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Effects of solar and geomagnetic activities on the sub-ionospheric very low frequency transmitter signals received by the DEMETER micro-satellite

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ABSTRACT

In the framework of seismic precursor electromagnetic investigations, we analyzed the very low frequency (VLF) amplitude signals recorded by the Instrument Champ Electrique (ICE) experiment on board the DEMETER micro-satellite. The sun-synchronous orbits of the micro-satellite allowed us to cover an invariant latitude of between –65° and +65° in a time interval of about 40 min. We considered four transmitter signals emitted by stations in Europe (France, FTU, 18.3 kHz; Germany, DFY, 16.58 kHz), Asia (Japan, JP, 17.8 kHz) and Australia (Australia, NWC, 19.8 kHz). We studied the variations of these VLF signals, taking into consideration: the signal-to-noise ratio, sunspots, and the geomagnetic activity. We show that the degree of correlation in periods of high geomagnetic and solar activities is, on average, about 40%. Such effects can be fully neglected in the period of weak activity. We also find that the solar activity can have a more important effect on the VLF transmitter signal than the geomagnetic activity. Our data are combined with models where the coupling between the lithosphere, atmosphere and ionosphere is essential to explain how ionospheric disturbances scatter the VLF transmitter signal.

1. Introduction

Electromagnetic phenomena over a wide frequency range have been recognized as precursors to earthquakes. Precursor emissions have been found to cover a large frequency spectrum, as reported by several studies: ultra-low frequency (ULF) [Fraser-Smith et al. 1990, Molchanov et al. 1992, Hayakawa et al. 1996], extremely low frequency/ very low frequency (ELF/VLF) [Gokhberg et al. 1982, Parrot and Lefeuvre 1985], low frequency (LF) [Biagi and Hayakawa 2002], and high frequency (HF) [Warwick et al. 1982]. These first investigations were supported by laboratory experiments, where the stress of the rock was shown to release free electrons and electric charges, as reviewed by Parrot [1995], Hayakawa and Molchanov [2002], and Molchanov and Hayakawa [2008].

1.1. Very low frequency transmitter signals over seismic regions

VLF transmitters are primarily devoted to navigation and communication with military submarines. Most of the energy radiated by such transmitters is trapped between the ground and the lower ionosphere, which forms the Earth-ionosphere waveguide. The remote sensing of the ionosphere using different techniques, like the ground vertical sounding [Liperovskaya et al. 2008, Liperovsky 2008a, b, Pulinets et al. 2002], has shown anomalies in the electron density of the ionosphere above seismic regions. The complementarity of ground-based and space observations allows us local and spatial cover of earthquake regions.

The DEMETER micro-satellite was devoted to the study of electromagnetic pre-seismic emissions using a series of experiments that provide a more complete view of these phenomena [Parrot et al. 2006]. The use of electric and magnetic field measurements on board the DEMETER micro-satellite have demonstrated that the intensity levels of transmitter signals decrease a few days before a seismic event occurrence [Molchanov et al. 2006]. Molchanov et al. [2006] estimated the variations in the VLF signals emitted by transmitters in Australia (code: NWC), France (code: FTU), Germany (code: DFY), and Japan (code: JP). These showed drops in their VLF signals a few days before the occurrence of large earthquakes (magnitudes >5.5) in Europe and in Asia. Later, several investigations [Rozhnoi et al. 2007, Boudjada et al. 2008, Muto et al. 2008, Slominska et al. 2008] confirmed this drop in VLF intensity. It is important to note that the decrease in the VLF intensity also concerns the natural whistler emissions, as reported by Boudjada et al. [2010] for the L'Aquila earthquake (April 6, 2009). Hence, it was seen that the signal of the DFY transmitter was 'damped' from 5 days before to a minimum of one day before the earthquake. Also, the VLF whistler emission, which is generated mainly in the magnetosphere, decreased from 7 days before and attained a minimum on the day of the L'Aquila seismic event. The disturbance of both of these VLF signals (i.e. transmitter and whistler emission) might largely be due to the earthquake preparation zone. This indicates that not only the lower part of the ionosphere is disturbed, but also the higher part, at the altitudes of the DEMETER satellite.

1.2. Effects of solar and geomagnetic activities on the Earth ionosphere

The influence of geomagnetic activity, and also solar activity, cannot be neglected in studies of pre-seismic anomalies related to the Earth ionosphere. Several parameters, like the Kp-index, Ap-index, Dst-index and the sunspot numbers, are taken into consideration to separate ionospheric anomalies that are associated with earthquakes from others that are principally linked to geomagnetic activity. In general, the selected earthquake events are analyzed during periods of relatively quiet geomagnetic activity.

Rozhnoi et al. [2007] suggested that the effects of geomagnetic activity (described by the Dst-index) can be neglected, because such effects were absent in VLF transmitter signals in the Hawaii islands (code NPM) and in Australia (code NWC) for Japanese seismic events (November to December 2004, August 2005). Boudjada et al. (2008, 2010) considered the Kp-index, and showed that the geomagnetic activity was weak for the European earthquakes that occurred in Italy (December 2004, April 2009). However, the general behavior of the geomagnetic activity is similar to the VLF intensity variations.

2. Data investigation

In the following subsections, we describe the steps in the analysis of the relationships between the solar/geomagnetic activities and the VLF transmitter signals. First, we consider the VLF observations recorded by the Instrument Champ Electrique (ICE) experiment above the VLF transmitter ground-based stations. After this, we estimate the signal-to-noise ratio, and we fill the gaps in the data by using the interpolation technique. This allows us to give an averaged estimation of the VLF intensity and the corresponding standard deviation. Then we select specific periods, between August 8, 2004, and December 31, 2006, when the sunspot number, or the daily Ap-index, was large. In the last step, we proceed to the correlation of the solar/geomagnetic activities and the VLF averaged signals.

2.1. Methods of analysis

The ICE experiment [Berthelier et al. 2006] provides a survey from ULF to HF for each half-orbit. The survey consists of a dynamic spectrum that shows the intensity level variations *versus* the frequency ranges and the observation times. Each dynamic spectrum comprises 980 sequential spectra, each of which consists of 1024 frequency channels. The high spectral resolution of the experiment (pixel size,

Transmitter code	Frequency (kHz)	Latitude (°)	Longitude (°)	ICE: Closest frequency (kHz)
NWC	19.8	-21.5	114	19.8047
FTU	18.3	+46.4	1.05	18.3008
JP	17.8	+32.0	130	17.7930
DFY	16.56	+52.5	13.0	16.5625

Table 1. Main features of the VLF stations and closest frequencies to the transmitter.

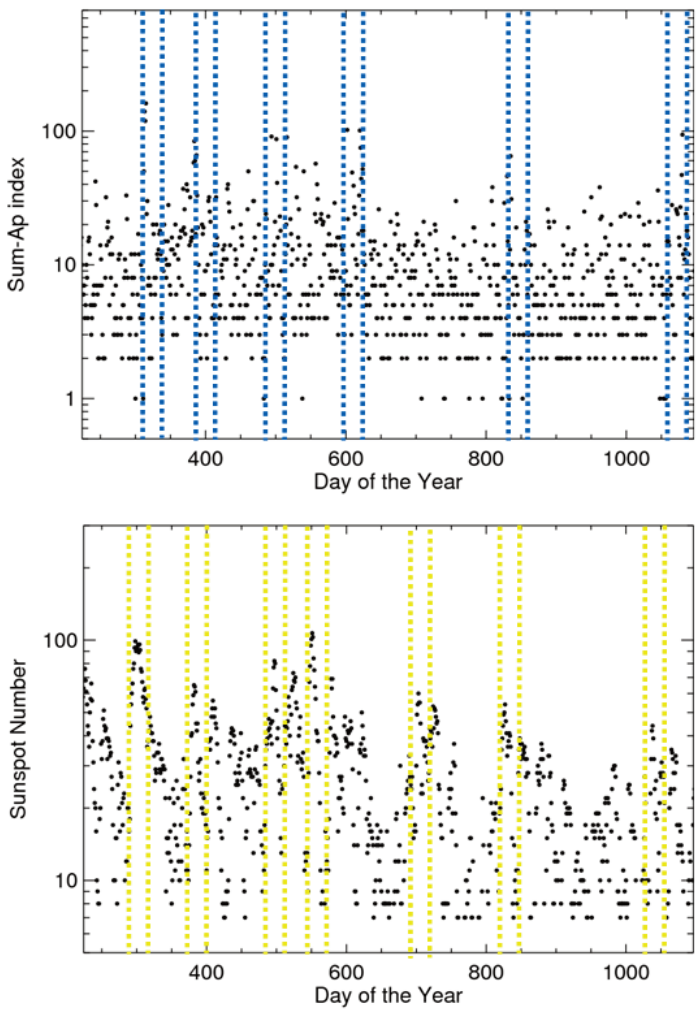

Figure 1. Daily Ap-index (upper panel) and sunspot number (lower panel) variations *versus* DOY (first day: January 1, 2004). The period investigated starts from August 8, 2004 (DOY 221) and goes to December 31, 2006 (DOY 1098). The blue and yellow vertical lines indicate the periods of high geomagnetic and solar activities.

2.048 s × 19.51 Hz) allows the recording of ionospheric components like the hiss, chorus, and whistlers, and the transmitter artificial signals. We use the so-called survey mode, which allows the recording of low bit-rate data all around the Earth at invariant latitudes <65°. We center our attention on the VLF signals associated with four transmitters: (a) the NWC transmitter (Australia: latitude = –21.5°, longitude = 114°), the FTU transmitter (France: latitude = +46.4°, longitude = 1.05°), the JP transmitter (Japan: latitude = +32°, longitude = 130°) and the DFY transmitter (Germany: latitude = +52.5°, longitude = 13.5°). We select the DEMETER orbits during periods where this micro-satellite was above the transmitter station. A 'rectangle' area centered on the VLF transmitter station is selected, with latitude and longitude ranges of about 10°. This allows daily collected measurements of the ICE experiment for frequencies close to the VLF transmitter frequency. Table 1 lists the main features of the VLF stations and the closest frequencies to the transmitter.

2.2. Solar and geomagnetic activities

Figure 1 shows the variations of the daily Ap-index (upper panel) and the daily sunspot number (lower panel) *versus* the day of the year (DOY; starting from January 1, 2004). In each panel of Figure 1, the beginning and the end of the time intervals where the high activity was recorded are indicated by colored vertical dashed lines. This time interval corresponds to about several days, on average. Table 2 and Table 3 list the sunspot numbers associated with the solar activity, and the daily Ap-index linked to the geomagnetic activity, respectively. For each maximum of activity, Table 2 and Table 3 give: the observation date, the corresponding DOY, the Ap-index or the sunspot number, and the probable common event. It is clear from Figure 1 that the decrease in the solar activity (minimum in June 2006) is followed by a decrease in the geomagnetic activity. Hence, events (a), (b), (c) and (d), as reported in Table 2 and Table 3, are probably correlated with a time delay of about 17 days, 51 days, 8 days and 42 days, respectively. The other events show first the growth of the geomagnetic activity, followed by the increase in the solar activity. Selected periods are used to study the presence, or not, of any correlation between these activities and the VLF flux density linked to the ground-based transmitter signal.

Date	Day of year	Daily sunspots	Significance
2004 10 24	0298	099	a
2005 01 16	0382	065	
2005 05 11	0497	082	
2005 07 04	0551	107	b
2005 12 03	0703	060	
2006 04 06	0827	054	c
2006 11 03	1038	044	d

Table 2. Sunspot numbers associated with the solar activity.

Date	Day of year	Daily Ap index	Significance
2004 11 10	0315	161	a
2005 01 10	0376	084	
2005 05 10	0494	091	
2005 08 10	0602	102	b
2006 04 14	0835	065	c
2006 12 10	1080	094	d

Table 3. Daily Ap-index linked to the geomagnetic activity.

2.3. Correlations between the geomagnetic and solar activities and the very low frequency transmitter signals

Figure 2 shows the variations in the VLF transmitter signals as recorded by the ICE experiment above the corresponding stations. We consider the period beginning on August 11, 2004, to December 31, 2006. The maximum VLF intensity is about 8 ×10^5 mV^2 m^{-2} Hz^{-1} for the NWC transmitter, 9 ×10^4 mV^2 m^{-2} Hz^{-1} for the FTU transmitter, 8 ×10^3 mV^2 m^{-2} Hz^{-1} for the JP transmitter, and 3 ×10^3 mV^2 m^{-2} Hz^{-1} for the DFY transmitter. The NWC transmitter is remarkably intense when it is compared to the others, e.g. it is two orders of magnitude more intense than the DFY transmitter. We note the presence of gaps in the data, because the ICE experiment was not operating or the transmitter was stopped. For example, the common gap of about 23 days for all of the stations between September 27, 2005 (DOY 616 in Figure 2) and October 19, 2005 (DOY 659 in Figure 2) is due to the absence of observations for the DEMETER satellite. Sometimes the transmitter was not in operation, as seen in Figure 2, where the VLF signals from the other transmitters were recorded. We correlated the VLF transmitter signals with the selected periods of solar and geomagnetic activities, as reported in Table 2 and Table 3, respectively. For this, we used a routine written in the Interactive Data Language (IDL) software, that allows the estimation of the degree of correlation and the corresponding lag. The formula is:

$$P_{xy}(L) = \begin{cases} \dfrac{\sum\limits_{k=0}^{N-|L|-1}(x_{k+|L|}-\bar{x})(y_k-\bar{y})}{\sqrt{\left[\sum\limits_{k=0}^{N-1}(x_k-\bar{x})^2\right]\left[\sum\limits_{k=0}^{N-1}(y_k-\bar{y})^2\right]}} & \text{for } L<0 \\ \dfrac{\sum\limits_{k=0}^{N-L-1}(x_k-\bar{x})(y_{k+L}-\bar{y})}{\sqrt{\left[\sum\limits_{k=0}^{N-1}(x_k-\bar{x})^2\right]\left[\sum\limits_{k=0}^{N-1}(y_k-\bar{y})^2\right]}} & \text{for } L\geq 0 \end{cases}$$

This function $P_{xy}(L)$ computes the cross-correlation of two sample populations X and Y as a function of the lag L. In this case, $\bar{x}$ and $\bar{y}$ are the means of the sample populations x= = (x_0, x_1, x_2, ... , x_{N-1}) and y = (y_0, y_1, y_2, ... , y_{N-1}), respectively

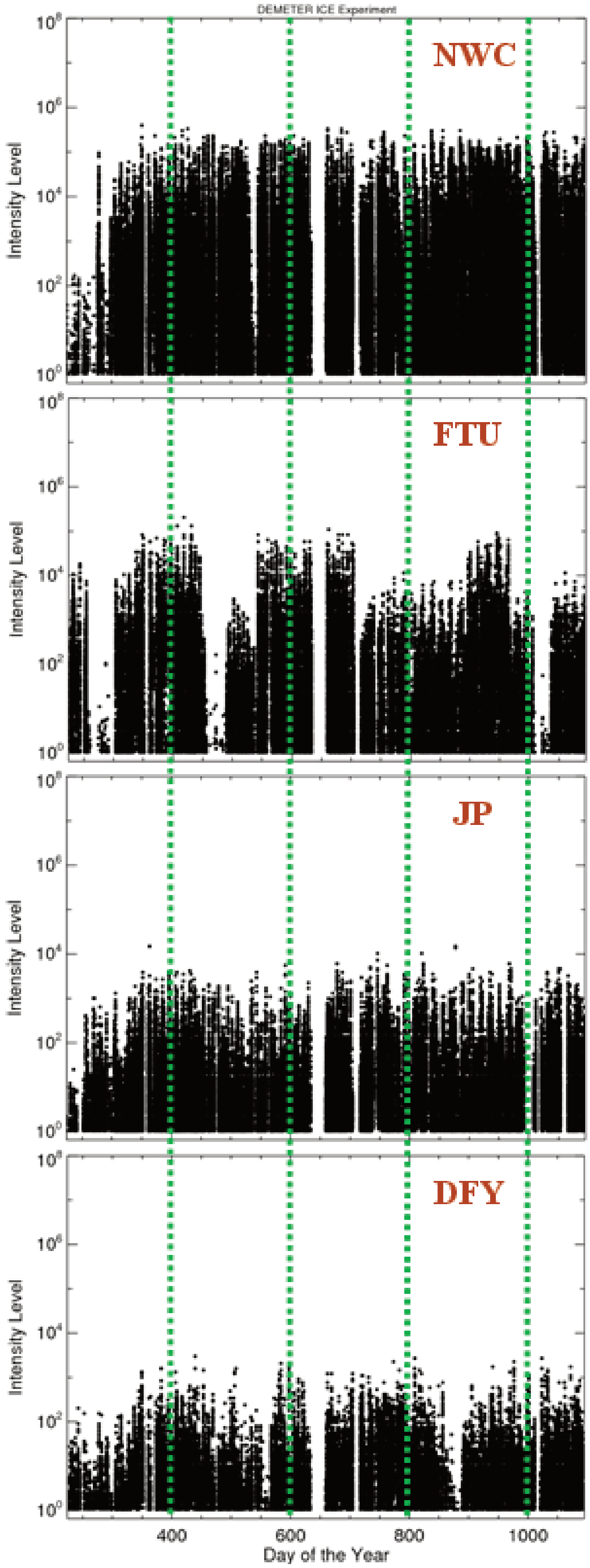

Figure 2. Flux density variations *versus* the DOY for the VLF transmitter stations in Australia (NWC, top panel), France (FTU, second panel), Japan (JP, third panel), and Germany (DFY, bottom panel).

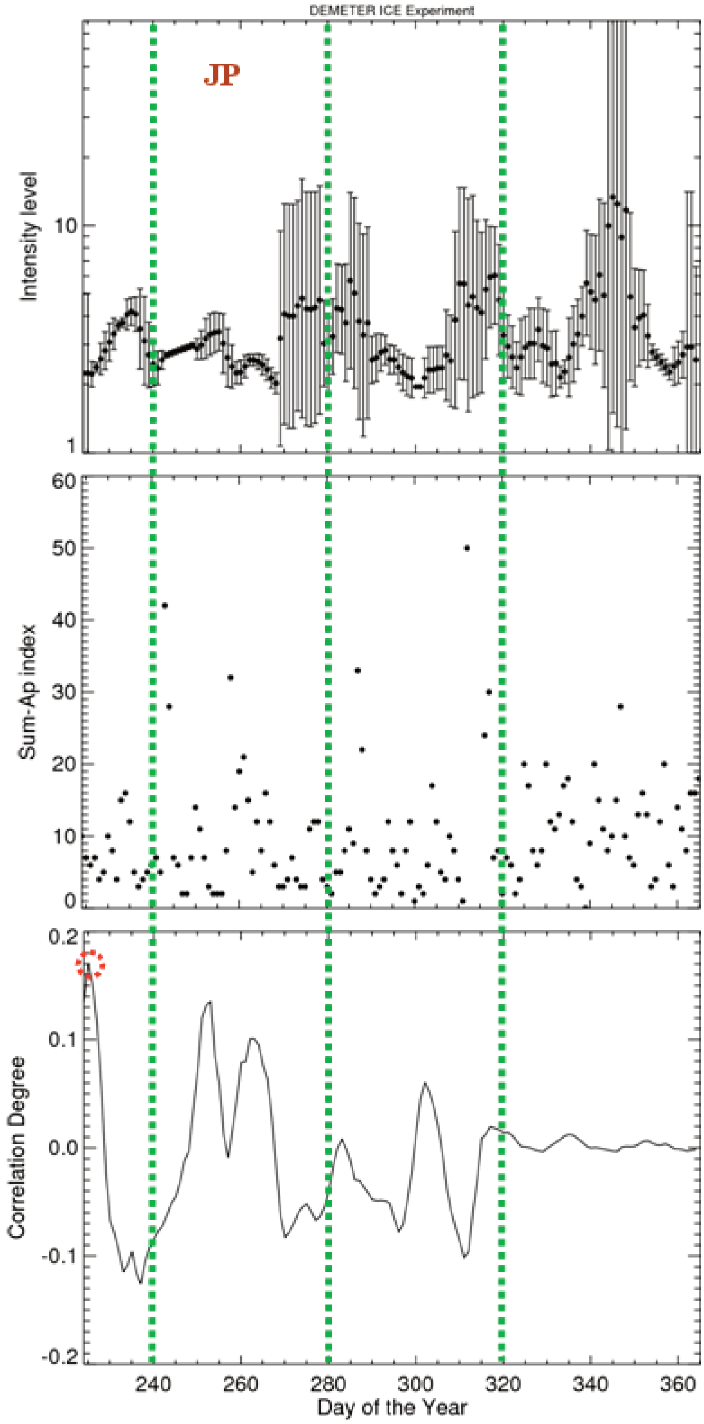

Figure 3. The VLF transmitter signals (top panel) and the daily Ap-index (second panel) and their estimated degree of correlation (bottom panel). The degree of correlation is about 15%, with a lag of <1 day.

[Fuller 1976]. Figure 3 shows the procedure to estimate the degree of correlation. We used two sets of data, one from the JP transmitter, and the other from the daily Ap-index, for the same period from August 24, 2004 (DOY 237) to December 26, 2004 (DOY 306). Figure 3 shows the averaged transmitter signal of the JP signal (first panel), the daily Ap-index (second panel), and the degree of correlation (third panel). In this example, the degree of correlation is about

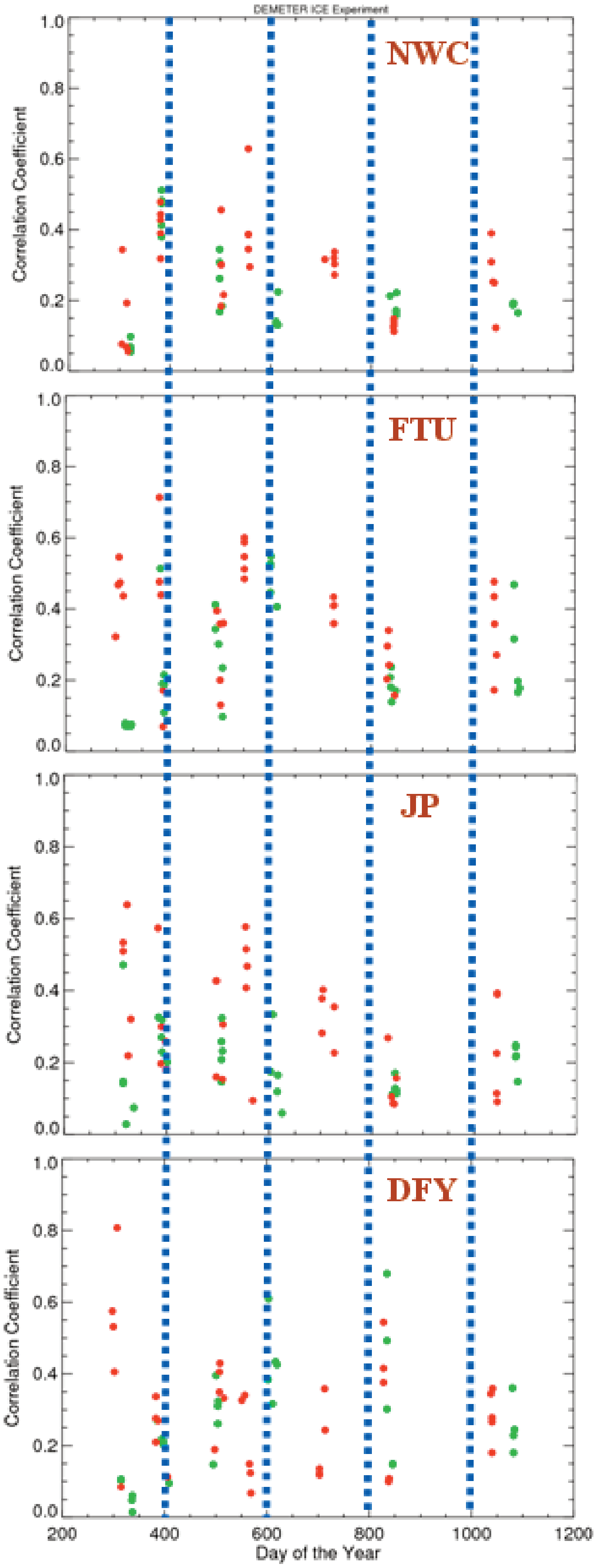

Figure 4. Variations in the degree of correlations *versus* the DOY. The red/green circles correspond to the degrees of correlations between the sunspot/Ap-index and the VLF transmitter signals, for the Australia (NWC, top panel), France (FTU, second panel), Japan (JP, third panel) and Germany (DFY, bottom panel)

15%, with a time lag of less than one day. In the correlation processes, we consider three different signal-to-noise ratios of 1.0, 10 and 100 [Schroeder 2000]. The aim is to determine the dependence, or not, of the correlation on the signal-to-noise ratio. The results are shown in Figure 4, where the green and red indicate the correlation of the VLF signal with the geomagnetic and solar activities, respectively. First, the correlation is, on average, <40% for all of the stations. Secondly, the solar activity might have a more important effect on the VLF transmitter signal than the geomagnetic activity. Thirdly, the variations in the correlation coefficients *versus* the DOY are similar for all of the stations. Hence a decrease in the correlation from August 2004 (coefficient of correlation of about 50%) to November 2005 (coefficient of correlation of about 20%) is evident when combining all of the stations. Fourthly, only in one case is the degree of correlation in the order of 80%, as shown in the fourth panel of Figure 4 (i.e. for the DFY transmitter).

3. Discussion and conclusions

We studied the variations in the VLF transmitter signals recorded by the ICE experiment on the DEMETER micro-satellite. The orbital features allowed us to cover a time interval of about 40 min for all longitudes and the invariant latitude range between –65° and +65°. The subsequent analysis investigates the influence of the solar and geomagnetic activities on the reception of the VLF transmitter by the DEMETER micro-satellite. In the following, we discuss our main results: (a) the influence of the solar and geomagnetic activities on the detection, or not, of precursor electromagnetic emissions; and (b) the way to explain how the VLF signal is disturbed along its path to the satellite.

3.1. Effects of the solar and geomagnetic activities on the transmitter signals

We considered here a period of investigation over more than two years. This allows us to select different time intervals where we can note enhancements of the geomagnetic and solar activities. We have estimated the degree of correlation for four VLF transmitter stations. The correlation was, on average, about 40%. As shown in Figure 1, the Ap index and the sunspot number reached over 100 during these strong geomagnetic and solar activities. The effects of these activities can be considered in the analysis of the pre-seismic precursors, although it is still not dominant. This effect can be neglected when the daily Ap-index or sunspot number is <20. Also, we see that the control of the solar activity is usually dominant when it is compared with the geomagnetic activity. This result is interesting, because it shows that ionization of the D- and E-layers of the ionosphere disturbs the path where the VLF transmitter signals propagate in particular under the effects of the Sun.

In the literature, the investigations of pre-seismic ionospheric anomalies mainly report parameters that are related to the geomagnetic activity (like the Ap-index or Dst-index), and only a few investigations have analyzed solar activity effects [e.g. Liperovskaya et al. 2008]. However, we show in our studies that both can be considered to estimate their effects on the ionosphere.

3.2. Lithosphere-atmosphere-ionosphere coupling

The low degree of correlation (<40%) allows us to conclude that the drop in the VLF transmitter over seismic regions, as reported in several studies, might be related to the preparatory zone. The model proposed by Liperovsky et al. [2000] and Molchanov [2004] might explain how the gas–water release from the earthquake preparatory zone can disturb the ionosphere. These studies showed that an upward energy flux of atmospheric gravity waves can disturb the ionospheric electron density above seismic regions. A recent study of Stangl et al. [2011] found that for the L'Aquila earthquake, there was anomaly enhancements in the Total Electron Content (TEC) measurements. In a quasi-similar time interval, a drop in the intensity of the VLF electric field occurs. This study concluded that the paths of the VLF signals are deviated during their propagation in the turbulent ionosphere. The VLF signals drop because they only occasionally reach the DEMETER satellite. Other models have suggested that the ionospheric disturbances are linked to the changes in the atmospheric electricity (conductivity and vertical field) due to air ionization produced by radon released from an active tectonic fault before an earthquake. Space observations have reported electric fields of about 3 mV/m to 7 mV/m [Yokoyama et al. 2002, Chmyrev et al. 1989]. However, Liperovsky et al. [2005, 2008b] showed an electric field of the order of 1000 V/m. Recent investigations of Ampferer et al. [2010] and Denisenko et al. [2008] proposed much lower fields at the ionosphere level. This suggests that a further comparison of models and observations is recommended for the prediction of pre-seismic electromagnetic phenomena.

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