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Signature of a possible relationship between the maximum CME speed index and the critical frequencies of the F1 and F2 ionospheric layers: Data analysis for a mid-latitude ionospheric station during the solar cycles 23 and 24

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ABSTRACT

We analyze temporal variations of two solar indices, the monthly mean Maximum CME Speed Index (MCMESI) and the International Sunspot Number (ISSN) as well as the monthly median ionospheric critical frequencies (foF1, and foF2) for the time period of 1996–2013, which covers the entire solar cycle 23 and the ascending branch of the cycle 24. We found that the maximum of foF1 and foF2 occurred respectively during the first and second maximum of the ISSN solar activity index in the solar cycle 23. We compared these data sets by using the cross-correlation and hysteresis analysis and found that both foF1 and foF2 show higher correlation with ISSN than the MCMESI during the investigated time period, but when significance levels are considered correlation coefficients between the same indices become comparable. Cross-correlation analysis showed that the agreement between these data sets (solar indices and ionospheric critical frequencies) is better pronounced during the ascending phases of solar cycles, while they display significant deviations during the descending phase. We conclude that there exists a signature of a possible relationship between MCMESI and foF1 and foF2, which means that MCMESI could be used as a possible indicator of solar and geomagnetic activity, even though other investigations are needed.

1. Introduction

The ionosphere is the partially ionized plasma environment of Earth's upper atmosphere that extends from about 50–1000 km, depending on the geomagnetic and solar activity variations. The morphology of the ionospheric layers is controlled largely by the solar UV and EUV radiation intensities, which follow the sunspot cycle (Rishbeth and Garriott, 1969). The ionosphere is tightly coupled to the neutral atmosphere that is greatly influenced by lower atmospheric internal waves (Yiğit and Medvedev, 2015). Also, the interplanetary magnetic field variations can greatly shape plasma flow structures in the ionosphere (Yiğit et al., 2012), dynamically influencing plasma distributions in the ionosphere. The atmosphere above 50 km is so thin that the free electrons can exist for short periods of time before they are captured by nearby positive ions. The number density of free electrons is sufficient to affect the propagation of radio waves. Many communication systems use the ionosphere as a mirror to reflect radio signals and transfer them over long distances. Therefore, the ionosphere has a great importance for radio communications and navigation systems. Each ionospheric layer has a maximum frequency at which radio waves can be transmitted through and reflected back to Earth most efficiently. This frequency is known as the critical frequency. The ionosphere is transparent to the radio waves at frequencies higher than the critical frequency while waves will be reflected back to Earth at frequencies lower than the critical frequency. The F1 layer of the ionosphere exhibits dependence on the solar zenith angle, seasons and geomagnetic activity. Therefore, it is more pronounced in summer than in winter, always disappears during the night and sometimes during the winter days. On the contrary, the F2 layer is a permanent feature of the ionosphere

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under solar–terrestrial conditions.

Since the ionosphere is strongly affected by the solar radiation, the relationship between ionospheric variability and solar activity has been studied extensively by various authors (Forbes et al., 2000; Kane, 1992, 1995, 2006; Bremer, 2008; Ozguc et al., 2008; Atac et al., 2009; Liu et al., 2011; Chakrabarty et al., 2014, and references therein). Ionospheric variations can be considered on time-scales of (a) several days, including 27-day solar rotation, (b) semiannual, (c) annual, and (d) solar cycle. Bremer (2008) explained the long term changes in the parameters of the E-and F1-regions by an increasing atmospheric greenhouse effect (increase of CO_2). Elias and Ortiz de Adler (2006) explained the long term changes in the amplitude of foF2 observed at the southern crest of the equatorial anomaly at Tucuman by a trend in the magnetic dip angle, which was increasing during the analyzed 30 year interval with a rate of 0.35% per year. Mikhailov and Marin (2000, 2001), Mikhailov, de la Morena (2003), Mikhailov (2008), Elias and Ortiz de Adler (2006) explained long term variations observed at middle- and high-latitudes in the Northern Hemisphere by geomagnetic activity effects. Finally, some studies suggest that all three main factors must be considered, i.e., greenhouse gases, geomagnetic activity and Earth's magnetic field to explain the observed long term trends (Laštovička et al., 2006; Elias, 2009).

In this paper, we examine only the long-term variations of solar activity indices and ionospheric parameters foF1 and foF2, i.e., their solar cycle variations. Various solar activity parameters, such as sunspot numbers, solar flares, 10.7 cm solar radio flux, coronal mass ejections (CMEs), etc. can be used to investigate this relationship. Here, we used the ISSN and the Maximum CME Speed Index (MCMESI) as solar activity indices. The MCMESI may as well be used as a geomagnetic activity index because the most geoeffective events are caused by the solar flares and the CMEs. This index describes the measure of the linear speed of CMEs, and it was introduced in the work by Kilcik et al. (2011a) from the fastest CME speed measured for each day.

The phenomenon of ionospheric hysteresis has been known for a long time. Rao and Rao (1969) reported its dependence on the latitude with the maximum occurring at middle-latitudes and the minimum near Earth's equator and at high-latitudes. Buresova and Laštovička (2000) went further and described the shape and time of the hysteresis with regard to the history of the solar cycle. They reported that the hysteresis is the largest in the equinoctial months and appears to be associated with geomagnetic activity, which is higher at the declining phase of the solar cycle. Therefore, the most pronounced hysteresis can be expected during the equinoctial months from late declining to early rising phases of a solar cycle.

The long-term variations of solar and ionospheric indices and the shape of hysteresis curves among these parameters have extensively been studied in the past (Rao and Rao, 1969; Kouris, 1995; Buresova and Laštovička, 2000; Ortiz de Adler and Elias, 2008). In this paper, we present the first results that demonstrate that such relationships are seen between the MCMESI index and the ionospheric frequencies.

In the next section we describe the methodology, data analysis and results. In Section 3, discussion of the results, their implications, and the associated conclusions are presented.

2. Data, methods and results

Our study covers the time period starting in 1996, when the data from the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al., 1995) on the Solar and Heliospheric Observatory (SOHO) mission became available. This interval includes the entire solar cycle 23 (May 1996-December 2008) and the ascending branch of the current cycle 24 (December 2008 – onwards) and the long minimum which occurred between the cycles 23 and 24 (2006–2010). Two groups of indices that were used in this study are defined as follows.

2.1. Solar indices

(i) The Maximum CME Speed Index (MCMESI) derived from the SOHO LASCO CME catalog (Yashiro et al., 2004)[1]. The determination of the MCMESI is based on the measurements of the highest daily linear CME speed averaged over one month (for more details, see Kilcik et al., 2011a).

(ii) The International Sunspot Number (ISSN) from the National Geophysical Data Center[2] for the production, preservation and dissemination of the ISSN is presented as the reference to the sunspot cycle phases.

2.2. Ionospheric indices

The ionospheric data were obtained from the Space Physics Interactive Data Resource, SPIDR[3]. While the SPIDR web page includes ionospheric data from more than 200 stations. Only 12 stations have data that fully cover the investigated time interval. We chose to use data from the Chilton station, which has one of the best coverages of the ionospheric critical frequency data. We use hourly critical frequencies foF2 and foF1 recorded at Chilton Station, United Kingdom (51° 36′ N, 1° 18′ W) from 1996 to 2013. Monthly median values calculated from data taken at 14:00 LT (local time) for each day of that month. In Fig. 1 we present the variation of monthly total number of observing days with time.

As shown in this figure; there are three months gaps in both foF1 and foF2 data (January 2002, April 2002 and January 2004). In general, the foF2 data have much better temporal coverage, while the number of total observing days strongly decreased during the winter times for the foF1 data, as expected. But a few days of observations still exist except for the above mentioned three months. To calculate the monthly median values we used all existing data for each month. To remove the short term fluctuations due to the gaps (especially in foF1) in monthly median data and reveal the long term trend we used 12 steps running average smoothing method. Note that hysteresis plots are also produced from the smoothed data. Monthly median critical frequencies data are only used in correlation coefficient calculations. To further check the possible errors in both foF1 and foF2 data sets standard deviations of monthly values relative to the global average values were calculated. Based on these standard deviations and the 12 steps running average values, we derived the upper and lower significance limits, set at two standard deviations, for foF1 and foF2. We found that all monthly data points are inside the significance limits.

3. Methods

To investigate the relationship between the solar indices (ISSN and MCMESI) and the ionospheric critical frequencies (foF1 and foF2) two methods were applied. The first medhod is the cross-correlation analysis, which produces the degree of coupling with possible time delay between two compared data sets. To calculate the significance level of obtained correlation coefficients, Fisher's

[1] http://cdaw.gsfc.nasa.gov/CME_list/
[2] http:/www.ngdc.noaa.gov/
[3] www.spidr.ngdc.noaa.gov/spidr/