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MONITORING OF ATMOSPHERIC CHANGES RELATED TO SUN-EARTH INTERACTIONS

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Abstract: *Our upper atmosphere is affected by solar forcing, whose main sources are the ionizing radiation and space weather. The solar ionizing radiation changes in association with the 11-year solar cycle, 27-day rotation and solar flares. VLF soundings have confirmed the solar Lyman-alpha as responsible through the formation and maintenance of the ionized layer of our atmosphere, the ionosphere, which shows variations in close association with the 11-year solar cycle. Excess of X-ray radiation produced during the solar flares, when the solar radiation can increase in order of magnitude, strongly disturbs the lower ionosphere. Ionosphere studies using VLF technique have identified that even very weak solar flares (B2 as X-ray classification from GOES satellite) can be enough to affect the ionosphere during the minimum of solar activity, but this limit increases as the Sun becomes more active. The ionosphere is also affected by forcing coming from the lower-lying atmospheric layers. The influence of the planetary waves of neutral atmosphere origin has been observed, and it is dominant during the local wintertime. The studies have shown the influence of the Sun-earth interaction in the chemistry and dynamics of our atmosphere, and also the exchange of energy between the different atmospheric layers, which might affect the terrestrial and marine environment, especially in the polar region.*

Keywords: atmosphere, sun-earth interaction, atmospheric radio sounding

Introduction

The earth´s upper atmosphere is basically controlled by solar forcing from above, the solar ionizing radiation being responsible through the formation and maintenance of the ionosphere, the atmospheric layer being between about 60 km and 1000 km in height. The variability of the solar ionizing radiation is mainly due to the 11-year solar cycle, 27-day rotation and solar flares. The lower ionosphere (<100 km altitude), the D-region, is essentially maintained during quiet conditions by the solar Lyman-alpha radiation, which ionizes the minor neutral atmospheric constituent nitric oxide. Variations in the Lyman-alpha produce changes in the ionization rates of D-region associated with the 11-year solar cycle (Lastovicka, 2006). During periods when the Sun is active, the base of the ionosphere is strongly affected by the excess of X-ray emission of solar flares. The excess of X-ray emission is detected by very low frequency (VLF) radio technique, in the form of variations in the amplitude and phase of the signals propagating in the ground-ionosphere waveguide, because they depend sensitively on the waveguide electrical conductivity. The phase variations are called sudden phase anomalies (SPAs), and the study of their incidence has shown that the ionosphere reference height is lower (by about 1 km) at solar maximum (McRae & Thomson, 2004; Raulin *et al.*, 2006).

The ionosphere is also disturbed by forcing from below, which is mainly due to the upward propagating gravity and planetary waves originated in the neutral atmosphere. The effects of the neutral atmospheric waves in the ionosphere have been observed particularly during the wintertime (Lastovicka, 2006). The low ionosphere presents a complex and extremely variable behaviour due to these two external competitive forcings (Lastovicka, 2009), of difficult characterization. The base of the ionosphere (~60-70 km) is not accessible to in situ measurements, being only accessible by rockets or by ground-based soundings, which results in the ionospheric region being less understood.

The upper atmosphere is maintained and controlled by solar forcing from above, but it is also affected by the wave activity from the lower-lying layers, which shows a coupling between the different atmospheric layers in a wide range of heights (30 km to 300 km) from troposphere to the mesosphere. This coupling between the different atmospheric layers shows the Sun-Earth interactions that affect the upper atmosphere, can also indirectly/directly affect the lower atmosphere. Thus, the monitoring of the upper atmosphere is important to define the influence of the solar forcing on it, and how that can affect the lower-lying layers, which can help us to understand how they can affect the terrestrial and marine environment, especially in the polar region.

To improve our understanding of the external forcing in the ionosphere, simultaneous and integrated observations are desirable to evaluate the coupling processes with the magnetosphere, as well with the lower-lying atmospheric layers. The atmospheric studies at higher latitudes are especially important because there the signatures of the interplanetary space processes are footprinted. In the following we present the current capabilities for probing the ionosphere at Comandante Ferraz Brazilian Antarctic Station (EACF) and in South America, and some recent scientific results showing the response of the ionosphere to external forcing.

Material and Methods

The ionosphere at EACF (62.11° S and 58.41° W) has been probed by various radio sounding techniques, which give information about the ionospheric disturbances.

VLF technique is used to study the lower ionosphere, D-region, which is between 60 and 85 km. It consists in detecting signals at frequencies between 1 and 50 kHz, propagating over long distances inside the earth–ionosphere waveguide. The conductivity gradient and the reference height changes in the low ionosphere can be detected as amplitude and phase variations of the VLF signals. Since 2006, the VLF measurements at EACF have been done with an Atmospheric Weather Electromagnetic system for Observation, Modelling and Education receiver - AWESOME (Scherrer *et al.* 2008), which detects the VLF amplitude and phase with 20 ms time resolution of defined stations, as well as broad-band data in all frequency ranges. The VLF measurements at EACF are complemented with measurements done at Itapetinga Radio Observatory in Atibaia/SP (23.21° S and 46.51° W) using another AWESOME receiver, and by the South America VLF Network (SAVNET, Raulin *et al.*, 2009) that is operating with six receivers in South America, three of them in Brazil. The most powerful VLF transmitter stations tracked are from US Navy, which permits the study of different ionospheric paths, some of them inside the South Atlantic Magnetic Anomaly (SAMA).

The Total Electron Content (TEC) of ionosphere can be obtained from GPS measurements done with dual frequency receivers. This technique is based on the property that dual frequency radio signals (L1: 1.6 GHz and L2: 1.2 GHz) propagating through the ionosphere are subjected to a differential phase change due to the dispersive nature of the plasma. As a first–order approximation the differential phase shifts is directly proportional to the TEC, which is defined as the line integral of the electron concentration along the path from a satellite to a receiver. The ionosphere has been monitored at EACF since 2004 using a dual frequency Javad GPS receiver with best time resolution of 1s. The GPS measurements at EACF are complemented with data from the Brazilian GPS network (Rede Brasileira de Monitoramento Contínuo, RBMC) of the Instituto Brasileiro de Geografia e Estatística (IBGE), which nowadays has more than 60 operational receivers covering almost all the Brazilian territory (IBGE, 2010), and permits the study of the latitudinal extension of the ionospheric disturbances, from Antarctica to equatorial regions.

The lower ionosphere has being also probed using a relative ionospheric opacity meter (riometer) that monitors the background cosmic radio noise at 20-50 MHz received on the ground after crossing the ionosphere. At EACF, since the beginning of 2009, three 1-channel riometers at 30 and 38 MHz are operating. They consist of a simple dipole antenna that receives cosmic radio noise with a broad beam (>60°), two are for measuring intensity and one for polarization. This technique is based on the comparison of the received signal with a Quiet Day Curve (QDC) obtained during geomagnetically undisturbed days, which gives the attenuation of the signal and hence the cosmic radio noise absorption (CNA) at the monitored frequency. Most of the absorption occurs in the D-layer due the variations of the electron density produced by external forcing. The riometers at EACF are elements of the South America Riometer Network (SARINET - an International Scientific Cooperation between Japan, Brazil, Argentina and Chile) that is operating with an array of 11 riometers (1-channel and imaging) in operation in South America, four of them in Brazil.

We also used one ionosonde that consists of one transmitter at frequencies between 1 and 20 MHz, and one receiver that detects the reflected signals. The echoes of the signal reflected by the F and E regions of the ionosphere provide a profile of reflection frequency versus virtual height (ionogram), which gives the electron density (directly related to the reflection frequency) profile as a function of actual height (Piggott & Rawer, 1972). The vertical sounding plays a crucial role in understanding the temporal and spatial evolution of the ionosphere, as well the study of the coupling between different atmospheric layers. At EACF, in March 2009, a Canadian Advanced Digital Ionosonde (CADI), (MacDougall, 1997) with drifting measurements started to operate, which produces ionograms every 5 minutes and drift measurements every 2.5 minutes.

Results

The influence of the solar forcing in the ionosphere during the last long minimum of solar activity (2006-2008) was analyzed from the sudden phase anomalies (SPAs) of the VLF signal detected by the SAVNET network. SPAs are produced by the excess f the X-ray emission produced during solar flares. This study showed that 100% of the solar X-ray events with peak flux above 5×10^{-7} W/m^2 in the 0.1-0.8 nm wavelength range produce a significant SPA, but a weak X-ray event with flux of about 2.7×10^{-7} W/m^2 can be enough to affect the lower ionosphere in 20% of the cases (Figure 1), (Raulin *et al.*, 2010).

The solar forcing in the ionosphere was also studied using preterit daytime VLF amplitude from 2003 to 2009. The study considered the VLF signal from NPM transmitter detected at EACF. This data analysis, which covered the decay of the 23rd solar cycle, showed an overall decrease of about –0.63 dB/year in the VLF amplitude in close association with the Lyman-alpha emission decrease (Figure 2a), similarly the behaviour found during the decay of the 22nd solar cycle (Thomson & Clilverd, 2000). This behaviour during the decay of solar activity is explained by the reduction of the ionizing solar Lyman-alpha radiation, which ionizes the nitric oxide (NO) molecules (Nicolet & Aikin, 1960). The daytime VLF amplitude also shows an annual variation,

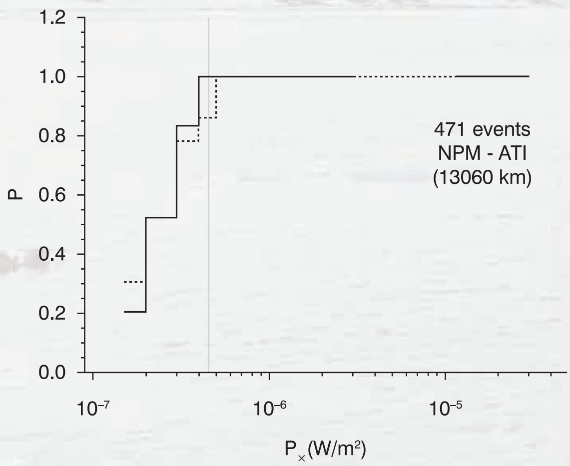

Figure 1. Solar flare probability detection P, as a function of the soft X-ray peak flux Px for the long NPM - ATI VLF propagation path, and for solar zenith angle greater (dashed line) or lower (full line) than 40 degrees. Figure adapted from Raulin *et al.* (2010).

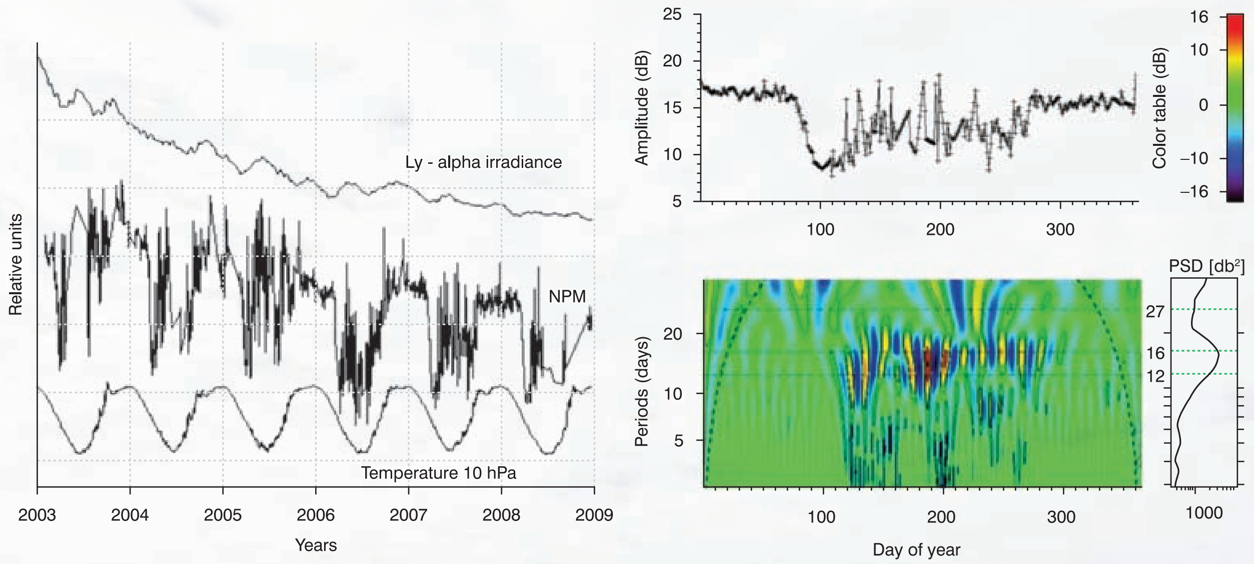

Figure 2. a) NPM Daytime VLF amplitude as received at EACF from 1/1/2003 to 31/12/2008 (NPM trace) compared with 27-day smoothed solar Lyman-alpha radiation (Ly-alpha irradiance trace) and the stratosphere temperature measured at southern midlatitudes (temperature trace). b) Wavelet analysis of daytime VLF amplitude for 2007.

decreasing from April to October, which can be explained by the reduction of solar illumination during the wintertime in the southern hemisphere (Figure 2b). During wintertime of all the years, the VLF amplitude showed pronounced fast increases, which in 2007 had a well defined 16-day period (Correia *et al.*, 2011a, b) as obtained from a wavelet analysis. This periodicity is typical of planetary waves of neutral atmosphere origin as observed by Day & Mitchell (2010) during the same period, and is in agreement with previous works (e.g. Lastovicka, 2006).

The impact of space weather in the ionosphere was also studied during the geomagnetic storm of 4 September 2008. During geomagnetic storms the magnetic field lines of the Earth changes and allows an increase in energetic particles, which can increase the radiation belts population, and in turn, in special conditions can precipitate and affect the ionosphere. The effects of these precipitating particles in the ionosphere were studied using the imaging riometer operating at Southern Space Observatory in São Martinho/RS. This riometer is an element of the SARINET network, which consists of 4 × 4 antenna dipoles at 38 MHz covering an area of 330 × 330 km at a height of 100 km, and is inside the South Atlantic Anomaly. The geomagnetic storm had an intensity of about −51 nT, which is considered to be moderate intensity, and was accompanied by increases in the Auroral Electrojet (AE) index of about 1500 nT (box in Figure 3a). The QDC was obtained considering the geomagnetically quiet days of September. Figure 3b shows the daily intensity of the cosmic noise (blue) from 3 to 8 for one central antenna of the array and the QDC curve (red) which shows an increase of absorption of cosmic noise during the geomagnetic storm. The preliminary results of the absorption imaging are in Figure 3c, which shows that the cosmic noise absorption started in the main phase of the geomagnetic storm, becomes stronger on 5th September, and suggests a northeastward drift during the recovery phase (Moro *et al.*, 2010). This ionospheric absorption can be attributed to the precipitation of energetic electrons in the SAMA region during the geomagnetic storm, which is in agreement with past riometer observations (Abdu *et al.*, 1973), as well from observations using ionosonde (Batista & Abdu, 1977) and VLF technique (Abdu *et al.*, 1981).

These recent studies confirmed that the ionosphere is controlled by the 11-year variation of the solar ionizing radiation, by the space weather impacts, as well as by the forcing from below of lower-lying atmospheric layers.

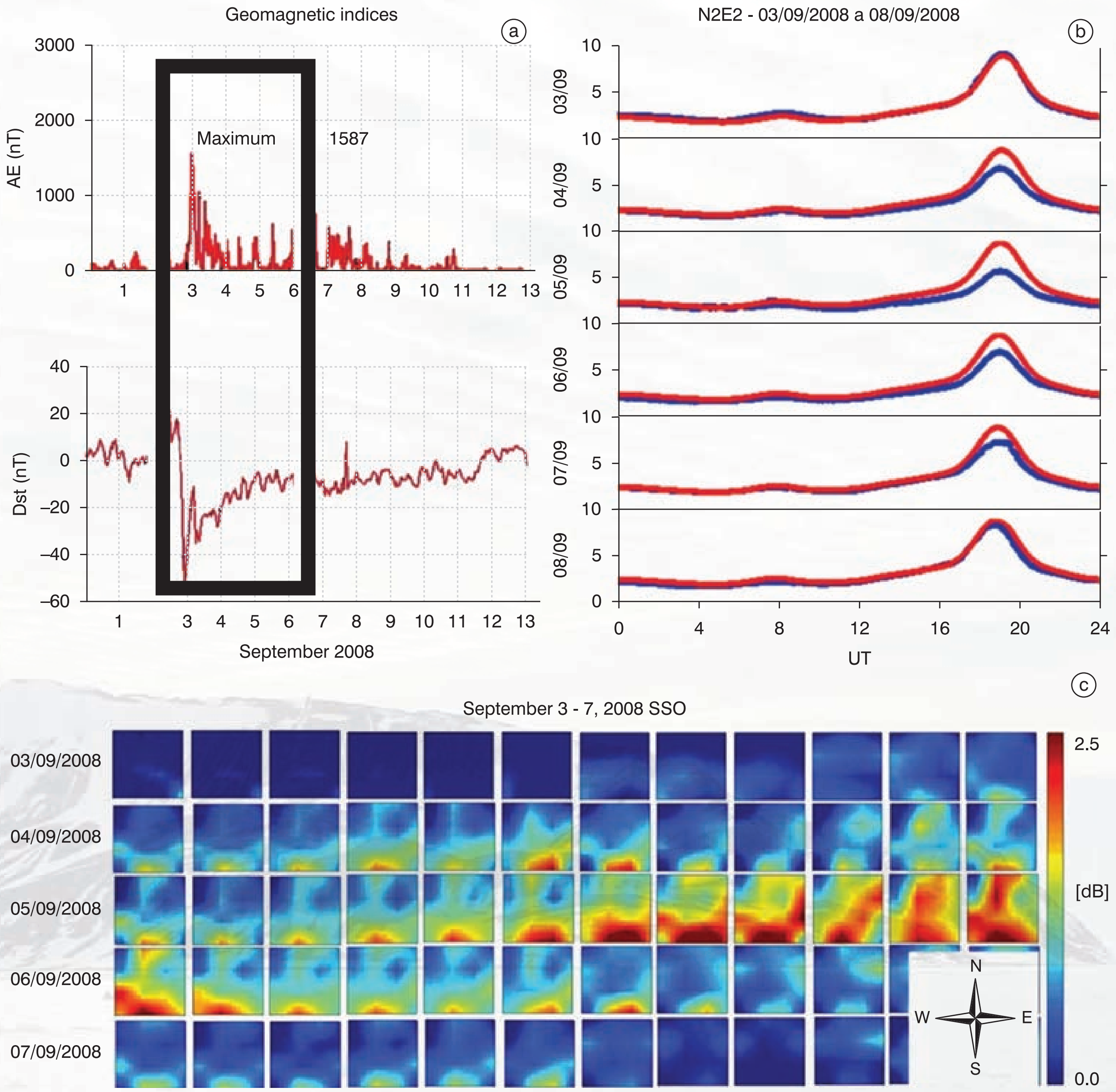

Figure 3. a) Geomagnetic indices for September 2008 (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html). In the black box is shown the geomagnetic storm that disturbed the ionosphere as observed by imaging riometer at SSO/RS. b) Comparison of the daily intensity of the cosmic noise (blue) with the QDC curve (red) during the geomagnetic storm. c) Time series of the absorption images at every 2 hours for 3-7 September 2008.

Discussion and Conclusion

The Sun is our main source of energy, and is responsible for life on Earth. But, it is also true that if the atmosphere did not exist, life conditions here would be very different. The atmosphere is responsible for filtering the solar radiation that is nocive to terrestrial and marine life, especially the X-rays and ultraviolet. The solar radiation changes following the 11-year solar cycle, so it is desirable to understand how our atmosphere responds to solar variations.

The ionospheric studies done during the decay of the last solar cycle improved our understanding about the main drivers affecting our atmosphere. They confirmed that solar ionizing radiation is the main driver of the ionosphere changes on an 11-year scale. Variations in shorter time scales (minutes to hours) occur in close association with the solar flares, when the excess of X-ray emission strongly affects the lower ionosphere. As the Sun becomes more active, the stronger are the solar flares and they can be accompanied by particle events, which increase the impacts in our atmosphere affecting lower heights especially in the polar region. On the other hand, the wave activity of the troposphere and stratosphere can also propagate upward and affect the ionosphere.

These results show there is a strong coupling between all atmospheric layers. So it is desirable to simultaneously monitor all the atmospheric layers to understand the energy exchange from the upper to the low atmosphere to characterize the influence of Sun-Earth interaction in the actual climate changes, which affect the terrestrial and marine environment. In the next few years, this monitoring will be very important because the Sun has just started to become active after a long minimum. The actual solar cycle is the 24th, which really started in January 2008, and some strong solar flares have been reported (SolarCycle24, 2010).

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