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STUDY OF THE LIGHTNING ACTIVITY OVER POLAND FOR DIFFERENT SOLAR ACTIVITY

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ABSTRACT. The question of the connection between solar and thunderstorm activity is not new. The discussion among scientists began before the cosmic era. The correlations of the ground-based registration of the cosmic ray flux and meteorological observations have been performed since the 50s of the 20th century. The discussed problem is related to the influence of cosmic rays on the creation of clouds, particularly thunderstorm clouds. The intensity of the galactic cosmic ray flux is controlled by the density and velocity of the solar wind. The increase in the solar wind flux during high solar activity leads to decreasing galactic cosmic ray flux, but on the other hand, the solar activity creates solar cosmic rays. Using data from the PERUN system and the DEMETER satellite, we tried to estimate the connection between the thunderstorm activity in Poland and solar activity during the period of the DEMETER operational activity (2004–2010). The influence of thunderstorms on the ionosphere and its dependence on solar activity is also discussed. However, due to the short time interval of the available data covering an insignificant part of the solar cycle, close to the minimum activity, our findings are not fully conclusive. No correlation was found between the cosmic ray flux and lightning activity given by the number of the discharges. However, some of the most energetic lightning discharges in the analyzed period occurred close to the minimum of the solar activity and their appearance is discussed.

Keywords: thunderstorms, solar activity, ionosphere, PERUN, DEMETER, Swarm

1. INTRODUCTION

The Sun is the main source of the energy coming to the Earth. The majority of energy has the form of broadband radiation from ultraviolet (UV) through visible light up to the infrared, and the flux of this energy is almost constant during the solar cycle. There is no doubt that the Earth's atmosphere – its dynamics and thermodynamics – is completely controlled by solar radiation. However, the question of how solar activity influences long-term changes in the atmosphere is still a current problem. This question is related to the interaction between the solar wind and galactic cosmic rays. The possibility of the influence of cosmic rays on lightning activity in the atmosphere was first suggested by Wilson (1925). The solar wind with higher density and velocity during higher solar activity more effectively scatters the flux of cosmic rays, but on the other hand, active Sun produces more energetic electrons and protons as well as fluxes of X-rays, which can play the same role as galactic cosmic rays. The physics of the generation of aerosols in the atmosphere due to the interactions of energetic particles with the neutral atmosphere is quite well known. A cosmic ray effect on low and high clouds has been given by Yu (2002). He argues that ions produced by cosmic rays are a source of aerosols and become a center of condensation, leading to the creation of clouds (Arnold, 2008). The correlation between galactic cosmic rays and cloud cover on an 11-year solar cycle basis was shown by carslaw et al. (2002), Marsh and Svensmark (2003), and Chum et al. (2021).

Our study aims to investigate the effect of lightning discharges on changes in the high layers of the Earth's atmosphere (460–660 km above the Earth's surface) related to storm activity depending on solar activity. This problem is related to the more general subject of the magnetosphere–ionosphere–atmosphere interactions via so-called global electric circuit (GEC) discussed in many papers, for example, Marsh and Svensmark (2003), Rycroft and Odzimek (2010), Füllekrug and Fraser-Smith (2011), Singh et al. (2011), Rycroft et al. (2012), Rycroft and Harrison (2012), and Dwyer and Uman (2014).

We cannot solve this problem for the standard 11-year solar cycle due to the limited operation time of the DEMETER satellite (2004–2010). This time corresponds to the declining solar activity (Fig. 1). We selected several storms from this period for analysis. Earlier scientific works on the relationship of storms and accompanying lightning discharges with the integrated ionosphere–magnetosphere physical system focused on changes in the lower layers of the Earth's ionosphere. Measurements made by the DEMETER satellite operating at an altitude of 660 km above the Earth's surface have shown that the effects of atmospheric storms in the lower atmosphere are visible and can also be tracked in the upper ionosphere. In this study, we present both satellite- and ground-based sources of information about the atmosphere–Earth system. The satellite data that we used originates from the DEMETER satellite. Ground-based measurements of atmospheric discharges are performed by PERUN systems (Vaisala SAFIR 3000 system operated by the Institute of Meteorology and Water Management – National Research Institute in Poland).

2. METHODOLOGY

2.1. PERUN System

The PERUN lightning detection and location system (originally Vaisala SAFIR 3000) is part of the terrestrial remote sensing system belonging to the Institute of Meteorology and Water Management – National Research Institute. Since its installation in Poland (06.09.2001), this system allows monitoring of the total electrical activity in the atmosphere above the country (ground and intercloud discharges), tracing the trajectory of storm cells, monitoring the density of the total number of discharges, and much more.

Currently, the PERUN system consists of nine global positioning system (GPS)-synchronized receiving stations, the antenna system which works in the Very High Frequency (VHF) bands (13.5–114.5 MHz), and the discriminant antennas in the Low Frequency (LF) band (300 Hz–3 MHz). The average length of the baseline of the system is 200 km (max. 225 km, min. 145 km). The height of installation of the antenna sets varies from 14 to 80 m. Data transmission from receiving stations takes place via VSAT (Very Small Aperture Terminal) satellite links (seven stations) or the WAN (Wide Area Network) (two stations). According to the system manufacturer, the effectiveness of the detection of electrical phenomena in the Earth's atmosphere is 95%. Currently, the error in the location of lightning discharges in the country is less than 1 km. Remote sensing data collected by the antenna units of the PERUN system are transferred to the Central Processing Unit in Warsaw, from where they are distributed to users (including weather forecasters) and other systems within the Institute of Meteorology and Water Management –National Research Institute and the Internet. With the use of advanced analytical programs, it is possible to create visualizations of the location of lightning discharges in Europe, isokeraunic maps, the trajectory of movement of storm cells, and many others.

The PERUN system is constantly maintained at the highest operational efficiency and improved with the use of new-generation sensors. The data received from the system is exchanged internationally with neighboring countries and also used for scientific studies.

2.2. Satellite DEMETER

DEMETER was a low-altitude satellite (710 km) launched in June 2004 onto a polar and circular orbit, which measured electromagnetic waves all around the Earth, except in the auroral zones. In December 2005, the altitude of the satellite was decreased to 660 km. The Extra Low Frequency/ Very Low Frequency (ELF/VLF) range for the electric field was from 10Hz up to 20 kHz. There were two scientific modes: a survey mode where spectra of one electric and one magnetic component were on-board computed up to 20 kHz and a burst mode where, in addition to the on-board–computed spectra, waveforms of one electric and one magnetic field component were recorded up to 20 kHz. The burst mode allowed for performing a spectral analysis with higher time and frequency resolution. Details of the wave experiment can be found in Parrot et al. (2006) and Berthelier et al. (2006). During the burst mode, the waveforms of the six components of the electromagnetic field were also recorded up to 1.25 kHz.

Langmuir's probe gave values of the electron concentration in the range 10^2–5×10^6 cm^{-3} and temperature in the range 1000–5000 K. The plasma analyzer instrument measured variations of ion density, temperature, and composition at a 4 s time resolution. An energetic particle detector measured electrons and protons with energies from 70 keV to 2.34 MeV every 4 s in survey mode or every 1 s in burst mode. The orbit of DEMETER was Sun synchronized with local time of measurements around 10 and 22. DEMETER operated till December 2010.

Using the aforementioned experimental systems, the search for correlations between thunderstorms and solar activity from DEMETER has been performed. The highest thunderstorm activity occurs during late evenings, when in a similar period, DEMETER had its flybys over Poland.

2.3. Solar activity data

The picture of solar activity is rather complicated; many dynamical processes such as prominences, flares, coronal mass ejections (CMEs), and many others are included in this state. All of them are associated with the so-called solar cycle (Hale cycle) related to quasiperiodic, with an 11-year period, changes in the solar magnetic field. To characterize this activity, some fundamental parameters are used. The parameters used in the everyday description of solar activity are the number of solar spots which are dark regions on the Sun's surface with a lower temperature than the surrounding area, but with a strong magnetic field and flux of radio emission with a wavelength of 10.7 cm. The solar cycles are numbered since 1755 when the sunspot number began being regularly registered. Figure 1 shows the 23–24 cycles which contain the interval of operation time of the DEMETER satellite. As is shown, this time interval corresponds to the descending and minimum phase of the solar activity, but Figure 2 contains more detailed information about the solar activity for the same time interval originating from satellite registrations.

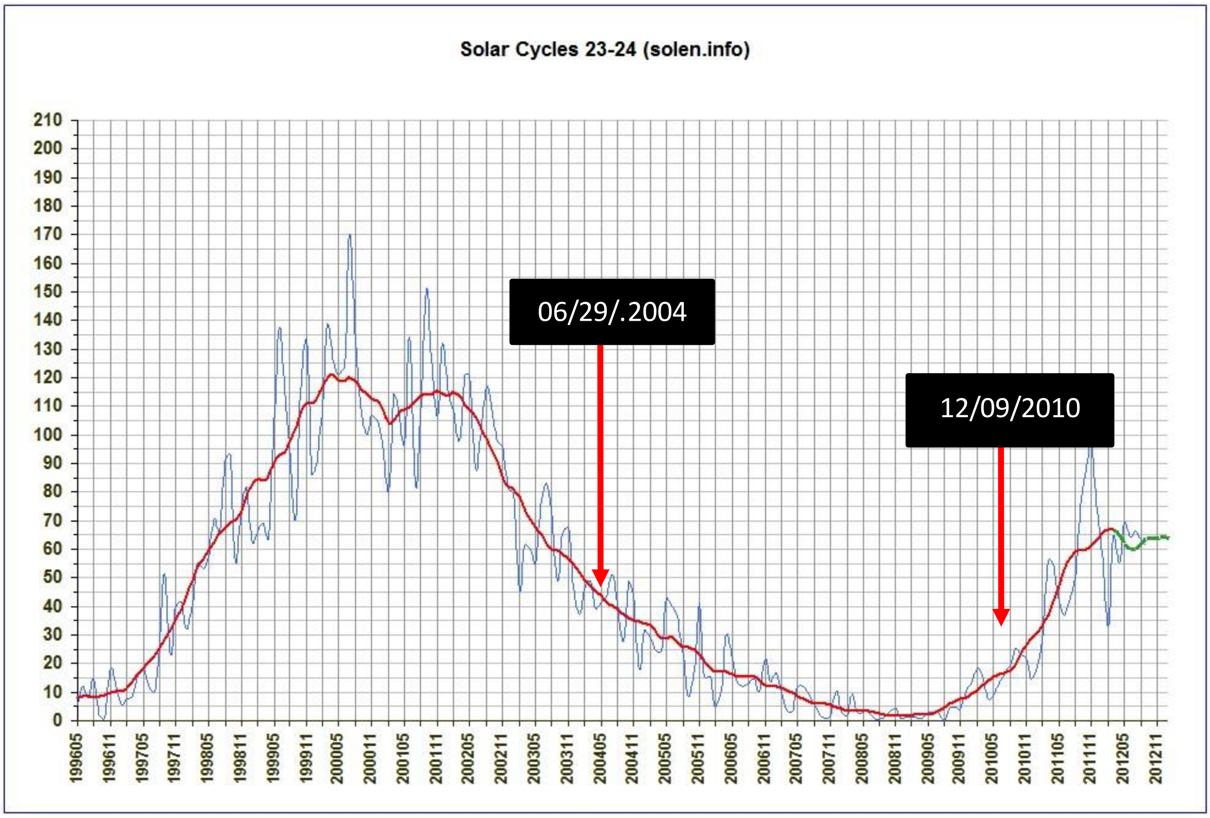

Figure 1. The 23rd–24th solar cycle. The red line shows an averaged sunspot number. The red vertical arrows indicate the time interval of DEMETER operation, 06.29.2004 is the day of launch, 12.09.2010 is the day of switch off of the satellite's payload (based on Alvestad, 2012).

Despite the low sunspot number in the vicinity of the years 2006–2007, quite a significant number of CMEs have been registered by SOHO and Stereo satellites, as it is shown in Figure 2a. Figure 2c presents several strong flares which are present close to the minimum of the sunspot number. Figure 2b confirms the absolutely minimum activity in the period of 2008–2009.

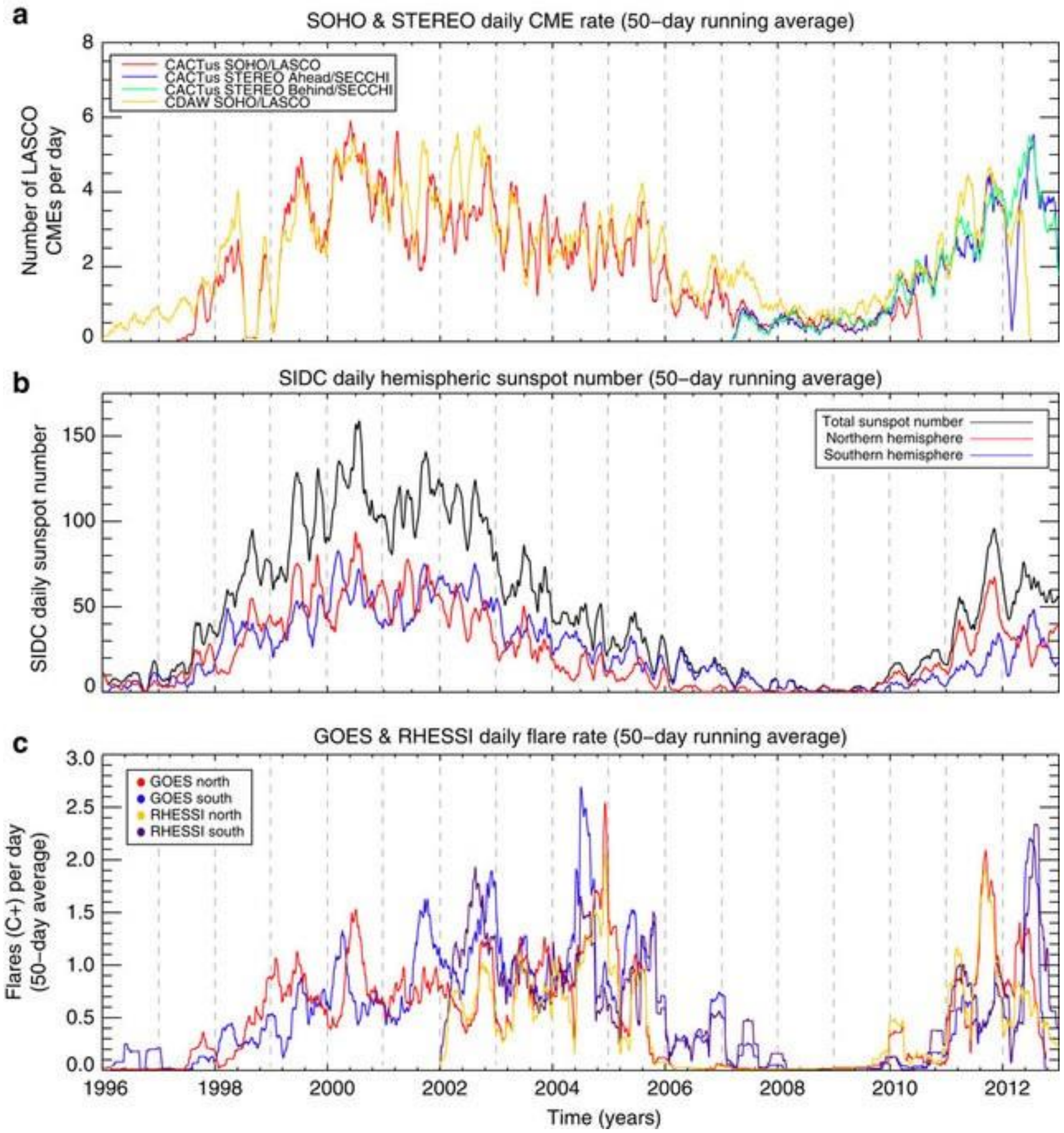

Figure 2. The satellite measurements of the solar activity are represented by a number of CMEs (a), sunspot number (b), and a number of strong flares (c) (McIntosh et al., 2015)

Using the information given in Figure 2, we selected years with a little higher activity (2005, 2006, 2007), with the presence of a higher number of CMEs and flares to compare with years of an absolute minimum of sunspot number (2008 and 2009).

3. RESULTS

3.1. Results from the PERUN system

The registrations of the PERUN system allow for statistical analysis of the storm's frequency of appearance as well as the lightning discharge type and estimated power. The analysis for the 2004–2010 period has been performed, which is the time when the DEMETER satellite was operational. However, the period in question is not long enough for the proper climatological analysis in terms of storm and lightning activity. Therefore, the trend lines cannot be calculated and drawn for such a short time span. Despite that, it can be stated that the overall number of detected and properly classified intercloud (IC) lightning discharges increased by a factor of 1.85, while positive cloud-to-ground discharges (CG+) increased by 4.2. At the same time, the negative cloud-to-ground discharges (CG–) increased by 1.75 with an interim low point in 2009. Similar behavior can be observed in the monthly run. The detected rise in the total number of discharges cannot be attributed to the modernization of the lightning detection and location system because there was none at that time. Figures 3 and 4 present the results of the PERUN system registrations. Figure 4 shows the monthly discharge readings of IC discharges, CG+, and CG– types. The maximal registrations correspond with the summer months and differ in consecutive years. The minimal number of lightning discharges of all kinds was registered in 2004, to reach its peak in 2007, except for the CG+ which maxed in 2010. There is no evident tendency that could be connected with solar activity changes, yet the mutual dependencies among the three kinds of lightning discharges mentioned above are typical and fell into the annual linear distribution of these phenomena in Poland known for years. To draw further conclusions, the longer time sequence needs to be examined in future research.

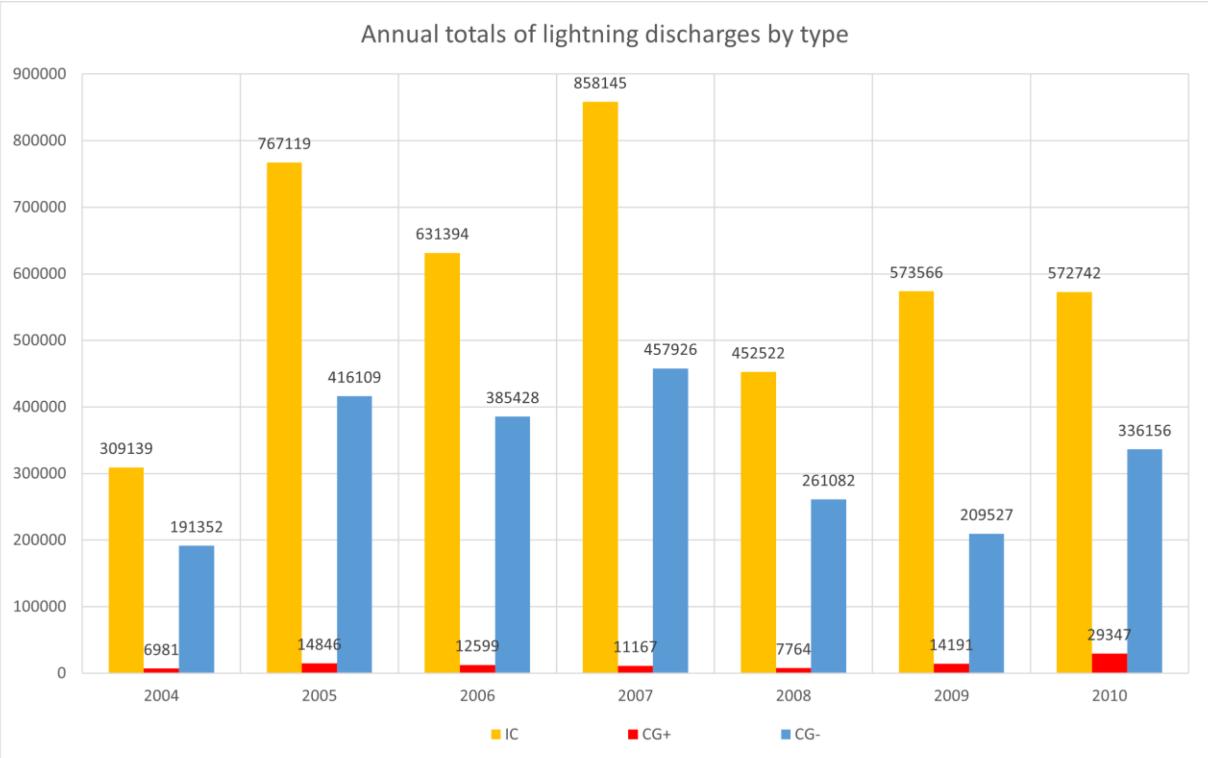

Figure 3. The total annual amount of lightning discharges in three basic types. As expected, the domination of IC discharges is clear. The visible maximum relates to the year 2007, which was not especially standing out in terms of solar activity.

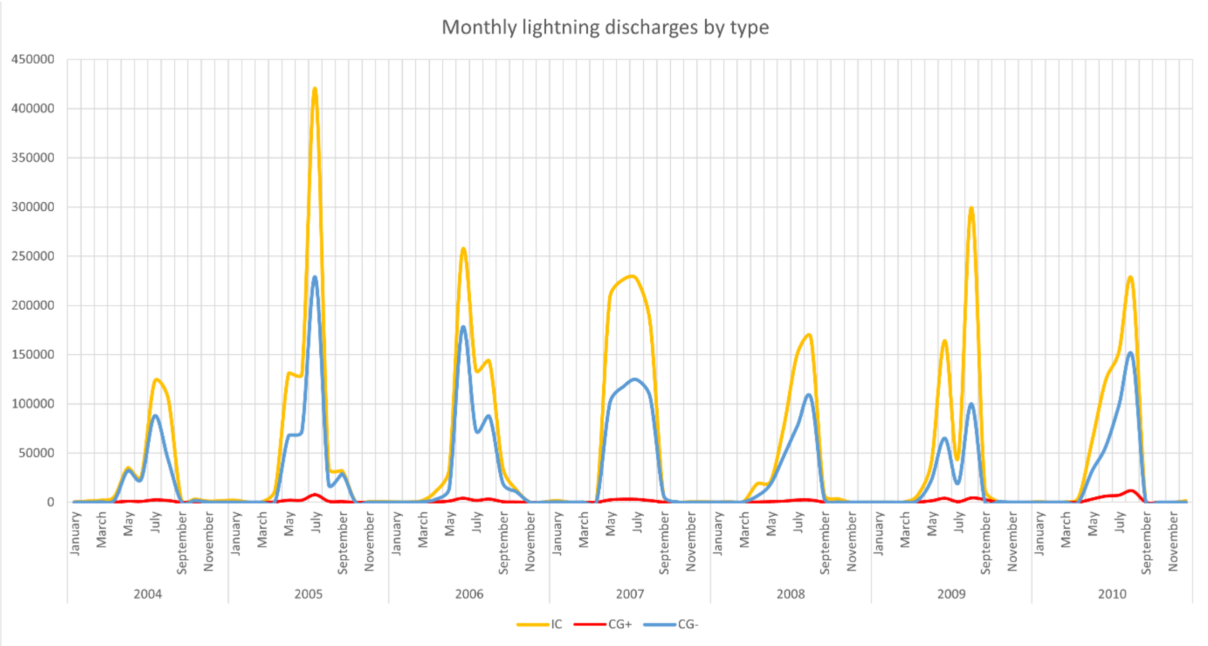

Figure 4. Monthly thunderstorm activity for the period of DEMETER operation. The color of lines indicates different types of discharge.

3.2. DEMETER's results

Thunderstorms' influence on the ionosphere has been reported in many publications (see e.g., Parrot, 2008, 2013). It can be seen in satellite registrations as well as in ground-based studies of the ionosphere. DEMETER satellite equipped with a rich set of plasma instruments gave an excellent view of these effects on the altitude of its orbit (660 km). The altitude of DEMETER's orbit is located over the maximum of the ionospheric F2 layer, so the effects of the atmospheric thunderstorm are weaker here than in E and F1 layers. However, the effects have been registered over many thunderstorm areas. We assume that plasma waves are the best tool to identify and correspond to the strength of thunderstorms. The amplitude of ELF and VLF emissions registered on board are assumed as a measure of the stroke's strength. In Figures 5–7, we present some representative registrations of waveforms and spectra taken by DEMETER over Poland during thunderstorms in the year of low solar activity (2009–2010), a little higher activity (2005, 2006), and year of the presence of high number of CMEs (2006 and 2007).

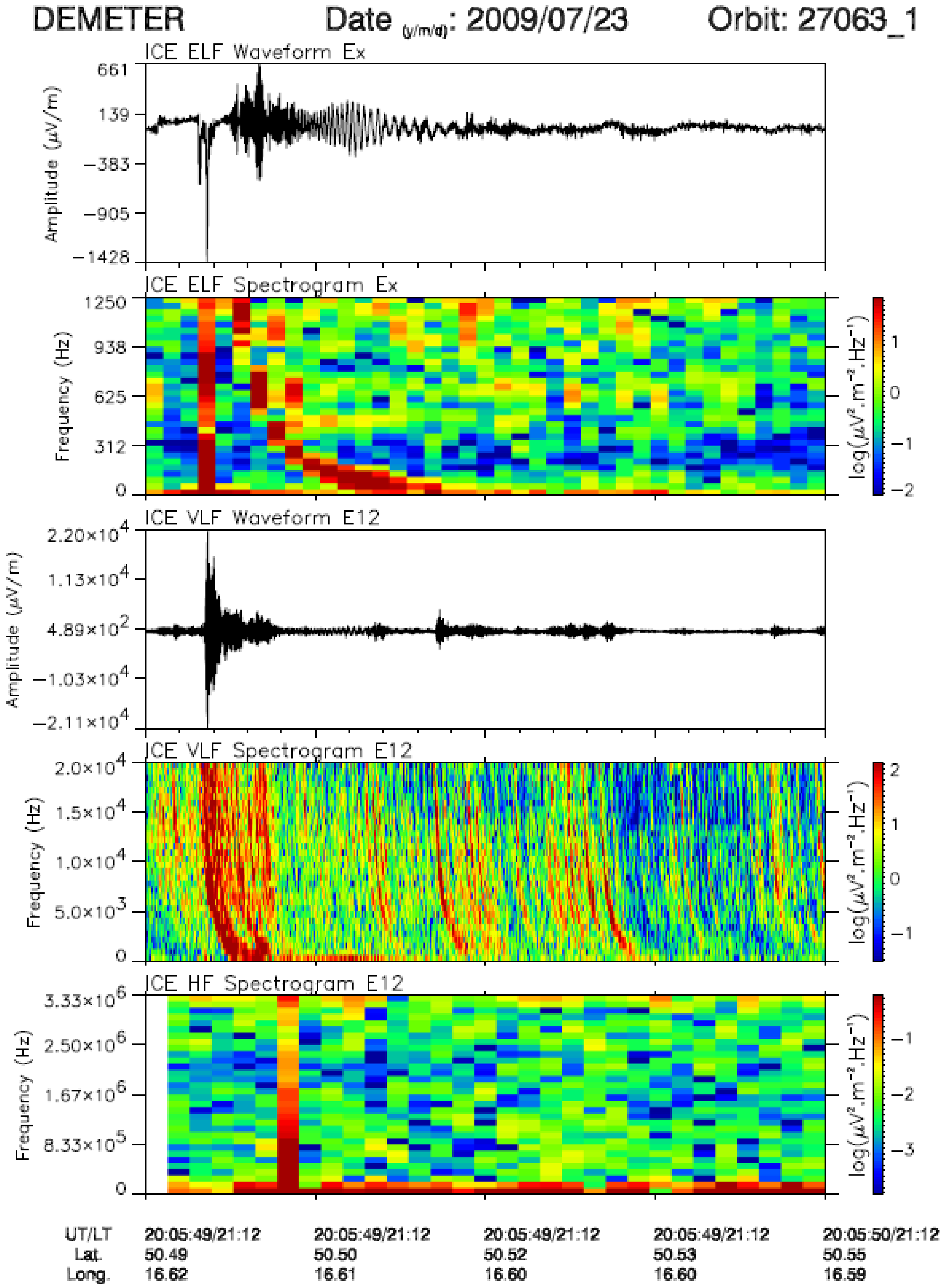

Figure 5a. The registrations of the waveform of the electric field in the frequency range ELF (upper panel) and spectrogram of it (lower panel), and in VLF (third panel) and spectrogram of it (lower panel). The bottom panel shows the spectrogram of high-frequency variations of the electric field. The figure presents measurements during thunderstorms on July 23, 2009 when there was a minimum of solar activity.

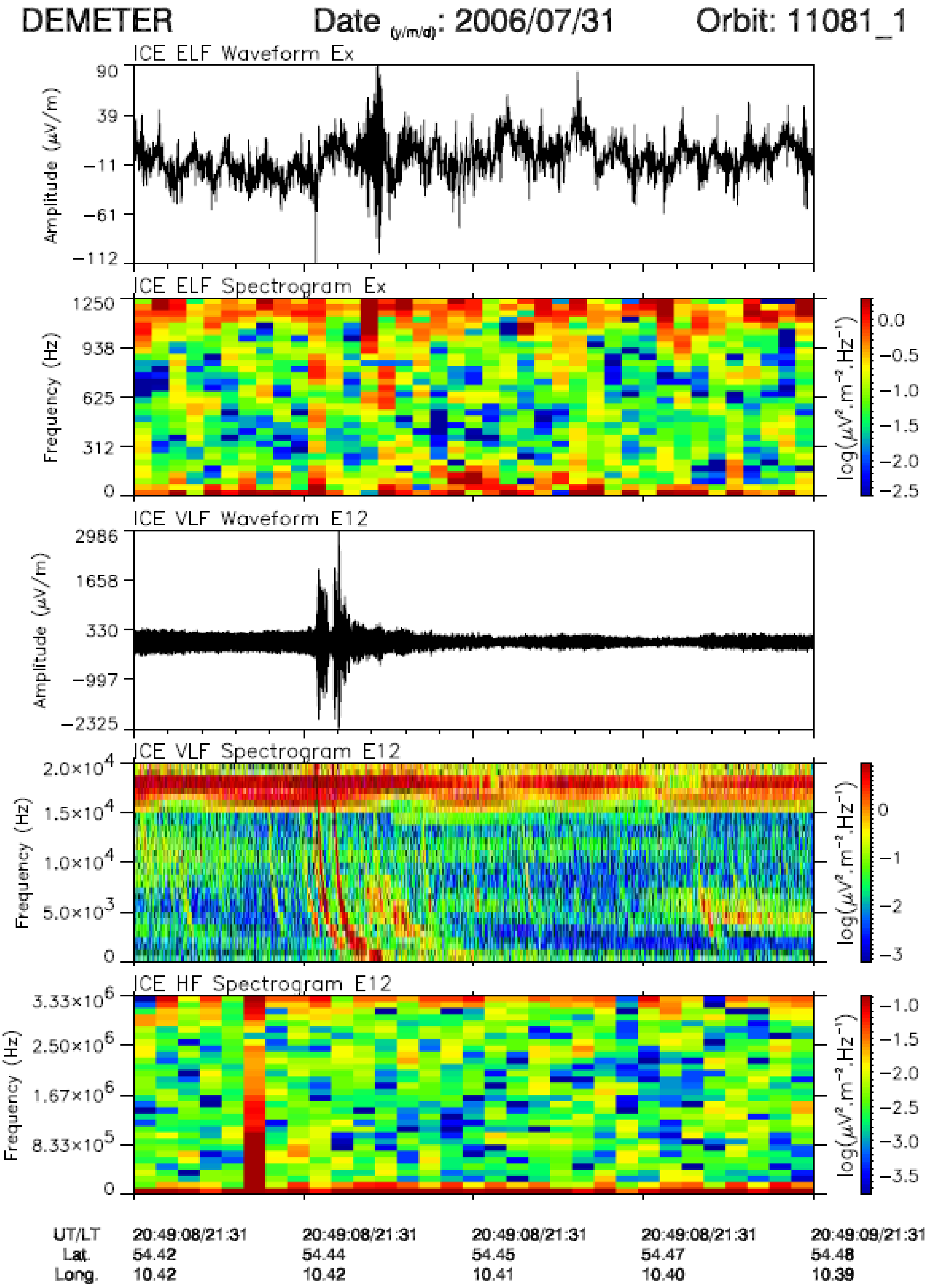

Figure 5b. The same as for Figure 5a, but for the year 2006 when CMEs occurred

Figures 5a and 5b give a comparison of the wave activity during thunderstorms in Poland in 2009 (Figure 5a) when the sunspot number was minimal (see Figure 1) with thunderstorms in 2006 (Figure 5b), a year with a significant number of CMEs (see the upper panel in Figure 2). Comparing the amplitude of ELF and VLF variations of the electric field, one can see the huge difference in amplitude reaching one order of magnitude. The spectrograms of the signals from the 2009 storm have components with higher value than those of the 2006 storm. The high-frequency emission in 2009 is one order of magnitude higher. One can say that emission during thunderstorms in the year of a minimum of solar activity is extremely high, which can be due to higher cosmic rays' flux.

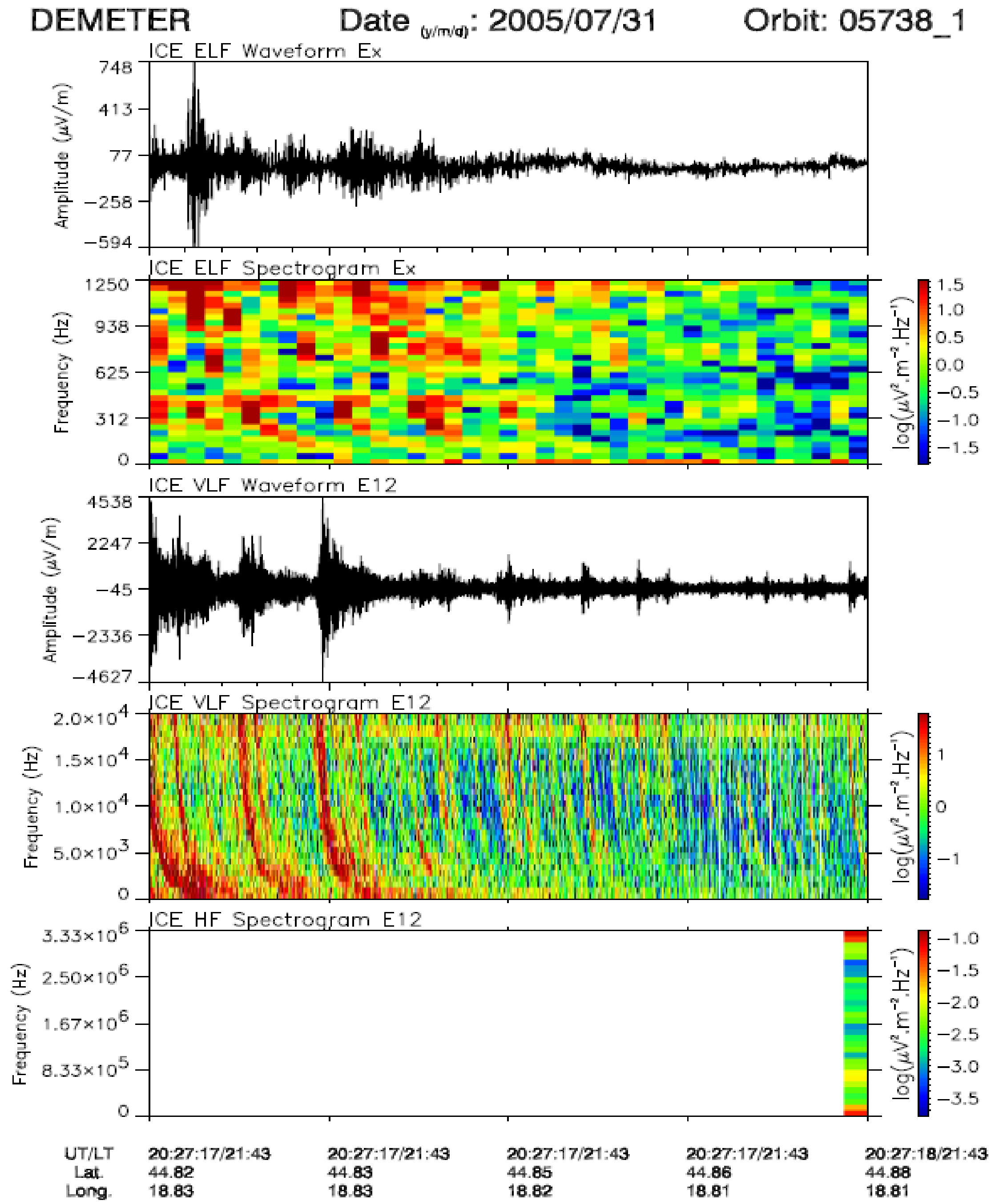

Figure 6a. The same as in Figure 5a, but for a thunderstorm in 2005 when the sunspot number was highest for the time of DEMETER operation.

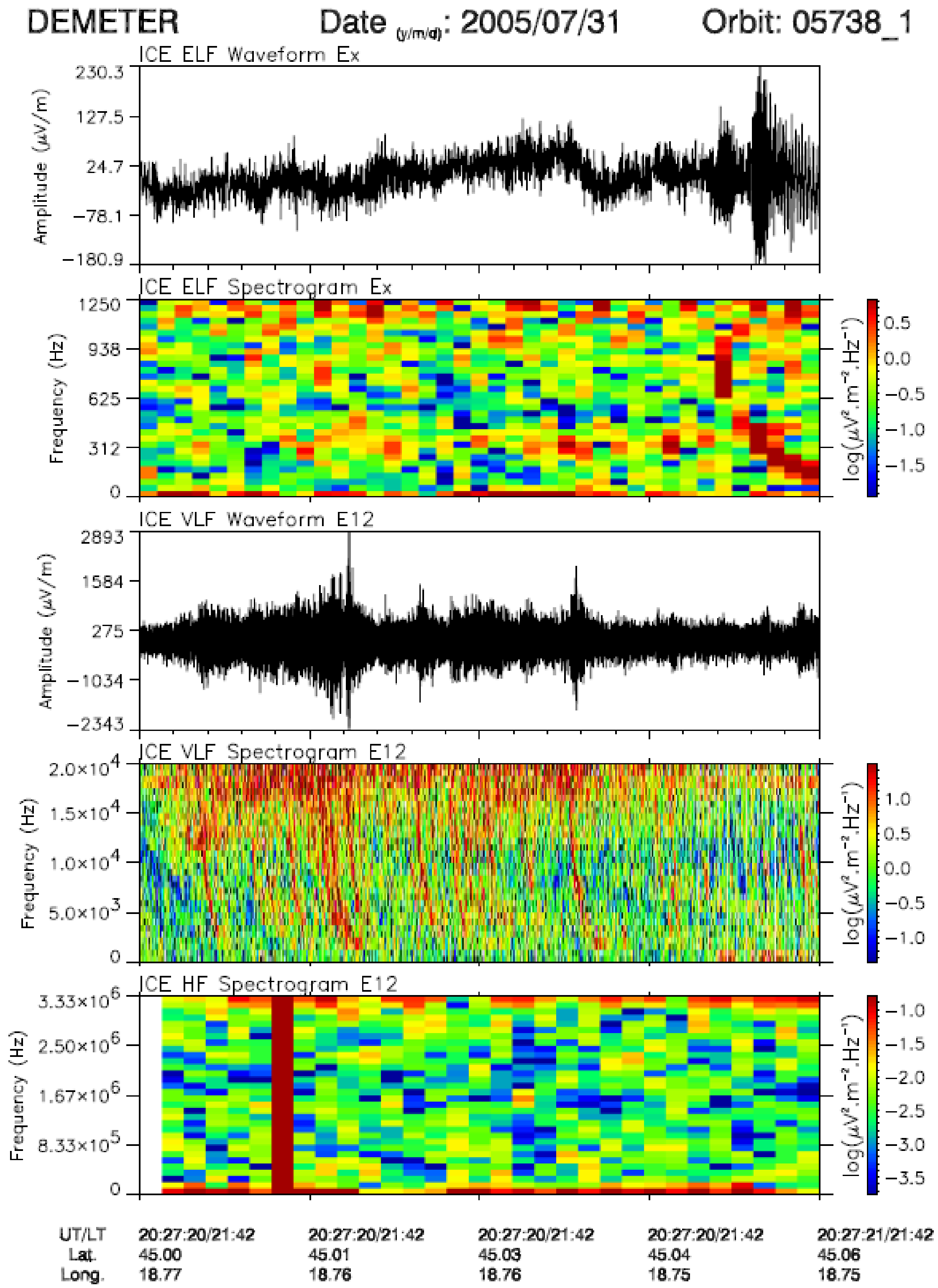

Figure 6b. The same as in Figure 5a, but for a thunderstorm in 2005 when the sunspot number was highest for the time of DEMETER operation (another example).

The year 2005 was the first year of the DEMETER being fully operational. Comparing with the cycle's maximum, it was a time of a moderate sunspot number and rather high number of CMEs. The signals recorded by DEMETER are also rather weaker than in the year 2009. It is shown in Figures 6a and 6b for a typical storm in this year on July 31.

Figures 7a and 7b compare the measurements by DEMETER from 2 years with very different solar activity. Figure 7a corresponds to the event of last year of DEMETER activity, which was the year of the very "quiet" Sun, whereas Figure 7b is related to the year of a significant number of CMEs. The ELF emissions were four times stronger in the year 2010 than in 2006, whereas the VLF emissions differed in one order.

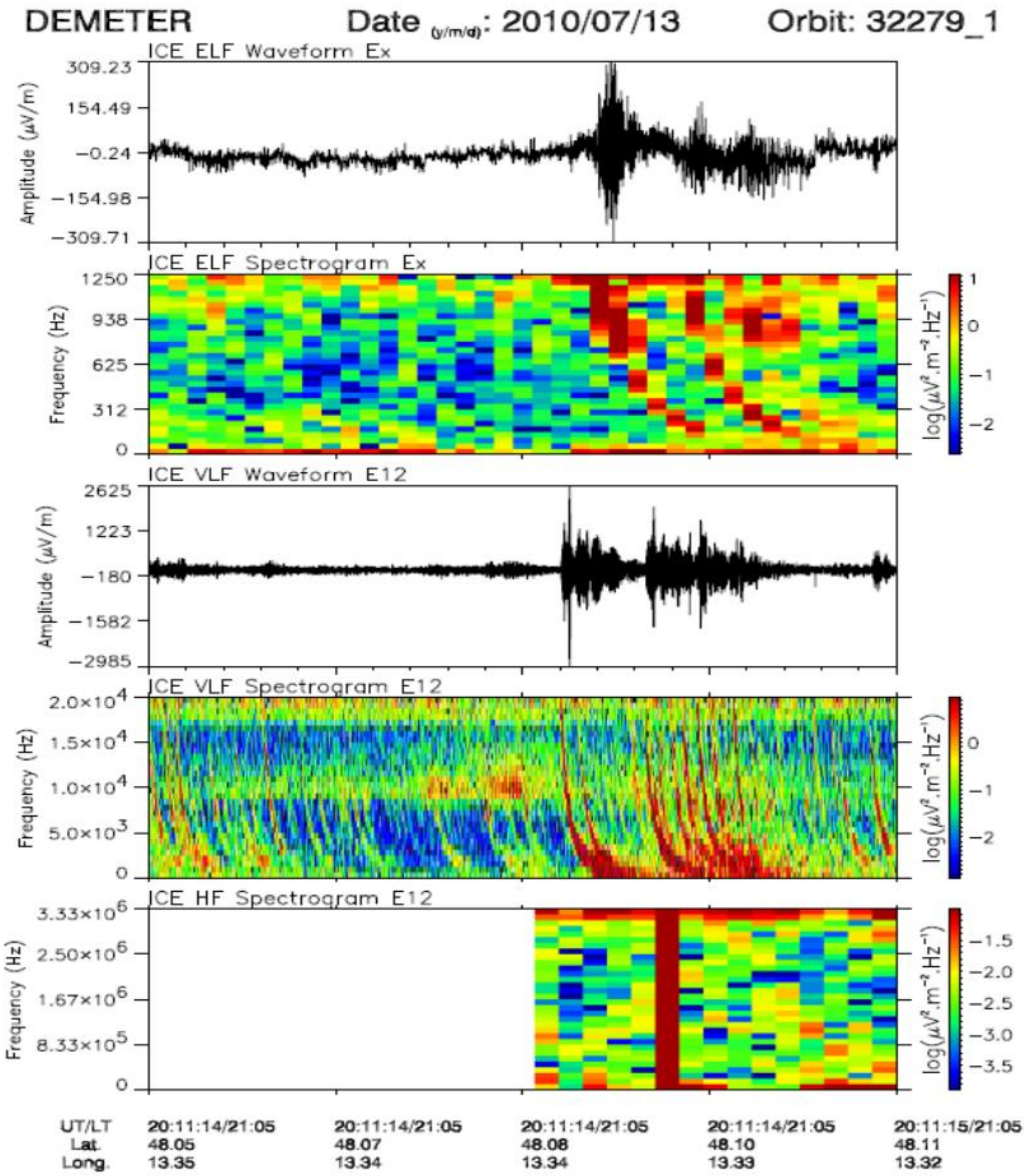

Figure 7a. The same as in Figure 5a, but for the year of very low sunspot number, 2010

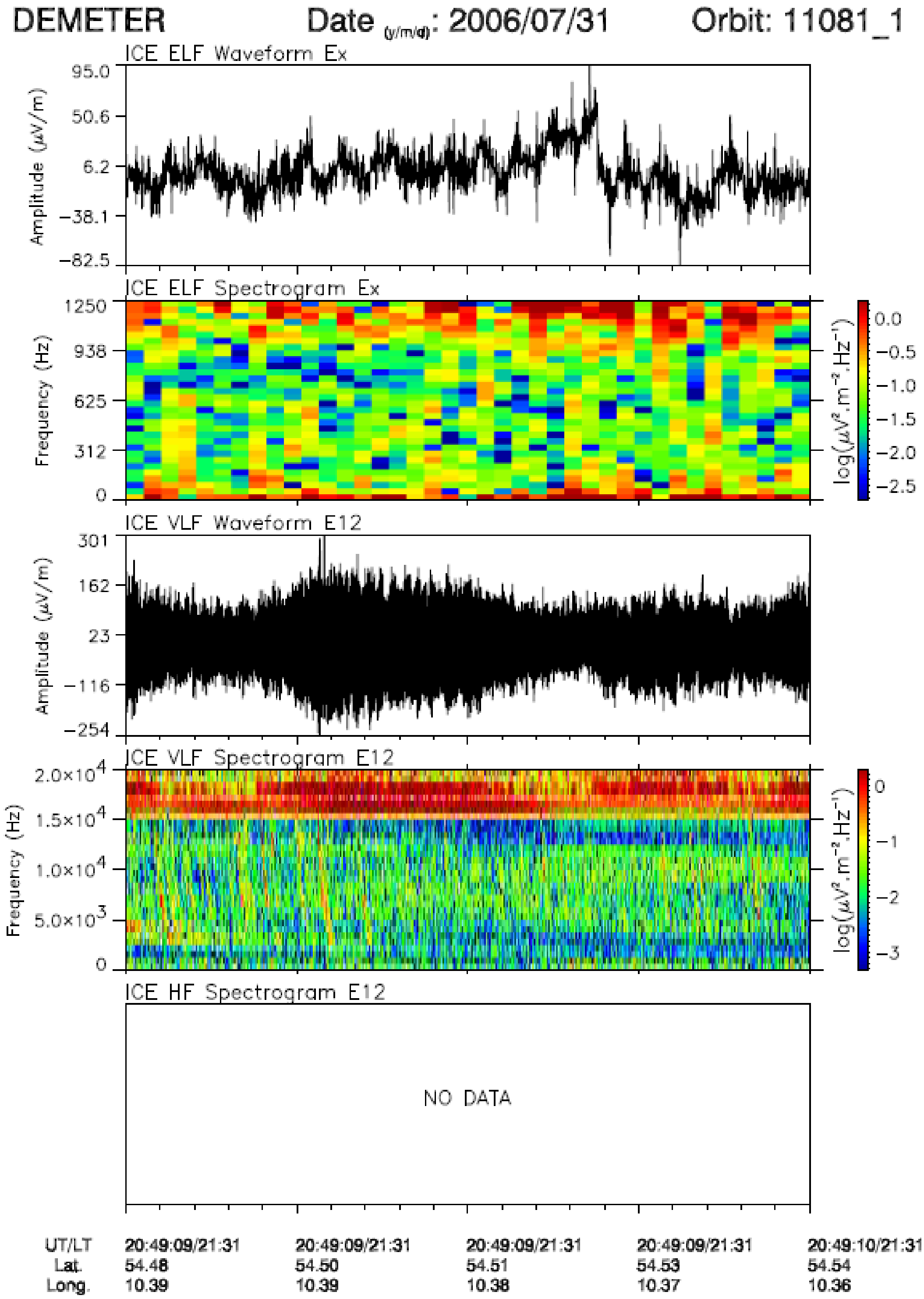

Figure 7b. The same as in Figure 5a, but for the year of a moderate sunspot number, 2006

4. CONCLUSIONS

Discussion of the influence of solar activity on the atmosphere has a long and very stormy history. This problem has a lot of aspects – influence on climate change, the intensity of rains, and the intensity and frequency of thunderstorms. Two facts from this discussion are without any doubt – the influence of solar activity on cosmic rays (see Fig. 8) and the correlation of the cloud coverage with cosmic ray flux (see e.g., Mironowa et al. 2015). Both facts have a good physical explanation.

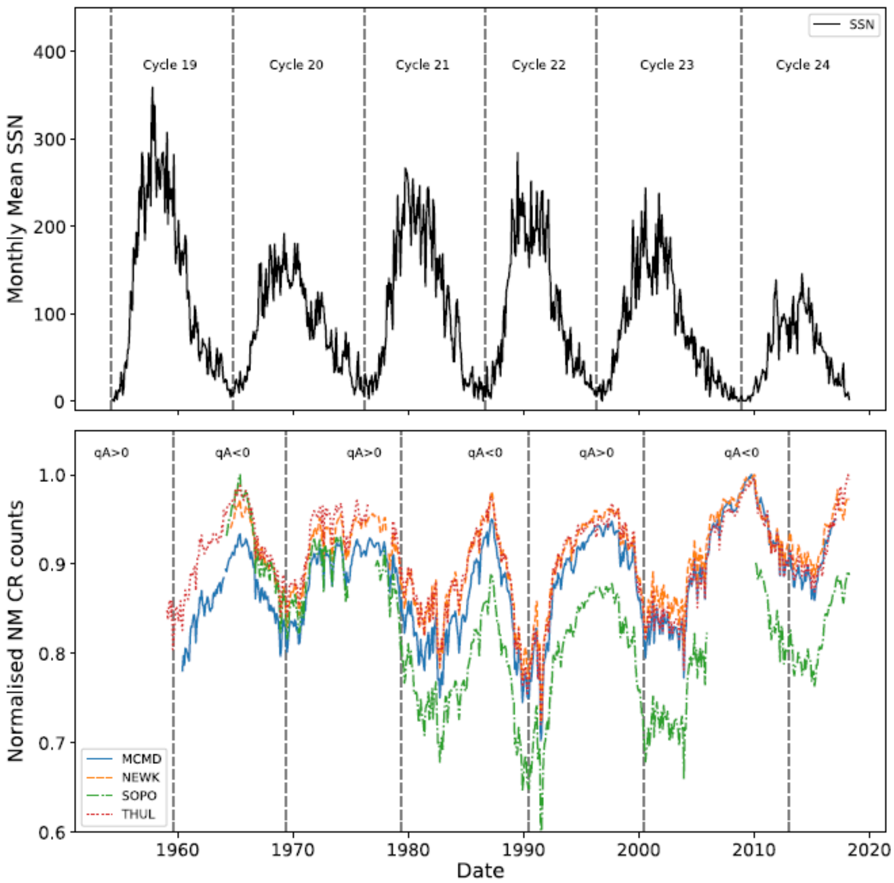

Figure 8. Correlation between solar activity represented by sunspot number (SSN upper panel) and cosmic rays'(CR) flux measured in four stations (MCMD = McMurdo, NEWK = Newark, SOPO = South Pole, THUL = Thule) (Ross and Chaplin, 2019)

Using data from the PERUN system and the DEMETER satellite, we tried to estimate the connection between the solar cycle and the thunderstorm activity in Poland. However, due to the short time interval of the available data covering an insignificant part of the solar cycle, close to the minimum activity, our findings are not conclusive, though some regularity has been seen. For the time of a very "quiet" Sun, the signals recorded by DEMETER in the ionosphere generated by thunderstorms are much stronger than those seen during the period with higher Sun activity (occurrence of CMEs). This, however, is not connected to the overall higher lightning activity given by the number of lightning counts (see Figures 3 and 4). It is possible that these highly energetic lightnings are the result of the decreased cosmic ray flux, as shown in Figure 8. It is not clear how the mechanism of correlation between cosmic ray flux and cloud cover given by Yu (2002) could result in such strong lightning discharges. Perhaps, there could be some relation between the cosmic rays and the electrification of clouds, which should be investigated.

Newer research of discussed problem with use of data from Swarm satellite constellation and the PERUN confirms the occurrence of strong thunderstorms during a year close to the minimum of the solar activity cycle 2017 (not published).

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