Summer-winter hemispheric asymmetry of the sudden increase in ionospheric total electron content and of the O/N$_2$ ratio: Solar activity dependence

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[1] The solar activity dependence of the summer-winter hemispheric asymmetry (SWHA) of the sudden increase in total electron content (SITEC) due to solar flares and of the O/N$_2$ ratio is statistically analyzed using global GPS-total electron content data and TIMED Global Ultraviolet Imager column O/N$_2$ ratio data. We focus on observations with nonnegligible residuals of the solar zenith angle (SZA) dependency of SITEC. We examined 109 SITEC events associated with flares larger than M5 X-ray class flare from 2000 through 2006 and compared the residual SITEC ($\delta$) to the O/N$_2$ ratio. We observed that the latitude gradient of $\delta$ has not only an annual variation but also a year-to-year variation that is similar to those of the O/N$_2$ ratio. The SWHA magnitude (defined as the annual maximum of latitude gradient) of both $\delta$ and O/N$_2$ decreases as the solar activity declines toward its minimum. The correlation coefficient between the annual SWHA magnitudes of $\delta$ and those of O/N$_2$ is 0.92, indicating strongly that the SWHA of O/N$_2$ is responsible for that of SITEC in both the annual and year-to-year variations. The X-ray classes of the solar flares have no clear correlation with the solar activity, F10.7 index. We observe that the SWHA magnitude of $\delta$ does not depend on the magnitude of solar flare but rather on the background solar activity through the SWHA magnitude of the O/N$_2$.


1. Introduction

[2] Solar flares cause an immediate increase in the plasma density of the Earth’s ionosphere as a result of the interaction of the enhanced extreme ultraviolet (EUV) and X-ray emissions with the neutral components in the upper atmosphere. This plasma density variation has been well known as sudden ionospheric disturbances (SIDs). The SID generally includes various ionospheric disturbances such as the sudden phase anomaly (SPA) of very low frequency (VLF) waves and the sudden increase in total electron content (SITEC), which are observed in different ionospheric subregions by different methods (see reviews by Mitra [1974] and Davies [1990]). SID is important because of its space weather implications. Immediate changes in total electron content (TEC) can affect radio communications and navigation.

[3] SITEC is generally considered to be a manifestation of electron density enhancement in the ionospheric $F$ region, where the electron density is produced mainly by the EUV portion of the solar spectrum [Tsurutani et al., 2005]. Since the beginning of 21st century, the two-dimensional imaging technique using TEC data from worldwide GPS receiver networks has been applied to SITEC studies [e.g., Afraimovich et al., 2001; Liu and Lin, 2004]. These studies have observed a solar zenith angle (SZA) dependence of SITEC [Zhang and Xiao, 2003; Wan et al., 2005]. Tsugawa et al. [2006a] statistically analyzed 91 clear SITEC events from January 2000 to May 2005 and revealed the summer-winter hemispheric asymmetry (SWHA) of SITEC is due to that of the O/N$_2$ density ratio in the ionospheric $F$ region.

[4] Although studies using GPS networks have clarified new characteristics of SITEC, there have been few studies on the solar activity dependence of SITEC. It may be expected that the magnitude of the SWHA of SITEC depends on solar activity because the neutral composition should basically depend on the solar activity. In this study, we investigate the solar activity dependence of the SWHA of SITEC using the procedure developed by Tsugawa et al.
The sudden increases in TEC observed during solar flares are investigated with the procedure developed by Tsugawa et al. [2006a]. In this procedure, first intense solar flares, larger than the M5 X-ray class, are selected in all the flare events from 2000 through 2006 using the X-ray solar flare list obtained from GOES observations. Second, the TEC increases are detected within ±30 min around the peak time of X-ray flux for each flare. In order to compare the increases in TEC to the O/N₂ ratio, we also use the O/N₂ ratio data from the GUVI instrument on the TIMED satellite [Christensen et al., 2003]. Tsurutani et al. [2005] and Huba et al. [2005] have indicated that the ionospheric TEC response to solar flare is caused mainly by the electron density variation in the F region and the upper E region where the solar EUV radiation, not the X-ray, ionizes the neutral particles. Since the detailed spectrum of solar radiation varies from flare to flare, the EUV and X-ray intensities do not always correspond to each other. Although we did not use any EUV data in this study, we believe that the intensity of EUV is correlated with the X-ray class in a statistical analysis with sufficient flare events because the X-ray class is measured by the flux of soft X rays whose spectrum band is close to the EUV spectrum. Our method for detecting SITEC events and for comparing TEC to O/N₂ is described in detail in the next section where we present a sample SITEC event.

3. Example of SITEC Event

[7] We present here the SITEC event for the X8.3 solar flare on 2 November 2003. Figure 1a, taken from Figure 2b of Tsugawa et al. [2006a], shows the temporal variation of 0.5–4 Å and 1–8 Å X-ray fluxes observed by the GOES 10 satellite. The data are normalized by the peak values. Both X-ray fluxes began increasing at 1703 UT, reached the maximum at 1723–1726 UT, and then gradually decreased. Figure 1b, taken from Figures 2d of Tsugawa et al. [2006a], shows time sequences of detrended TEC from all satellite-receiver paths at glps GPS receiver [−0.7°N, −90.3°E] in Puerto Ayora, Ecuador, closest to the subsolar point during the solar flare. Each detrended TEC curve is derived by subtracting the 60-min running average from the TEC data, where both the data and average include the instrumental bias in the satellite and the receiver. The upward (downward) arrows with numbers beside the TEC curve indicate the minimum (maximum) peak and the pseudorandom noise (PRN) numbers, respectively. Although all the TEC curves have different ionospheric penetration points (IPPs) within 300 km from the receiver location, they all increase by ~3 TECU a few minutes after the commencement of solar X-ray enhancement, then gradually increase for 15–20 min, and reach their maxima at 1730–1736 UT after the peak of X-ray fluxes. We regard such TEC enhancements as the SITEC event induced by the solar flare, and define the SITEC value at each IPP as the minimum-to-maximum amplitude of detrended TEC.

[8] Thus we examine the TEC data from all IPPs of all GPS receivers and obtain the global distribution of the...
SITEC values. Using this global SITEC values, we can find that the SITEC values depend linearly on cosine of SZA (cos $\chi$) as shown in Figure 2a, taken from Figures 3d of Tsugawa et al. [2006a]. In Figure 2a, each dot is derived from an IPP. The solid line represents the least squares regression line. In this event, the correlation coefficient is 0.65 and the average deviation is 0.24 TECU. The deviations of SITEC are larger than the data accuracy; therefore they indicate that SITEC values depend on other parameters in addition to SZA. These other parameters can be studied by examining the SITEC residuals, $\delta$, which are calculated by subtracting the cos $\chi$ linear regression from the observed SITEC values. Figure 2b, taken from Figures 3f of Tsugawa et al. [2006a], shows the $\delta$ versus latitude. The $\delta$ values are averaged within $\pm 5^\circ$ latitude bin. The error bars represent the standard deviations. The $\delta$ values in the winter (northern) hemisphere are larger than those in the summer (southern) hemisphere. The least squares regression line represented by the solid line has a gradient of 0.05 TECU/10$^\circ$.

4. Statistical Results

[10] We apply the procedure described in the previous section to all 225 SITEC events caused by solar flares larger than the M5 X-ray class from 2000 through 2006. Out of these flare events, 109 clear SITEC events are investigated to statistically reveal the solar activity dependences of the hemispheric asymmetry in the residual SITEC $\delta$. These clear SITEC events satisfy the following criteria [Tsugawa et al., 2006a]: (1) The number of IPPs is larger than 100. (2) The correlation coefficient between SITEC and SZA is larger than 0.3. (3) The average deviation of SITEC from the regression line with respect to SZA is smaller than 0.5 TECU.

[11] Figure 3a shows the latitudinal gradients of $\delta$ against day of year. Each point is obtained from a single SITEC event. The solid line represents the least squares regression line calculated with the data between $-30^\circ$ and $30^\circ$.

$$f(x) = \alpha \sin \frac{2\pi}{365.25}(x - \beta)$$  \hspace{1cm} (1)

where $\alpha$ is an annual amplitude and $\beta$ is a day lag. We obtain $\alpha = -0.032$ and $\beta = 76.1$ by fitting equation (1) to all
the data in Figure 3a. The regression curve in Figure 3a clearly shows that the latitudinal gradients of $d$ have an annual variation that is negative around the June solstice (southern hemispheric winter) and positive around the December solstice (northern hemispheric winter). This means that the residual SITEC $d$ is larger in the winter hemisphere than in the summer hemisphere. However, the deviations from the regression curve seem to be a little large around the solstices.

Figure 3b plots the same data as Figure 3a except that is plotted as a function of day number from 1 January 2000. Each curve shown as a solid line represents the annual variation using a sine curve defined as equation (1) with the day lag $b$ obtained from Figure 3a and fitted with least squares method to the corresponding annual data during $b + 365.25i < x < b + 365.25(i + 1)$, where $i$ is last digit of year. Although the amplitude of regression curve in 2002–2003 is determined by fitting to the data only around the June solstice for lack of clear events around the December solstice in 2002, the successive annual regression curves clearly show that the annual amplitude of the latitudinal gradient of $d$, which corresponds to the SWHA magnitude of $d$, gradually decreases from 2000 to 2006.

Figure 3c show the daily averaged latitudinal gradients of GUVI O/N$_2$ in the same format of Figure 3a. The data for all days from 2002 through 2006 are plotted regardless of the flare event occurrences and colored according to LT sectors of the observations. The solid curves represent least squares fitted sine curves to all the data (a,c) or to every 1-year period data (b,d).

Figure 3. Annual and year-to-year variations of the latitudinal gradient of (a–b) residual SITEC, $d$, and (c–d) GUVI O/N$_2$. Positive (negative) values mean that the data in the northern hemisphere are larger (smaller) than those in the southern hemisphere. Each data point of $d$ corresponds to a flare event. The data points of GUVI O/N$_2$ are daily plotted from 2002 through 2006 regardless of the flare event occurrences and colored according to LT sectors of the observations. The solid curves represent least squares fitted sine curves to all the data (a,c) or to every 1-year period data (b,d).
In the same format as Figure 3b, the year-to-year variation of latitudinal gradients of GUVI O/N2 are shown in Figure 3d. The regression curves are obtained with equation (1) and the day lag from Figure 3c. Although the amplitude of regression curve in 2001–2002 is derived from the data of the first quarter of 2002, the successive annual regression curves from 2001 to 2006 clearly show that the latitudinal gradients of GUVI O/N2 ratio at the solstices gradually decrease from 2001 to 2006.

Figure 4a shows the year-to-year variation of daily $F_{10.7}$ index. The $F_{10.7}$ indices for all the days from 2000 through 2006 are plotted regardless of the flare event occurrence. The solid lines designate the annual average values corresponding to the annual curves for O/N2 shown in Figure 3d. The $F_{10.7}$ index is a daily measurement of the noise level of 10.7-cm solar radiation flux at the Earth’s ground. This index is frequently used as a proxy for the solar radiation in the wavelengths that produce photoionization in the Earth’s ionosphere [e.g., Kane, 1992; Rishbeth, 1993; Su et al., 1999]. The $F_{10.7}$ values decreased gradually from 150 to 250 in 2000–2001 to ~80 in 2005–2006, demonstrating the descending phase of solar activity. Figure 4b shows the year-to-year variation of observed X-ray classes for the flare events. Each data point corresponds to a solar flare event. Contrary to the $F_{10.7}$ index, there is no clear tendency in the year-to-year variation of X-ray class.

Table 1 summarizes the annual SWHA magnitudes, defined as the annual maxima of latitude gradients, of residual SITEC $\delta$ (first line) and GUVI O/N2 (second line). These annual values are obtained from the peak values of the corresponding least squares fitted sine curves as shown in Figures 3b and 3d. Table 1 also lists the average values of daily $F_{10.7}$ index (third line) during the annual periods. The $F_{10.7}$ average values are high in 2000–2001 and have the maximum of 191 in 2001, then gradually decrease to 80 in 2006. This gradual decrease clearly indicates that this period is in the descending phase of solar activity cycle. Similar to the $F_{10.7}$, the annual SWHA magnitudes of $\delta$ gradually decrease from 4.6 [$10^{-2}$TECU/10$^{-17}$] in 2001 to 1.8 in 2006, though the values in 2000 are larger than that in 2001. The year-to-year variation of the SWHA magnitude of GUVI O/N2 also show a gradual decrease from 6.1 [$10^{-2}/10^{-17}$] in 2001 to 2.8 in 2006.

5. Discussion

It has been well known that solar flare-induced SITEC values depend on the SZA [Zhang and Xiao, 2003; Tsurutani et al., 2005; Wan et al., 2005]. Tsugawa et al. [2006a] statistically analyzed 91 SITEC events from January 2000 to May 2005 using the worldwide GPS receiver network and revealed that the SITEC value is linearly dependent on the cosine of SZA with nonnegligible residuals in almost all the flare events. They also revealed that the residual SITEC, $\delta$, in the winter hemisphere is larger than that in the summer hemisphere. By comparing the seasonal variation of latitudinal gradient of both $\delta$ and $F$-region O/N2 density ratio from the MSISE-90 model, they first suggested that the SITEC phenomena induced by solar flares depend not only on the SZA, but also on the O/N2 density ratio in the ionospheric $F$-region.

There have been few observational studies focusing on the SWHA of O/N2. One of reasons for this would have been a difficulty of the long-term global observations of this parameter. In this study, we examined the column O/N2 ratio observed by the TIMED/GUVI instrument in 2002–2006 and found that the annual variation observed in the

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<th>Unit</th>
<th>2000</th>
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<tbody>
<tr>
<td>Residual SITEC</td>
<td>$10^{-2}$ TECU/10$^{-6}$</td>
<td>6.2</td>
<td>4.6</td>
<td>2.3</td>
<td>2.3</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>GUVI O/N2</td>
<td>$10^{-2}/10^{-17}$</td>
<td>-</td>
<td>6.1</td>
<td>4.3</td>
<td>4.3</td>
<td>3.6</td>
<td>2.9</td>
</tr>
<tr>
<td>$F_{10.7}$</td>
<td>$10^{-22}$ W/m$^2$/Hz</td>
<td>175</td>
<td>191</td>
<td>162</td>
<td>122</td>
<td>103</td>
<td>86</td>
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latitude gradient of the observed O/N₂, shown in Figures 3c, is quite similar to that of δ. The comparable day lags β of 76.1 for δ and 86.4 for GUVI O/N₂ designate that the phases of their annual variations are almost coincident. The consistent annual variations of the two observational values strongly confirm that the SWHA of O/N₂ ratio is responsible for that of SITEC.

In addition to the annual variations of latitude gradient of δ and O/N₂, we examined their year-to-year variations. As shown by Figures 3b and 3d and Table 1, the SWHA magnitude (defined as the annual maximum of latitude gradient) of both δ and GUVI O/N₂ gradually decreases from 2000–2001 to 2006 as the solar activity declines from its maximum toward its minimum. Figure 5a shows these SWHA magnitudes against yearly F10.7 averages. The annual SWHA magnitudes of O/N₂ (solid circles) increase almost linearly with F10.7 index except at the annual average F10.7 of 162 (during 2002). The correlation coefficient (r₁) between the SWHA magnitudes of O/N₂ and F10.7 is 0.95, indicating that the SWHA of O/N₂ ratio strongly depends on the background solar activity. The annual SWHA magnitudes of the residual SITEC δ (open diamonds) are also correlated with the annual F10.7 index. The correlation coefficient (r₂) between the SWHA magnitudes of δ and O/N₂ is 0.78. Their relationship, however, seems not to be linear. While their magnitudes slightly increase with F10.7 when F10.7 is smaller than 160 (during 2002–2006), their magnitudes are 2–3 times larger at F10.7 of 175–191 (during 2000–2001) than those at F10.7 of 80–162. Figure 5b shows the correlation between the SWHA magnitudes of δ and those of O/N₂. Their correlation coefficient (r₃) is 0.92, much larger than r₂, indicating that the SWHA magnitudes of δ directly depend on those of O/N₂ rather than on the background solar activity level.

The dayside ionosphere at midlatitudes is formed by the balance between the production rate due to the photo-ionization of atom oxygen O and molecular N₂ from the E region through the F region and the loss rate due to the chemical reaction of molecular N₂ and oxygen ion O⁺ in the F region under the strong influence of ambipolar diffusion processes. The F region electron density and TEC at midlatitudes are well known to be correlated with O/N₂ ratio in the ionospheric F region [e.g., Rishbeth et al., 2000; Mendillo et al., 2005]. Sudden increases in the EUV radiation (assumed to be coincident with the X-ray) during solar flares cause immediate enhancements of ion/electron density in the lower F region and the E region rather than around the F₂ region. In the former region, the ion lifetime is much shorter than 1 min due to the chemical reaction between electron and NO⁺ (O₂⁺) which result from the chemical reaction between N₂ (O₂) and O⁺. On the other hand, in the latter region, the ion (O⁺) lifetime can be several tens of minutes. As shown in Figures 1, the sudden increases in TEC reached the maximum a few minutes after that in the X-ray flux. We examined the average time delay of the SITEC peak from the peak of the X-ray flux and found it was 3.6 min. Comparing this time delay to the ion lifetime in the ionospheric subregions, the peak height of electron density enhancement can be between the lower F region and F₂ region, where the processes of the electron production due to the photoionization and the electron loss due to the chemical reaction equilibrate a few minutes after the peak of solar flares. In these processes, the background O determines the enhancement of photoionization, and N₂ determines the O⁺ loss due to the chemical reaction. Therefore the F region O/N₂ ratio plays an important role in the determination of SITEC peak.
The SWHA of O/N$_2$ can be explained by the global wind circulation pattern in the thermosphere, that is, the continuous solar input at high summer latitudes drives a prevailing summer-to-winter wind with upwelling in the summer hemisphere and with downwelling in the winter hemisphere. The ionospheric O/N$_2$ ratio is large (small) due to the upwelling (downwelling) wind in the summer (winter) hemisphere. This seasonal (or hemispheric) asymmetry of O/N$_2$ ratio is well known to be responsible for the F region electron density winter anomaly at midlatitudes, that is, the winter daytime density is higher than that in summer. Rishbeth et al. [2000] investigated the annual variations in the ionospheric F2 region using a coupled thermosphere-ionosphere computational model (CTIP), and suggested that the hemispheric asymmetry of total solar radiation (daily insolation) associated with the solar declination is the principal driver of the thermospheric circulation. Since the magnitude of this hemispheric asymmetry depends on the absolute solar radiation, the solar activity affects the thermospheric circulation, and accordingly the SWHA of O/N$_2$ ratio. Numerical simulations using a thermosphere/ionosphere model are needed to further study the relationship between the SWHA of O/N$_2$ and the solar activity.

Contrary to the F10.7 and the SWHA magnitudes, there is no clear tendency in the year-to-year variation of solar flare’s X-ray class as shown in Figure 4b. It would be reasonable to consider that the flare X-ray class depends on the magnitude and/or the structure of the localized solar magnetic field around where the flare occurs rather than on the activity of the entire sun. The SWHA magnitude of $\delta$ would depend little on the magnitude of solar flare, even though this can affect the magnitude of SITEC.

6. Summary

The solar activity dependence of the summer-winter hemispheric asymmetry (SWHA) of the solar-flare-induced SITEC in the ionosphere is statistically studied using the SOPAC GPS data. The relationship of the SITEC to the O/N$_2$ ratio in the ionosphere is also studied using the O/N$_2$ data from the TIMED/GUVI observation. The statistical results of 109 clear SITEC events from 2000 through 2006 are summarized as follows.

1. Similar annual variations are seen in the latitude gradient of GUVI O/N$_2$ and residual SITEC, $\delta$, defined as the values obtained by subtracting the solar-zenith-angle dependent components from the true SITEC values. This result strongly suggests that the SWHA of O/N$_2$ ratio is responsible for that of SITEC.

2. The annual SWHA magnitudes (annual maxima of latitude gradient) of $\delta$ and GUVI O/N$_2$ decrease according to the descending phase of F10.7 from 2000–2001 to 2006. The correlation coefficient between the annual SWHA magnitudes of $\delta$ and those of O/N$_2$ is 0.92. This indicates that the SWHA of O/N$_2$ ratio in the ionospheric F region can affect that of the SITEC phenomena not only in the annual variation but also in the year-to-year variation.

3. During 2000–2006, while F10.7 index gradually decreases, indicating the descending phase of solar activity, the X-ray classes of the solar flares have no clear correlation with the solar activity cycle. This indicates that the SWHA magnitude of $\delta$ does not depend on the magnitude of solar flare, but rather on the background solar activity through the SWHA magnitude of the O/N$_2$.

27 Modelling and coordinated observations with other observation techniques, such as incoherent scatter radars, ionosondes, and satellites are needed to understand the details of the relationship between the SWHA magnitude of $\delta$ and that of the O/N$_2$ ratio.

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