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Nonlinear dependence of ionospheric F_2 layer critical frequency on solar activity in southern latitudes during solar cycle 23

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Abstract

Latitudinal, seasonal, and diurnal variations in the nonlinear response of F_2 layer critical frequency (foF_2) with respect to 10.7 cm solar flux data (F10.7) in southern stations during the 23rd solar cycle (1996–2008) are investigated. A two-segmented linear fit method is used in both ascending and descending phases of the cycle, thus revealing the nonlinear response of foF_2 with F10.7. The rate of change in foF_2 with respect to F10.7 may decrease (saturation) or increase (amplification) at high solar activity epochs. Furthermore, the foF_2 values for the same F10.7 value differ between the ascending and descending phases of the cycle (hysteresis). The linear temporal increment of foF_2 with F10.7 at low solar activity epochs is more evident in low-latitude stations. A low-latitude station, Vanimo, shows clear evidence of saturation in all seasons. In high-latitude stations, the effect is weak in the midnight to morning hours, particularly during the descending phase of the cycle. The amplification effect is dominant only at high latitudes mainly during early morning hours of March Equinox. Negative hysteresis effect is observed to be stronger at lower latitudes, but positive effects are seen to be stronger at higher latitudes.

Keywords: Ionosphere; F_2 layer critical frequency; Saturation; Amplification; Hysteresis

1. Introduction

Solar extreme ultra violet (EUV) and X-ray radiations cause photoionization of neutral molecules to produce ions and electrons in the ionosphere. The ions recombine to form neutral atoms or ionize other molecules yet again through dissociative recombination. Neutral thermospheric winds, ExB drift, and ambipolar diffusion, among other processes, redistribute the charge concentration. This charge redistribution depends on latitude, longitude, local time, season, and solar activity, which may substantially disturb the propagation of radio waves through ionosphere, consequently affecting high-frequency radio communication, especially in the F_2 region. The critical frequency of F_2 layer (foF_2), peak electron density of F_2 layer plasma (NmF_2), and total electron content (TEC) are some of the ionospheric parameters, which are usually used for studying ionospheric F_2 layer variations. foF_2 is strongly controlled by solar activity, especially the solar EUV flux variations. Hence, foF_2 variability studies depend much on their dependence on solar indices. Sunspot number (R_Z) and solar 10.7 cm radio flux (F10.7) are the commonly used proxies for solar EUV activity because the EUV data are available only for a limited period (Liu et al., 2006). Many researchers have suggested F10.7 as a better solar EUV proxy than sunspot number for analyzing ionization effects (Laštovička et al., 2006; Wintoft, 2011; Mielich and Bremer, 2013). F10.7 measures solar radio emission in a 100 MHz wideband centered at 2800 MHz (wavelength of 10.7 cm), averaged over an hour. It is

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expressed in solar flux units (sfu), where 1 sfu = 10^{-22} W m^{-2} Hz^{-1} (Tapping, 2013).

Solar EUV flux is primarily responsible for the formation of ions and electrons in the ionosphere. It has been observed that foF_2 shows a good linear relationship with low and moderate values of solar EUV proxies, while the linearity between foF_2 and the solar parameters breaks down beyond a particular value of solar index (Balan et al., 1993). After a linear increase at low and moderate solar activities, the ionospheric foF_2 value remains constant or even decreases during high solar activity indicating the saturation effect (Balan et al., 1994; Liu et al., 2003). The saturation effect of foF_2 with different solar indices was studied, and the impact was found to be more with R_z than F10.7 and almost absent with solar EUV intensity (Kane, 1992). Many other researchers have also found the response of foF_2 against F10.7 as nonlinear and with solar EUV as linear during intense solar cycles. They have also emphasized on the nonlinear relationship between solar EUV and F10.7-cm fluxes (Balan et al., 1993). Later on, the saturation effect of foF_2 was observed not only with respect to sunspot number and F10.7, but also with solar EUV data (Liu et al., 2006). In addition to the nonlinearity of solar EUV and F10.7, thermospheric dynamics and composition were also pointed out as key factors that cause the saturation effect of foF_2. The significance of dynamic processes that induce the saturation effect was addressed as the equatorial fountain effect and prereversal enhancement (PRE) of equatorial ExB vertical drift and meridional wind circulation (Balan et al., 1996; Chen and Liu, 2010).

Amplification, an effect opposite to saturation, is usually observed at mid and high latitudes. During the process, the variation in foF_2 with solar indices is low at low solar activity, whereas foF_2 suddenly increases during high solar activity (Liu et al., 2004). The effect is mainly attributed to the rapid recombination loss around the F_2-peak at medium solar activity level, especially during local winter (December), because of the reversal of neutral winds (Chen et al., 2008). Along with the saturation and amplification effects of foF_2 with F10.7, hysteresis effect is also observed with foF_2 exhibiting different values for the ascending and descending phases of a solar cycle, even for the same value of F10.7 (Kane, 1992; Rao and Rao, 1969; de Adler and Elias (2008)). The hysteresis effect of foF_2 was attributed to the delayed response of solar EUV with F10.7 and the differences in geomagnetic activity in ascending and descending phases of the solar cycle (Mikhailov and Mikhailov, 1995; Kane, 2005).

The modeling of ionospheric parameters such as monthly averages of the electron density, electron temperature, ion composition, ion temperature, and ion drift at the ionospheric altitudes ranging from 60 km to 1000 km is essential for radio propagation studies and space weather concerns. The International Reference Ionosphere (IRI) is an empirical standard model that formulates ionospheric parameters such as the peak electron density, electron and ion temperatures, the critical frequency, and the maximum height of F_2 layer (Bilitza, 2001). The nonlinear effects discussed above can affect the IRI predictions to a long extent. The amplification, hysteresis, and saturation effects of foF_2 with respect to F10.7 in the southern hemisphere need detailed study, because the IRI predictions are reported to be more accurate in the northern hemisphere (Bilitza and Reinisch, 2008).

This work investigates latitudinal, seasonal, and diurnal effects of saturation, amplification, and hysteresis effects of foF_2 in southern stations with respect to F10.7 in detail. The stations selected are Vanimo (2.70°S, 141.30°E, magnetic latitude 11.19°S) - low-latitude station, which falls on the crest of equatorial anomaly; Townsville (19.63°S, 146.85°E, magnetic latitude 28.95°S) - low-latitude station; Canberra (35.3°S, 149.1°E, magnetic latitude 45.65°S) - mid latitude station; and Hobart (42.92°S, 147.32°E, magnetic latitude 54.17°S) - a mid-high latitude station. The stations fall at different latitudes but in more or less same longitudes; therefore, the local time for the stations falls within a difference of only one hour. The geographic locations of the stations are indicated in Fig. 1. The thick black dotted line indicates the magnetic equator determined from the IGRF model (wdc.kugi.kyoto-u.ac.jp/igrf/point/index.html).

2. Data and analysis

The present study is based on ionospheric foF_2 hourly data (0.1 MHz) collected from http://www.sws.bom.gov.au/World_Data_Centre/1/3 and F10.7 (sfu) data collected from http://omniweb.gsfc.nasa.gov., during the 23rd solar cycle (1996–2008), which covers both quiet and disturbed days.

To study the latitudinal, seasonal, and diurnal variations in the nonlinearity of foF_2 against F10.7 at solar active periods, the piecewise two-segmented linear regression technique is employed, which is reported to be better

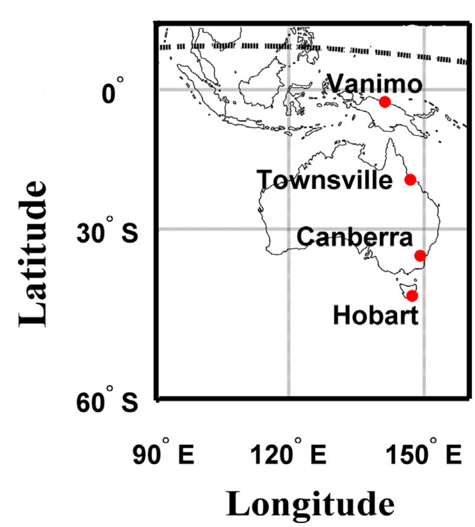

Fig. 1. Geographic locations of stations considered in the study. The thick black dotted line indicates the magnetic equator.