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Advances in Space Research 62 (2018) 821–828

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

The effect of geomagnetic activity changes on the ionospheric critical frequencies (foF2) at magnetic conjugate points

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Received 13 April 2018; received in revised form 28 May 2018; accepted 29 May 2018
Available online 7 June 2018

Abstract

In this work, we investigate the possible effects of geomagnetic activity on the ionospheric critical frequencies (foF2) in geomagnetic conjugate points. For this purpose, hourly foF2 data measured for the year 1976 from the ionosonde stations Akita, St. John's and Resolute Bay in the Northern hemisphere and their corresponding magnetic conjugate ionosonde stations Brisbane, Halley Bay and Scott Base in the Southern hemisphere are examined. Planetary geomagnetic activity "3h-K_p" indices are used as a geomagnetic activity indicator. foF2 data in the magnetic conjugate points (MCP) are investigated by using a superposed epoch analysis method. This analysis is done depending on the response of foF2 to geomagnetic activity variations in MCP based on geomagnetic stormy days around equinoxes (March 21, September 23) and solstices (June 21, December 21), and the results obtained from these MCP are compared. From these results, it is found that foF2 values in magnetic conjugate pairs give similar reactions to geomagnetic activity variations simultaneously, although this relationship differs according to the seasons and magnetic latitudes of the stations.

Keywords: Ionospheric critical frequency; Geomagnetic activity; Magnetic conjugate; Superposed epoch analysis

1. Introduction

The number of studies related to geophysical phenomena at magnetic conjugate points (MCP) has increased after a number of observatories were established all over the world and the discovery of the trapped radiation belts. These studies have focused primarily on two main questions: (i) how can one determine the positions of the magnetic conjugate pairs? (ii) do geophysical phenomena, especially those occurring in the upper atmosphere, occur at the same time and in a similar manner at MCP by virtue of the magnetic field linkage? The magnetic field has been used to solve these questions. This magnetic field has only the geomagnetic field component with origin in the Earth's interior and depends substantially on the model of the geomagnetic field configuration in the magnetosphere. The results of these studies which were performed using magnetic models have been used for the definition of MCP and classified display of the conjugate phenomena. Two points on the Earth's surface, linked by a geomagnetic field line, are generally called conjugate points. Conjugate phenomena are phenomena which occur simultaneously and in a symmetric manner in a conjugate area, and are substantially produced by actual linkage of magnetic field lines between the northern and southern hemispheres. They are classified into three categories: (i) phenomena which propagate simultaneously towards the northern and southern

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https://doi.org/10.1016/j.asr.2018.05.035
0273-1177/

conjugate points with a common origin situated around the equatorial plane, (ii) phenomena which substantially propagate from one end of a field line towards the other, (iii) phenomena trapped in a flux tube and appearing alternately and periodically at the northern and the southern conjugate points (Wescott, 1966; Campbell and Matsushita, 1967; Cole and Thomas, 1968; Oguti, 1969; Barish and Wiley, 1970).

After the development of satellite technology, the structure of the Earth's magnetosphere has been investigated in detail and studies about MCP and upper atmosphere phenomena at these points have concentrated on the aurora regions. Because the ejection of mass, momentum and energy carried by solar winds occur mostly on the magnetosphere-ionosphere-thermosphere system at high latitudes, the magnetic conjugate effects can be observed more clearly and simultaneously in aurora regions. Results from these studies indicate that the phenomena such as particle precipitation, field-aligned currents, geomagnetic storms, substorms and auroral displays exhibit a simultaneous and symmetric appearance at aurora regions of both hemispheres even though the magnetic fields in the polar regions are rather open. The open field lines in the polar regions of both hemispheres combine with the interplanetary magnetic field (IMF) in the regions of magnetospheric cusps and tail lobes, and this combination creates open magnetic flux tubes. The magnetic flux tubes are connected to the polar ionospheres at one end and to the interplanetary field at the other end. So, the solar wind plasma enters the ionosphere from the magnetosphere along with the open magnetic flux tubes and causes conjugate events to occur in polar regions (Makita et al., 1981, 1983; Sato et al., 1986; Mann and Schlapp, 1987; Nagata, 1987; Stenbeak-Nielsen and Otto, 1997; Lazutin et al., 2000; Schunk and Nagy, 2000; Østgaard et al., 2004, 2007; Grocott et al., 2005; Green et al., 2009; Momani et al., 2011; Lyatskaya et al., 2014).

In addition to these studies which are performed at high latitudes, there are those studies which are performed about magnetic conjugate phenomena and determination of conjugate points at middle and low latitudes using satellite data, the international reference ionosphere (IRI) model, magnetospheric model and total electron content (TEC) data. These studies indicate that many ionospheric features at low and middle latitudes exhibit degrees of magnetic conjugacy and simultaneity (Besprozvannaya, 1991; Otsuka et al., 2004; Martinis and Mendillo, 2007; Foster and Rideout, 2007; Le et al., 2009; Gulyaeva et al., 2011; Abdu et al., 2012; Ganushkina et al., 2013; Gulyaeva et al., 2013; Wichaipanich et al., 2017). Although much work has been done on magnetic conjugate points up to now, it is still being investigated how to detect the conjugate points in the low, medium and high latitude regions correctly and how the ionospheric parameters change at these points since there are only very few possibilities to monitor the real conjugacy with simultaneous observations in both hemispheres and very few studies which are performed using real ionospheric data. In addition to this, the existing magnetic field models are not able to give the true conjugate points with high accuracy. There is a good number of additional factors which may change the given field line configuration including the hemispherical asymmetric strong field-aligned currents (Ganushkina et al., 2013).

In this study, we investigate the effect of geomagnetic activity changes on the ionospheric critical frequencies (foF2) for different seasons from 6 ionosonde stations which are approximately MCP by using a superposed epoch analysis (SEA) method. The analysis shows that these effects are simultaneous and show symmetric appearances between different responses to the increase of geomagnetic activity on foF2 values at approximately magnetic conjugate pairs. Following the results obtained from this study, it is thought that the data and analysis used in the study will provide important contributions to researchers when it is decided whether or not the points considered to be approximate conjugate pairs are magnetic conjugate.

The organization of the paper is as follows. In Section 2, we give the data analysis method. In Section 3, we discuss the data analysis results and in Section 4, we present our conclusions.

2. Materials and method

In order to investigate the effect of geomagnetic activity changes on the foF2 variations in magnetic conjugate points, we used 6 ionosonde stations (three in the northern hemisphere, three in the southern hemisphere) which were identified as approximate conjugate pairs by Oguti (1969). The magnetic coordinates (MC) calculated from the IGRF model (http://omniweb.gsfc.nasa.gov) for 1976 and the geographic coordinates (GC) of these stations are given in Table 1. The reason for taking into account only foF2 values for the year 1976 is that the best foF2 data were taken for six stations only in the year 1976. We also used three hours of planetary geomagnetic activity index (K_p) data to determine geomagnetic activity level for the same year in addition to foF2 data. foF2 and K_p data were taken from Space Physics Interactive Data Resource (SPIDR) and these data were directly downloaded through http://spidr.ngdc.noaa.gov/spidr/.

In our analysis, we calculated hourly K_p values from three hours K_p data by using the linear interpolation method for investigating the hourly effect of geomagnetic activity on foF2. Thus, the effect of K_p variations on foF2 was investigated for each hour. The times with $K_p \leq 2^+$ are geomagnetic quiet times while those with $K_p > 2^+$ are defined as geomagnetic active times. Our analysis is done for geomagnetic stormy hours for the periods around March 21, June 21, September 23 and December 21 to investigate the seasonal geomagnetic activity variations on foF2 values taken from the magnetic conjugate pairs.

In this work, we used the SEA method to study the effect of geomagnetic activity variations on foF2. This method is a very strong statistical method and is applied to time series analysis. The SEA is used to identify the effect of an event or events on the system occurring through the time series period and to measure the magnitude of response of this

Table 1
The geographic coordinates (GC) and magnetic coordinates (MC) of the approximate conjugate points.

Station	GC	MC	Conjugate Point GC	Conjugate Point MC
Akita (AK539)	39.7°N, 140.1°E	32.2°N, 210.1°E	22.1°S, 137.7°E	32.2°S, 210.1°E
Brisbane (BR52P)	27.5°S, 152.9°E	36.7°S, 227.9°E	43.8°N, 160.8°E	36.7°N, 227.9°E
St. John's (SJJ47)	46.7°N, 307.3°E	56.03°N, 30.1°E	69.1°S, 334.8°E	56.03°S, 30.1°E
Halley Bay (HBA7N)	75.5°S, 333.4°E	61.2°S, 27.7°E	52.2°N, 304.3°E	61.2°N, 27.7°E
Resolute Bay (RB974)	74.7°N, 265.1°E	83.9°N, 309.1°E	75.8°S, 148.7°E	83.9°S, 309.1°E
Scott Base (SQ67Q)	77.9°S, 166.8°E	79.8°S, 324.3°E	69.7°N, 267.4°E	79.8°N, 324.3°E

Table 2
Cross correlation coefficients of calculated δfoF2 values for the stations in magnetic conjugate points.

Magnetic conjugate pairs stations	March equinox	June solstice	September equinox	December solstice
Brisbane-Akita	0.95	0.86	0.93	0.87
Halley Bay-St. John's	0.83	−0.75	0.80	−0.77
Scott Base-Resolute Bay	0.93	−0.85	0.94	−0.83

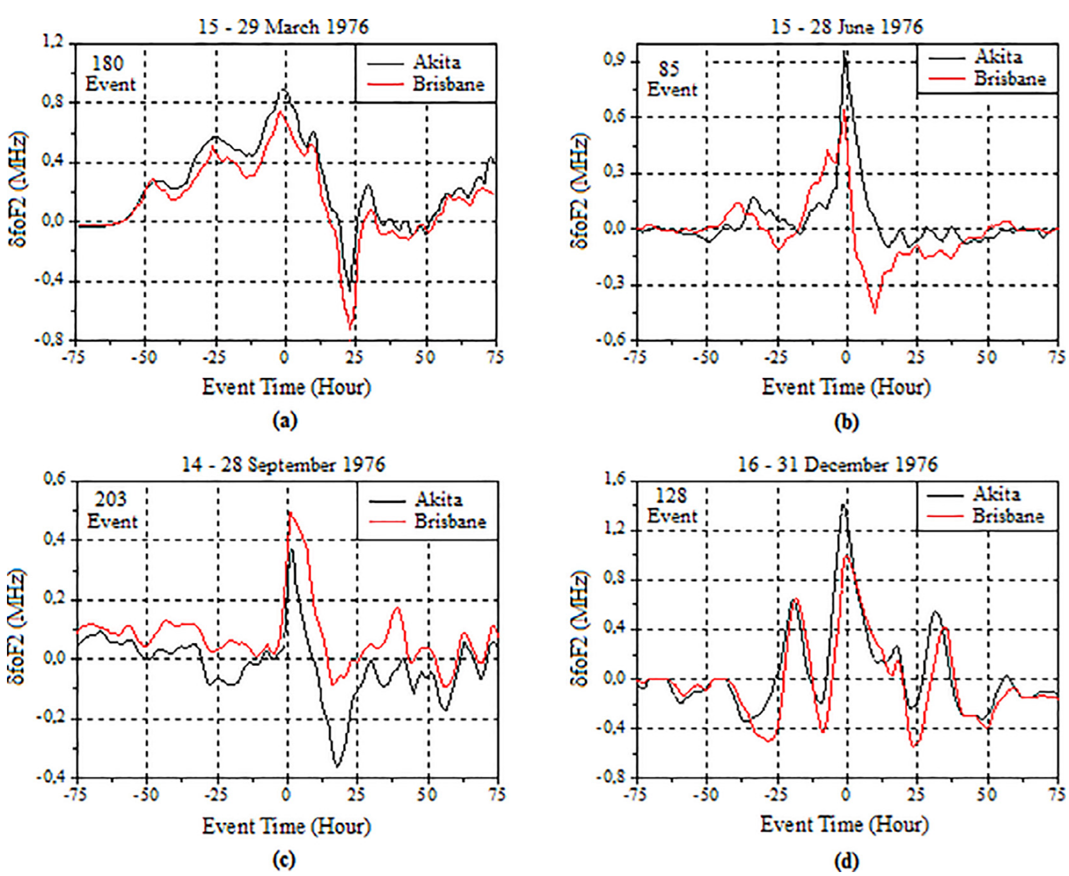

Fig. 1. Superposed epoch plots of δfoF2 as a function of time for Akita and Brisbane (a) during 15–29 March 1976, (b) during 15–28 June 1976, (c) during 14–28 September 1976, (d) during 16–31 December 1976.

system against this event. From this analysis, we found the reaction of the system against the identified event. If the events occurring throughout the physical processes can be identified properly, the results obtained from SEA would be expected to exhibit the effects of dynamical components on the system.

In our analysis, the $K_p > 2^+$ times are chosen as event moments. In the year 1976, 180 events during the period of March 15–29, 85 events during the period of June 15–28, 203 events during the period of 14–28 September and 128 events during the period of December 16–31 were detected. Superposed epoch analysis was carried out for all foF2 values and for foF2 values in geomagnetic quiet hours using the hours of $K_p > 2^+$ as time zero. The values obtained from the analysis for the foF2 values in the geomagnetic quiet hours were then subtracted from the values that were obtained from the analysis for all the foF2 values. The resulting values are δfoF2 values. This statement is defined in Eq. (1) below:

$$\delta foF2 = foF2_{(K_p > 2^+)} = foF2_{(All)} - foF2_{(K_p \leqslant 2^+)} \quad (1)$$

The δfoF2 values show how and what size of foF2 reacted to the increase of geomagnetic activity. These values are plotted as a function of time (Tulunay, 1994, 1995; Davis et al., 1997). The abscissa (time) axis shows about three days before and after the event. The ordinate gives the δfoF2 values. This analysis was done separately for each season and for each station, and then the behavior of δfoF2 values obtained for the stations in approximately magnetic conjugate pairs were compared with each other. Since the δfoF2 values obtained for each station by this analysis method include the superposed total effect of all the hours of the days in the analysis periods, the effect of the local time difference of the stations on δfoF2 values has ceased to exist. Thus, the values of δfoF2 for stations located in different longitudinal positions can be compared with each other. In addition to this, cross correlation coefficients of δfoF2 values calculated along with different seasons in Table 2 change within the confidence interval 0.05 for ionosonde stations at magnetic conjugate points.

3. Results and discussion

The variation of the calculated δfoF2 values for Akita and Brisbane ionosonde stations as a function of time during different seasons of 1976 is shown in Fig. 1.

From Fig. 1, it is seen that the foF2 values give the highest response to the increase of geomagnetic activity around the event (zero time) for both stations and all seasons. The increase of geomagnetic activity in different seasons caused an increase in foF2 values in a range of 0.4–1.5 MHz at the time of the event. Approximately 25–50 h after the event,

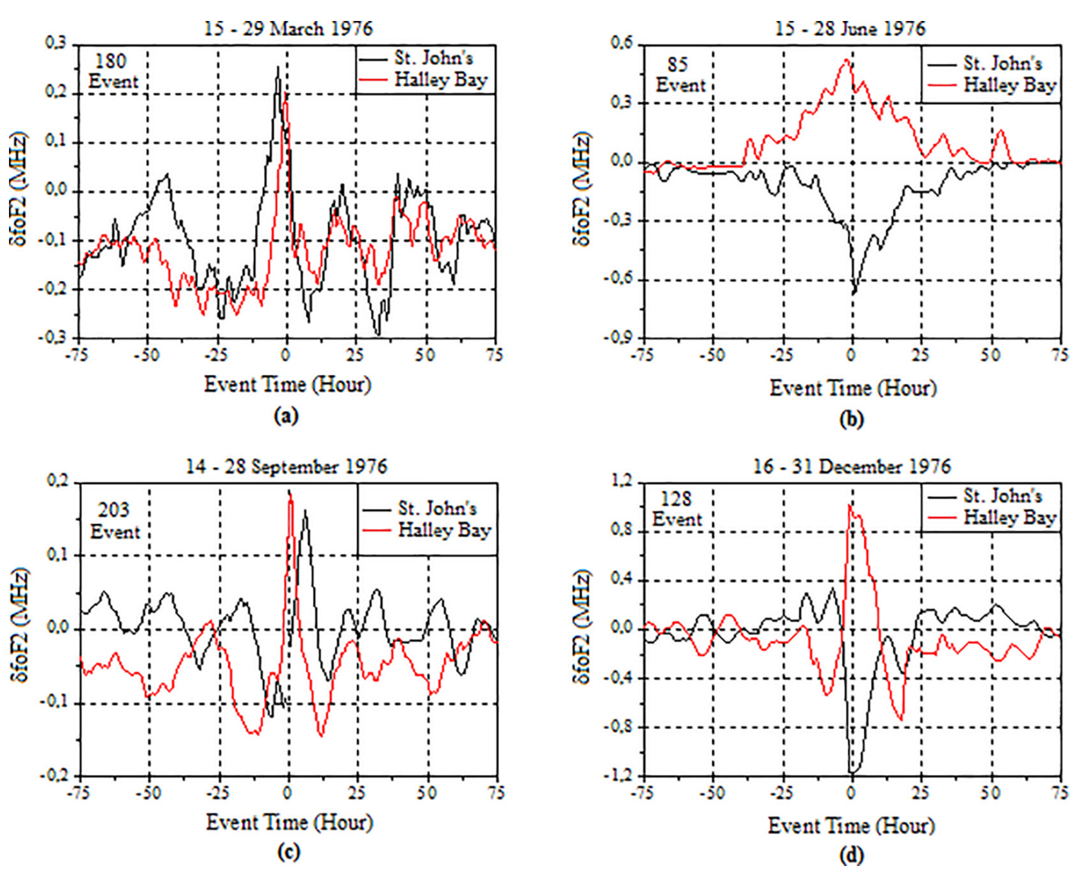

Fig. 2. Superposed epoch plots of δfoF2 as a function of time for St. John's and Halley Bay (a) during 15–29 March 1976, (b) during 15–28 June 1976, (c) during 14–28 September 1976, (d) during 16–31 December 1976.

the effect of the increase in geomagnetic activity on the ionosphere is almost ineffective. A positive and higher correlation is clearly seen when we examine the δfoF2 values for these two stations during the March and September periods throughout the entire event time. So, the foF2 values of both stations show a synchronized and very similar response to the increase in geomagnetic activity for these seasons.

In the September and December periods, a shift of about three hours is observed among the responses of foF2 values to the increase of geomagnetic activity. However, it is seen that these seasons have a positive correlation and similar reaction to the March and September seasons when we examine the variations of δfoF2 values which were calculated in both stations during the events.

The variation as a function of event time of the calculated δfoF2 values for St. John's and Halley Bay ionosonde stations during the different seasons of 1976 is showed in Fig. 2.

Throughout the entire seasons, foF2 values in St. John's and Halley Bay stations appear to give the highest response to the increase of geomagnetic activity near to the event. The effect of the geomagnetic storms on the ionosphere continues for the next 75 h after the event. When we examine the δfoF2 values calculated during the March and September seasons, it is observed that the foF2 values are increased between 0.1 and 0.3 MHz by the increase of geomagnetic activity. However, a shift ranging from about three to five hours is observed among the responses of δfoF2 values of the two stations to the increase of geomagnetic activity. A positive correlation is clearly seen when we examine the δfoF2 values during all event times. In contrast to this, these stations have a lower correlation than the δfoF2 values obtained for Akita and Brisbane during the same seasons. When we examine the δfoF2 values calculated during June and December, it is seen that the responses given by the foF2 values to the increase of geomagnetic activity are synchronous but in the opposite direction.

Due to the geomagnetic storms during both seasons, the foF2 values in the St. John's station decrease in a range of 0.6–1.2 MHz while the foF2 values in the Halley Bay station increase in a range of about 0.5–1.0 MHz. So, the δfoF2 values calculated for the two stations have a negative correlation across the entire event time period.

The δfoF2 values calculated for Resolute Bay and Scott Base stations during different seasons of 1976 change as a function of time as seen in Fig. 3.

Similar to other stations, the highest responses of foF2 values at the Resolute Bay and Scott Base stations to the increase of geomagnetic activity during all seasons appear during the event. Depending on the level of geomagnetic

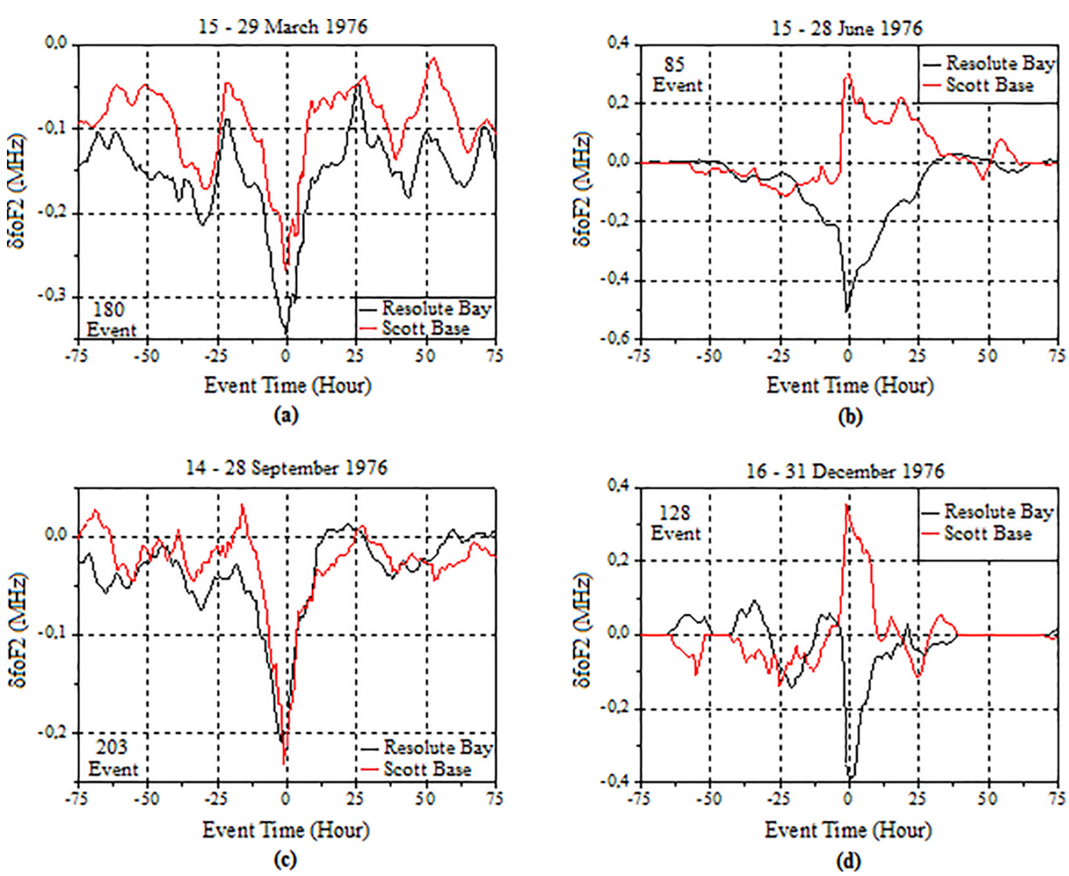

Fig. 3. Superposed epoch plots of δfoF2 as a function of time for Resolute Bay and Scott Base (a) during 15–29 March 1976, (b) during 15–28 June 1976, (c) during 14–28 September 1976, (d) during 16–31 December 1976.

activity, the effect of the geomagnetic storms on the ionosphere continues for the next 50 to 75 h after the event. From the graphs of the δfoF2 values calculated for March and September, it is seen that the increase in geomagnetic activity around the event reduces the foF2 values between 0.2 and 0.4 MHz. In addition to this, the changes in δfoF2 values of the two stations during all events are highly correlated. When we examine the δfoF2 values calculated during June and December, it is seen that the response of foF2 values to the increase of geomagnetic activity is synchronous but in the opposite direction similar to the structure at St. John's and Halley Bay stations exhibited for the same seasons. Due to geomagnetic storms during both seasons, the foF2 values in the Resolute Bay station decrease in a range of 0.4–0.5 MHz, while the foF2 values in the Scott Base station increase in a range of about 0.3–0.4 MHz. Thus, the δfoF2 values calculated for the two stations show a structure with negative valued correlation over nearly all event times for both seasons.

These similar changes in the δfoF2 values obtained from the Resolute Bay and Scott Base stations in the polar regions are consistent with the concept of open magnetic flux tubes, which reveals conjugate events in polar regions with open magnetic field lines.

In Table 2, cross correlation coefficients of δfoF2 values calculated along with different seasons for stations at magnetic conjugate points is shown. As seen in Table 2, cross correlation coefficients for all magnetic conjugate pair stations have the highest value in the March and September equinox periods. The cross correlation coefficients obtained for the Halley Bay-St. John's magnetic conjugate pair stations are smaller than the cross correlation coefficients obtained for the other magnetic conjugate pairs.

In addition to this, the cross correlation coefficients of magnetic conjugate pair stations at high latitudes have negative values at the solstices.

4. Conclusions

In different seasons, the differences of response magnitudes of foF2 values according to the increase of geomagnetic activity at MCP is due to the difference of the magnitude of geomagnetic activity levels during the investigated periods. In addition to this, the decrease of the response of foF2 to the increase in geomagnetic activity and increase of magnetic latitude during the same seasons for both hemispheres is due to the decrease in drift velocity ($\mathbf{E} \times \mathbf{B}$) depending on the decrease of the horizontal component of Earth's magnetic field, and the decrease in electron density in the ionosphere with increasing magnetic latitude.

During the March and September, the δfoF2 values of all the stations of the magnetic conjugate pairs were positively correlated while the δfoF2 values of conjugate pairs stations as St. John's-Halley Bay and Resolute Bay-Scott Base located in high magnetic latitudes have negative correlation values in June and December. This is because electric fields in both hemispheres have the same direction during March and September, and electric fields for both hemispheres during the June and December have a reverse structure after about 50° magnetic latitude. This is a result of the conjugate property of the ionospheric electric field (Gurnett, 1970; Cauffman and Gurnett, 1971; Wang et al., 2008; Ilma et al., 2012). Thus, the δfoF2 values of all magnetic conjugate pair stations have a positive correlation in March and September because of the same direction of electron drift ($\mathbf{E} \times \mathbf{B}$) in both hemispheres. However, a negative correlation between δfoF2 values of conjugate pairs stations located in high latitudes appears for June and December.

Also, the meridional winds have a controlling influence on the dynamical processes and therefore on the spatial and temporal features of the distribution of plasma of the ionosphere at all latitude sectors. The direct action of the meridional winds on the ionosphere cause transport of plasma along the magnetic meridian. The disturbance-induced equatorward winds have a component directed upwards along the field line, and this produces an upward drift of ionization. Since F region recombination depends on the densities of N_2 and O_2 molecules, which decrease rapidly with height, this raising of the ionization produces a large decrease in the overall loss rate. Conversely, the solar-induced poleward winds move the ionization down to lower heights where it decays much more rapidly. It is found that during the solstices the meridional winds exhibit the neutral airflow from the summer to the winter hemisphere, while during equinoxes the meridional winds exhibit a more symmetric neutral airflow. In this way, the magnetic meridional winds contribute to the development of an asymmetric distribution of the electron density between the Northern and Southern Hemispheres during the solstices and contribute to the development of an symmetric distribution of the electron density between the Northern and Southern Hemispheres during the equinoxes (Rishbeth, 1972; Anderson, 1973; Bittencourt and Sahai, 1978; Titheridge, 1995; Souza et al., 2000; Lomidze et al., 2015). Therefore, for the equinox periods, the δfoF2 values of all magnetic conjugate pairs stations behave in a similar way and have positive correlation coefficients, while, for the solstice periods, the δfoF2 values of St. John's-Halley Bay and Resolute Bay-Scott Base conjugate pairs stations exhibit opposite behavior and have negative correlation coefficients. The δfoF2 values of Brisbane and Akita stations have positive correlation coefficients during the solstice periods, because both these stations are located at low enough latitudes and should not be sensitive to the effect of two meridional circulations.

The obtained results of the SEA by using the foF2 data in 1976 taken from the MCP stations and the K_p data from the same year are that the responses of foF2 values to the increase of geomagnetic activity of these points show a very similar structure in different hemispheres. This shows that these stations which are not fully conjugate according to the IGRF model are conjugate stations at a reasonable rate in the results of the analysis. This is due to the fact that the locations of the stations are largely magnetic conjugate pairs.

Acknowledgement

The authors would like to thank the members of the Space Physics Interactive Data Resource (SPIDR) for making data accessible for obtaining and further processing. The authors would also like to thank anonymous referee(s) for very useful comments and guidance that improved the presentation of the paper.

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