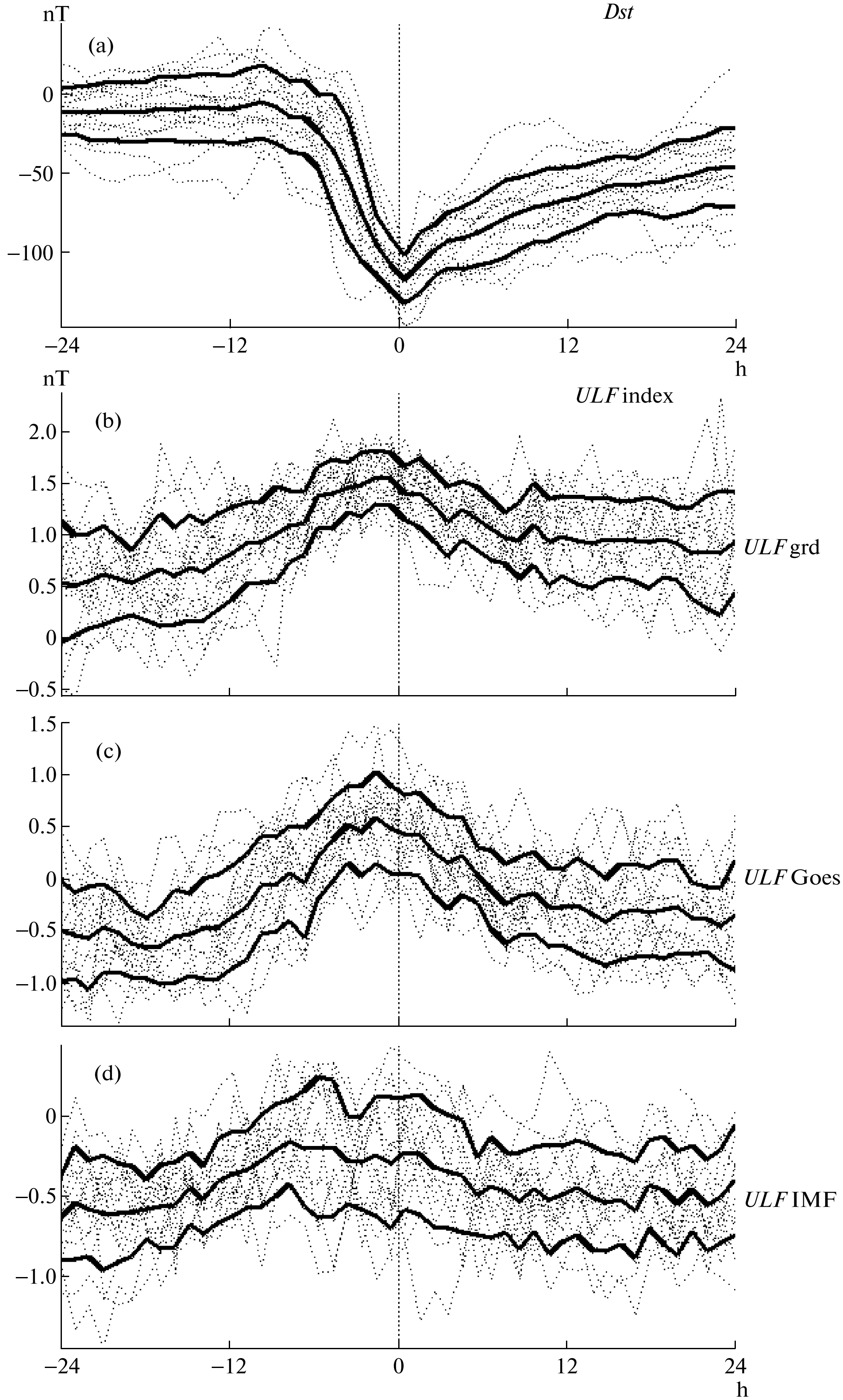

Fig. 2. Averaged variations in the *Dst* and *ULF* indices on the Earth's surface, in the magnetosphere, and in the interplanetary space during 19 magnetic storms.

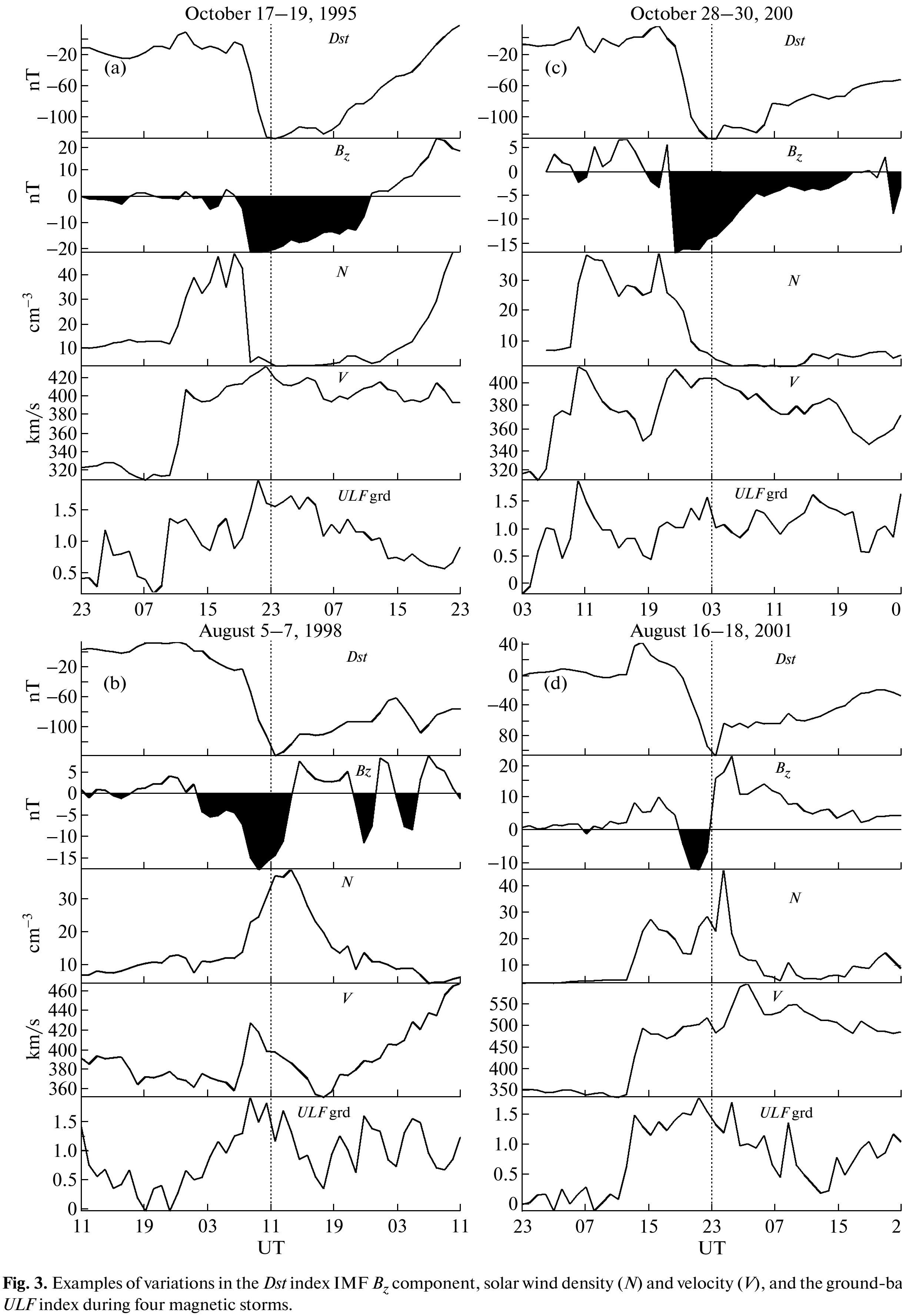

Fig. 3. Examples of variations in the *Dst* index IMF B_z component, solar wind density (*N*) and velocity (*V*), and the ground-based *ULF* index during four magnetic storms.

negative IMF B_z values during this storm phase was accompanied by a short-term increase in the *ULF* index (Fig. 3c). Note that a gradual increase in the solar wind velocity did not result in an increase in wave activity at that time.

4. DISCUSSION OF RESULTS

Very many works are devoted to studying Pc5 geomagnetic pulsations; however, the nature and spatial features of these oscillations have been studied insufficiently. In many respects this is related to the fact that the class of Pc5 pulsations combines different types of oscillations with periods in the same range but with different generation origin. In contrast to other types of geomagnetic pulsations, Pc5 oscillations are characterized by not only large periods but also huge amplitudes, reaching 30–100 nT at auroral latitudes and 300–600 nT under the conditions of strong magnetic disturbance (see, e.g. [Kleimenova and Kozyreva, 2005]).

It is considered that the Kelvin–Helmholtz instability at the magnetopause or in the entrance layers of the magnetosphere is the main generally accepted source of Pc5 pulsations. This can be confirmed by an increase in the amplitude of Pc5 pulsations with increasing solar wind velocity detected in several works (see, e.g. [Engebretson et al., 1998] and references therein). In addition to field line resonance, Pc5 pulsations in the magnetosphere can also be generated due to the development of the drift–mirror instability of the ring current under the conditions of large β (see [Pilipenko, 1990] and references therein). These waves have large azimuthal numbers ($m \sim 50$–100), are mainly registered on satellites, and are as a rule not observed on the Earth's surface. In addition, morning Pc5 pulsations can result from oscillations of the three-dimensional current system of the westward electrojet (see, e.g. [Motoba et al., 2002]). Generation of the global magnetospheric cavity mode in the Earth's magnetosphere can be one more source of Pc5 pulsations (see, e.g. [Kivelson et al., 1984]). In this case poloidal oscillations, which are characterized by a considerable compression component in the radial direction, originate in the magnetosphere. Such oscillations were often observed on geostationary satellites in the postnoon sector of the Earth's magnetosphere (see, e.g. [Hudson et al., 2004]). Oscillations can also result from a direct penetration of waves from the solar wind (see, e.g. [Kepko et al., 2002]). Thus, ULF pulsations can result from the simultaneous action of different sources.

Comparing the variations in the level of ground-based (Fig. 2b) and intramagnetospheric (Fig. 2c) activity, we can state that daytime wave turbulence in the magnetosphere increases faster and more intensely than on the Earth's surface at the beginning of strong magnetic storms. Consequently, geomagnetic pulsations on the Earth's surface represent only part of magnetospheric wave activity. Among other sources, these pulsations are also caused by hydromagnetic waves in the solar wind (Fig. 2d), which can penetrate immediately into the magnetosphere (see, e.g. [Kepko et al., 2002]). A comparison of Figs. 2c and 2d indicates that the level of wave turbulence in the solar wind during the storm main phase is even slightly lower than during the initial phase, whereas this level sharply increases in the magnetosphere. This makes it possible to assume that wave activity in the Earth's magnetosphere mostly results from the action of intramagnetospheric mechanisms.

It is known that the main phase of a magnetospheric storm is accompanied by the development of magnetospheric substorms and irregular geomagnetic pulsations. One would think that wave activity during the storm main phase should also be higher in the nighttime sector than in the daytime one. However, our studies indicated that the pattern is opposite (Fig. 2). To understand this situation, we constructed the maps of the global distribution of the geomagnetic pulsation intensity ($nT/\sqrt{mHz}$) in the frequency band corresponding to the oscillation spectral maximum in coordinates corrected geomagnetic latitude (CGM) and magnetic local time (MLT) for the time intervals near the maximum of the magnetic storm main phase.

As an example, we demonstrate two maps for the magnetic storm of August 17–18, 2001 (Fig. 4), the main phase of which is illustrated in Fig. 3d, and the magnetograms of the stations located in the Earth's morning (CMO, CHD, TIX) and nighttime (SOD) sectors. The maps indicate that activity of Pc5 pulsations in the morning sector is higher than in the evening and nighttime sectors. Intense Pc5 pulsations as a rule develop during the substorm recovery phase. Thus, the substorm, caused by a sudden change in the solar wind density, began at about 1845 UT (Fig. 3d). The substorm onset in the evening sector was accompanied by a short-term burst of irregular pulsations of the Pi3 type, which is shown at 1600–2000 MLT on the upper map (Fig. 4). In this case Pc5 pulsations, which were most intense near CMO (0800 MLT) and were used to calculate the *ULF* index, were simultaneously observed in the morning sector (0200–0800 MLT). The second map, constructed for 2000–2100 UT (Fig. 4), corresponds to the substorm development phase, which was observed at that time near local midnight (SOD) and was not accompanied by nighttime geomagnetic pulsations. Intense oscillations, which were used to calculate the *ULF* index, were simultaneously registered in the morning sector during the late recovery phase of the previous substorm. The situation was approximately the same during all studied storms. This allows us to conclude that morning geomagnetic pulsations during the substorm recovery phase mainly contribute to daytime wave activity in the course of the magnetic storm main phase.

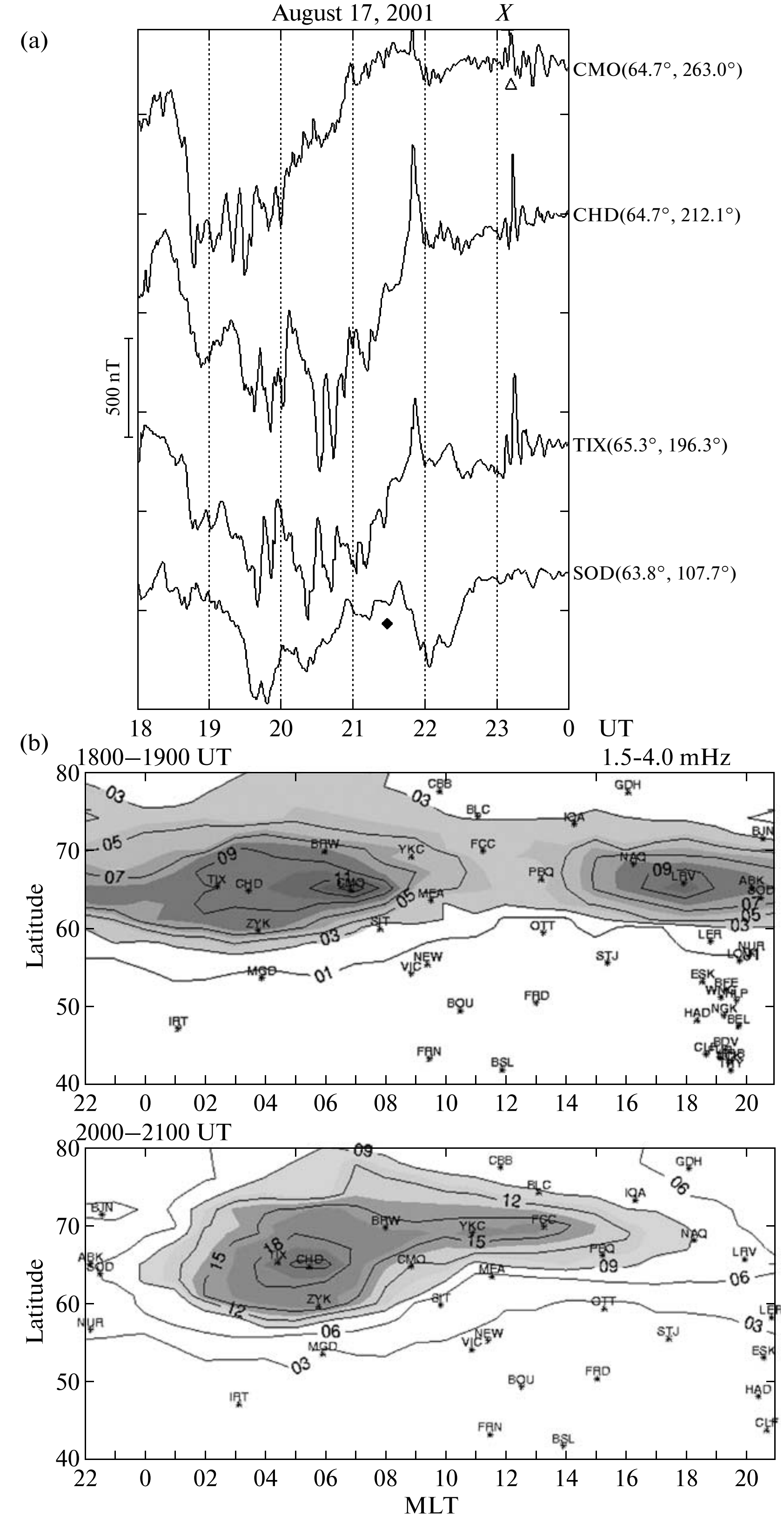

Fig. 4. An example of magnetograms for the morning (CMO, CHD, TIX) and nighttime (SOD) sectors and the maps of the spatial distribution of global ULF activity during the main phase of the magnetic storm of August 17–18, 2001, illustrated in Fig. 3d.

5. CONCLUSIONS

We analyzed the level of daytime wave geomagnetic turbulence at frequencies of Pc5 pulsations (2–6 mHz) during 19 strong magnetic storms (Dst_{min} varied from −100 to −150 nT), using a new *ULF* index of wave activity. We found out that the intensity of daytime geomagnetic pulsations at auroral latitudes is maximal during the magnetic storm main phase rather than during the recovery phase as was considered previously. We indicated that geomagnetic pulsations during the substorm recovery phase mainly contribute to daytime wave activity in the course of the magnetic storm main phase. At the beginning of a magnetic storm, daytime wave turbulence in the magnetosphere increases faster than on the Earth's surface. This indicates that only part of the wave energy can reach this surface. The value of the *ULF* index decreases when the IMF B_z component turns northward and the storm recovery phase develops.

Note that these results were obtained when we analyzed strong magnetic storms related to interplanetary magnetic clouds that approached the Earth. During the main phase of such storms, substorms usually develop not only in the nighttime sector but also in the evening and morning sectors. In the case of weak and moderate storms, caused by high-speed streams from coronal holes (see, e.g. [Zhang et al., 2006]), regularities can be different since main substorm activity is as a rule registered only in the nighttime sector.

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