The effect of ~27 day solar rotation on ionospheric \( F_2 \) region peak densities (\( N_mF_2 \))

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[1] Ionospheric \( F_2 \) region peak electron densities (\( N_mF_2 \)) observed from 11 ionosonde stations in the East Asian-Australian sector from 1969 to 1986 have been used to investigate the effect of ~27 day solar rotation on the ionosphere. These stations were located from the magnetically equatorial regions to the middle latitudes in both hemispheres. We found that, averaged over all stations and for 18 years, the normalized standard deviation of the midday ~27 day variations of \( N_mF_2 \) was 8% and that of the midnight variations was 10%. We applied different data analysis methods, including Fourier transform, band-pass filter, and multiple linear regression analysis, to determine quantitatively the sources of the observed ~27 day variations of \( N_mF_2 \) and their relative contributions to these variations. Our results show that the ~27 day variations in solar radiation and geomagnetic activity, caused by solar rotation, are the main drivers of the ionospheric ~27 day variations. They accounted for more than 85% of the variations seen in the \( N_mF_2 \) ~27 day variation, and their contributions became about 95% at higher latitudes. At geomagnetically low latitudes, the contribution of the ~27 day variation in solar EUV radiation was greater than that of the ~27 day variation in geomagnetic activity. However, the contribution from geomagnetic activity became more significant and was even larger than the contribution of solar radiation at higher latitudes, especially at midnight. At all latitudes the correlation between the ~27 day variations of \( N_mF_2 \) and solar radiation was evidently positive, whereas that between \( N_mF_2 \) and geomagnetic activity was positive at geomagnetically low latitudes and became negative at higher middle latitudes. We did not find large seasonal or solar cycle changes in the ~27 day variations of \( N_mF_2 \). These variations, however, did show significant differences between the two hemispheres.


1. Introduction

[2] Ionosphere \( F_2 \) region peak electron densities (\( N_mF_2 \)) are controlled by photochemical and plasma transport processes. The chemical process involves primarily photodissociation of the thermosphere by solar extreme ultraviolet (EUV) radiation and molecular recombination, while the transport processes are the motion of the ionospheric plasma by neutral winds, electric fields, and ambipolar diffusion. Changes in these processes with geophysical conditions result in variations of \( N_mF_2 \) with periods from less than 1 s to 11 year solar cycle or even longer. In this paper, we focus on the morphology and mechanisms of the ~27 day variation of \( N_mF_2 \). There have been many studies of \( N_mF_2 \) variations with this periodicity [e.g., Bartels, 1950; Titheridge, 1973; Kane et al., 1995; Forbes et al., 2000; Rishbeth and Mendillo, 2001; Pancheva et al., 2002; Rich et al., 2003; Prabhakaran Nayar et al., 2004; Wang et al., 2007; Oinas et al., 2008; Astafyeva et al., 2008; Afrainovich et al., 2008; Liang et al., 2008; Hocke, 2008; Min et al., 2009; Borries and Hoffmann, 2010]. However, the latitudinal, seasonal, local time, and solar cycle changes of this variation are not fully understood. In addition, although almost all these previous studies relate the observed ~27 day \( N_mF_2 \) variations to the integrated effects of solar EUV and geomagnetic activity variations with the 27 day solar rotation period, there have been very few studies on the relative contributions of these processes to the ~27 day variation of \( N_mF_2 \). In this paper we try to obtain more physical insight into these issues by analyzing ionospheric data over more than a solar cycle in the East Asian-Australian sector.

[3] Changes in solar EUV radiation are produced by the nonuniform distribution and motion of EUV radiation sources, such as active regions, over the Sun surface as well
as the random fluctuation of radiation intensity. As the Sun rotates with a quasi-27 day period, the solar EUV flux measured at 1 AU shows a variation with a broad spectral peak between about 22 and 32 days [Pap et al., 1990; Kane et al., 2001; Kane, 2002, 2003a; Woods et al., 2005; Ma et al., 2007]. Similarly, there are also quasi-27 day variations in solar wind and interplanetary magnetic field (IMF) as solar active regions near solar maximum and corotating interaction regions (CIRs) near solar minimum rotate with the Sun. The lifetime of solar active regions and CIRs can last longer than one solar rotation period. These recurrent variations in solar wind and IMF produce periodic geomagnetic activity of ~27 days when solar wind and IMF interact with the magnetosphere [Schreiber, 1998; Parker, 2005].

[4] Both the ~27 day variation in solar EUV radiation and the ~27 day variation in geomagnetic activity have effects on ionospheric \( N_m F_2 \). However, the significance and characteristics of their impacts can be different. \( N_m F_2 \) is, in general, directly proportional to the intensity of solar EUV radiation. On the other hand, the effect of geomagnetic activity is very complicated. A large amount of joule heating is deposited at high latitudes during geomagnetically active periods. This causes upwelling of molecular rich air in the auroral region and downwelling of atomic rich air at middle and low latitudes and thus changes in thermospheric composition and plasma density [e.g., Burns et al., 1991; Fuller-Rowell et al., 1994]. Geomagnetic storms can also produce penetration electric fields and enhance neutral wind circulation that alter global ionospheric plasma distribution and density [e.g., Prölls, 1993, 1995; Lei et al., 2008a; Wang et al., 2008, 2010]. Thus, during geomagnetic storms, there are regions of enhanced ionospheric electron densities (positive storm effect) and regions of depleted ionospheric electron densities (negative storm effect) [e.g., Fuller-Rowell et al., 1994; Burns et al., 1995; Prölls, 1995; Buonsanto, 1999; Mendillo, 2006, and references therein]. This leads to a complicated response of ionospheric \( N_m F_2 \) to solar rotation. There has been evidence that recurrent geomagnetic activity, which is related to the 27 day solar rotation period or its harmonics, has a significant impact on global ionospheric plasma densities [Apostolov et al., 2004; Lei et al., 2008b; Wang et al., 2011].

[5] There are cases of \( N_m F_2 \) changes that do not have a good one-to-one correlation with solar EUV variations. For instance, Kane [2003b] showed that the ~27 day sequences of EUV and \( N_m F_2 \) did not always have similar fluctuations; thus the influences of other factors, such as geomagnetic activity, on \( N_m F_2 \) must have been substantial. Oinats et al. [2008] studied the effect of the 27 day variation of solar radiation on \( N_m F_2 \) at Irkutsk from 2003 to 2005. They showed that ionospheric peak densities had a good correlation with ~27 day solar EUV activity, especially during Northern Hemisphere fall and winter. There were, however, times that this correlation was relatively poor. They ascribed this poor correlation to strong influence by periodic geomagnetic activity. These studies suggest that it is necessary to investigate the integrated effect of the ~27 day variation of solar radiation and the ~27 day recurrent geomagnetic activity on the ionosphere simultaneously, as well as their relative contributions to this effect. So far there have not been many studies of this nature reported in the literature.

[6] The main purpose of this paper is to statistically study the effect of ~27 day variations in solar EUV radiation and geomagnetic activity on ionospheric \( F_2 \) region plasma densities. The \( N_m F_2 \) data between 1969 and 1986 from 11 ionosonde stations located at different geomagnetic latitudes in the East Asian-Australian sector are used. We use \( F_{10.7} \) as a proxy for solar EUV radiation and the daily averaged \( Ap \) index as a proxy for geomagnetic activity. We apply a Fourier transform and band-pass filter to obtain information of ~27 day (period between 22 and 32 days) variations in \( F_{10.7} \). \( Ap \) and \( N_m F_2 \) to investigate the significance of ~27 day variations in these parameters and the changes of these variations with latitude and solar cycle. We then use multiple linear regression analysis to study the relative, as well as the integrated, contributions of the ~27 day solar EUV radiation variation and the ~27 day recurrent geomagnetic activity to the observed ~27 day changes in ionospheric peak densities. Solar rotation can also introduce ionospheric variations with other periods, such as ~9, ~13.5, ~40.5, and ~54 days [e.g., Pap et al., 1990; Kane et al., 1995; Wang et al., 2011]. This paper deals only with the variations with the quasi-27 day period.

2. Data

[7] In this paper we use \( N_m F_2 \) data obtained from 11 ionosonde station in the East Asia-Australian sector from 1969 to 1986. These observatories, located at different geomagnetic latitudes, are roughly at the same longitude as given in Table 1. The ionospheric data (CD-ROM of

<table>
<thead>
<tr>
<th>Station</th>
<th>Geographic Latitude</th>
<th>Geographic Longitude</th>
<th>Geomagnetic Latitude</th>
<th>Range of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magadan</td>
<td>60.1°N</td>
<td>151.0°E</td>
<td>53.2°N</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Irkutsk</td>
<td>52.5°N</td>
<td>104.0°E</td>
<td>41.1°N</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Wakkainai</td>
<td>45.4°N</td>
<td>141.7°E</td>
<td>35.3°N</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Kokubunji</td>
<td>35.7°N</td>
<td>139.5°E</td>
<td>25.5°N</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Manila</td>
<td>14.7°N</td>
<td>121.1°E</td>
<td>3.4°N</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Vanimo</td>
<td>2.7°S</td>
<td>141.3°E</td>
<td>12.5°S</td>
<td>1969–1979,1982–1986</td>
</tr>
<tr>
<td>Townsville</td>
<td>19.3°S</td>
<td>146.7°E</td>
<td>28.4°S</td>
<td>1969–1984,1986</td>
</tr>
<tr>
<td>Brisbane</td>
<td>27.5°S</td>
<td>152.9°E</td>
<td>35.7°S</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Canberra</td>
<td>35.3°S</td>
<td>149.0°E</td>
<td>43.9°S</td>
<td>1969–1986</td>
</tr>
<tr>
<td>Christchurch</td>
<td>43.6°S</td>
<td>172.8°E</td>
<td>48.0°S</td>
<td>1969–1985</td>
</tr>
</tbody>
</table>
Ionospheric Digital Database) used in this paper are provided by the World Data Center (WDC-A and WDC-D). The $F_{10.7}$ and $Ap$ data are obtained from the National Geophysical Data Center (NGDC).

The ionosonde observations give critical frequencies ($f_0F_2$) of the ionosphere, which are converted to $N_mF_2$ using the following formula:

$$N_mF_2 = \frac{1}{80.6} (f_0F_2)^2,$$

where the unit of $N_mF_2$ is $m^{-3}$ and that of $f_0F_2$ is Hz.

In this study we used midday (11:00–13:00 local time (LT)) and midnight (23:00–01:00 LT) averaged $N_mF_2$ values for each station.

### 3. Results

#### 3.1. Spectral Analysis

We first carried out a smoothing procedure, which was a 33-day moving average and shifted one day ahead at a time, on a time series of $F_{10.7}$, $Ap$, and $N_mF_2$ to isolate the ~27 day solar rotation effect. The relative changes of these

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**Figure 1.** Fourier spectra of $\Delta F_{10.7}$, midday $\Delta N_mF_2$ (11:00–13:00 LT), and $\Delta Ap$ for 1969–1986. The scale for $\Delta N_mF_2$ at each station is the same.
smoothed parameters, $\Delta f_i$, were then obtained using the following formula:

$$\Delta f_i = \left( f_i - \frac{1}{33} \sum_{j=i-16}^{j=i+16} f_j \right) / \left( \frac{1}{33} \sum_{j=i-16}^{j=i+16} f_j \right),$$

where $f_i$ stands for the time series of $F_{10.7}$, $Ap$, midday $N_mF_2$, and midnight $N_mF_2$.

[11] We then applied a Fourier transform to these relative changes and obtained their spectra from 1969 to 1986. Figure 1 gives the spectral distributions of the relative variations of midday (11:00–13:00 LT) $F_2$ peak densities ($\Delta N_mF_2$). Note that variations with periods longer than 32 days have been removed by the smoothing procedure. In this figure, the top lines in each plot are the spectra of $\Delta F_{10.7}$ for a particular year, the bottom lines are the spectra of $\Delta Ap$, and the 11 lines in between are the spectra of $\Delta N_mF_2$ for the stations given in Table 1. It is evident that, with the exception of 1970, $\Delta F_{10.7}$ had maximum spectral peaks around 27 days, indicating that the ~27 day variation was the predominant component of the daily variability of solar radiation. During solar minima of 1975 and 1976, changes of $F_{10.7}$ with solar rotation were relatively small. $\Delta Ap$ also had spectral peaks around 27 days. These spectral peaks did not show obvious solar cycle variations between 1969 and 1986. In addition, $\Delta Ap$ had noticeable spectral peaks at short frequencies, for instance, at 9 and 13.5 days. The amplitudes of

Figure 2. Same as Figure 1 but for midnight (23:00–01:00 LT).
these short-period spectral peaks were the same as or even larger than those of the ~27 day peaks in some years, for instance, in 1973, 1974, 1975, 1977, 1982, and 1984.

[12] During most of the years studied in this paper, $\Delta N_m F_2$ had spectral peaks around the 27 day period as well as at other shorter periods. There are several features in these spectra: (1) when $\Delta F_{10.7}$ and $\Delta A p$ both had large spectral peaks around 27 days, $\Delta N_m F_2$ also had significant spectral peaks in one or both hemispheres, such as in 1971, 1973, 1974, 1977, 1981, 1982, 1983, 1984, and 1985; (2) when $\Delta F_{10.7}$ or $\Delta A p$ had significant spectral peaks around 27 days, $\Delta N_m F_2$ also had significant spectral peaks in one or both hemispheres, such as in 1969, 1972, 1975 and 1976; (3) $\Delta N_m F_2$ at geomagnetically middle latitudes, in general, had larger amplitudes than at low latitudes and at the magnetic equator; (4) the 27 day spectral peaks were not always hemispherically symmetric, for instance, in 1983 the northern hemispheric stations experienced stronger ~27 day variations in $N_m F_2$ than the southern hemispheric stations did; and (5) there are many minor spectral peaks of $\Delta N_m F_2$ at periods shorter than 27 days. These spectral peaks seemed not related to changes in $F_{10.7}$ as they did not have noticeable spectral peaks at shorter periods. These minor, short-period variations of $\Delta N_m F_2$ did not always correspond to spectral peaks in $\Delta A p$ either, suggesting some of them might be caused by other sources, for instance, lower atmospheric large-scale planetary waves. The measurement noise is also a possible contributor to the short-period variations of $\Delta N_m F_2$.

[13] Figure 2 shows spectral distributions for midnight. The midnight spectra had two significant differences from those of midday. The first one is that, in general, the amplitudes of the ~27 day variations of midnight $N_m F_2$ were larger than those of midday. This is probably caused by the overall much lower $N_m F_2$ values at midnight. The second one is that the midnight ~27 day spectral peaks were hemispherically more symmetric than the midday peaks.

[14] Therefore, Figures 1 and 2 illustrate clearly that $\Delta N_m F_2$ had large ~27 day spectral peaks at geomagnetically middle latitudes and evident peaks at low latitudes and the magnetic equator in each year between 1969 and 1986 either in one hemisphere or both. With the exception of solar minimum years of 1975–1977, and 1970, there were always noticeable ~27 day peaks in $\Delta F_{10.7}$ in the years studied in this paper. $\Delta A p$, on the other hand, had ~27 day peaks in most years. This suggests that the ~27 day variations in solar radiation and geomagnetic activity are most likely the major causes of the ~27 day variations seen in the observed ionospheric $F$ region peak densities. In the next two sections, we examine the relative importance of the ~27 day variations of solar radiation and geomagnetic activity to the variations of the ionosphere in the same period.

3.2. The ~27 Day Variations

[15] To investigate the intensity of the ~27 day variation, we invert the Fourier spectra shown in Figure 1 to reconstruct filtered time series of $F_{10.7}$, $A p$, and $N_m F_2$ in the 27 day band (22–32 days). Figure 3 gives the filtered times series of $\Delta F_{10.7}$, $\Delta A p$, and midday $\Delta N_m F_2$ at Kokubunji from 1969 to 1980. The unfiltered series obtained from equation (2) are also shown in this figure for comparison (gray lines). It is evident that the filtered and unfiltered time series of $\Delta F_{10.7}$ were similar, suggesting that the ~27 day variation was the most significant day-to-day variation of $\Delta F_{10.7}$. This is consistent with the spectral structure of $\Delta F_{10.7}$ shown in Figure 1. However, there are some...
Figure 4. Day-to-day variations of $\Delta F_{10.7}$, $\Delta A_p$, and midday $\Delta N_mF_2$ after 27 day band-pass filtering.
Figure 5. Same as Figure 4 but for midnight $\Delta N_m F_2$. 
fluctuations of $\Delta F_{10.7}$ that cannot be reconstructed from the filtered series, for instance, near day 90 in 1980. This is probably related to the fact that the periods of these oscillations are often changed. Active regions and high-speed streams that give rise to the ~27 day variations in solar EUV and recurrent geomagnetic activity can be weakened or strengthened during successive solar rotations. On the other hand, there were pronounced short-period variations in both midday $\Delta N_m F_2$ and $\Delta Ap$ at Kokubunji. These short-period variations are also seen in the spectral analysis results in Figure 1.

[16] Figures 4 and 5 show reconstructed $\Delta F_{10.7}$, $\Delta Ap$, and $\Delta N_m F_2$ after 27 day band-pass filtering for midday and midnight, respectively. A total of 11 years of data between 1969 and 1986 is shown. In these two figures, the top line in each panel is the filtered time series of $\Delta F_{10.7}$ and the bottom one is that of $\Delta Ap$. Filtered $\Delta N_m F_2$ from 11 stations are illustrated between these two lines. Geomagnetic latitudes for each station are given on the right-hand side of the figure. Each vertical grid in the figures represents 25% variations in $\Delta F_{10.7}$ and $\Delta N_m F_2$ and 100% variations in $\Delta Ap$. For convenience, hereafter we denote the band-pass-filtered parameters $\Delta F_{10.7}$, $\Delta Ap$, and $\Delta N_m F_2$ as $\Delta_27 F_{10.7}$, $\Delta_27 Ap$, and $\Delta_27 N_m F_2$, respectively.

[17] For most of the time, $\Delta_27 N_m F_2$ changed as $\Delta_27 F_{10.7}$ varied. During midday, the changes in $\Delta_27 N_m F_2$ appeared to be smaller at lower latitudes than at middle latitudes, for instance, in 1979, 1978, and 1982. This, however, was not always the case as in 1975 and 1976 stations at equatorial latitudes had stronger ~27 day variations. There is no clear pattern of seasonal variations. In some years, strong equinoctial peaks occurred (1973 and 1974), whereas in other years there were evident solstice peaks (1980 and 1982). This is probably related to the fact that there were no consistent seasonal signatures in the ~27 day variations in both $\Delta_27 F_{10.7}$ and $\Delta_27 Ap$. Figures 4 and 5 also show that there are complicated and different ~27 day variations of $\Delta_27 N_m F_2$ in the two hemispheres. These variations change with season and latitude. This hemispheric asymmetry in the ~27 day variations of $\Delta_27 N_m F_2$ can be very large for some years, for instance, in 1978, 1982 and 1983. This is consistent with that shown in the Fourier spectra in the previous section. There are also no evident solar cycle changes of in $\Delta_27 N_m F_2$ at both midday and midnight.

[18] It is also interesting to note that, at middle and high latitudes, the ~27 day variations of $\Delta_27 N_m F_2$ were 180° out of phase with those of $\Delta_27 Ap$, for instance, days 60–120 in 1970, days 30–150 in 1973, days 210–300 in 1974, and days 240–360 in 1975. In addition, midnight $\Delta_27 N_m F_2$ variations appeared to be stronger than midday ones, especially around the equatorial anomaly regions.

[19] For each year we calculated the normalized standard deviations (NSDs) of $\Delta_27 F_{10.7}$, $\Delta_27 Ap$, midday $\Delta_27 N_m F_2$, and midnight $\Delta_27 N_m F_2$ in the 27 day band at each station. The NSD represents the intensity of the ~27 day variations in this band. Note here that the intensity of the variability in a particular frequency band depends on the bandwidth used.

[20] The top row of Figure 6 shows yearly averaged NSDs of band-pass-filtered $\Delta_27 F_{10.7}$ and $\Delta_27 Ap$. The NSD of $\Delta_27 F_{10.7}$ had year-to-year changes. It was larger during solar maximum than during solar minimum. During the declining phase of a solar cycle, from 1972 to 1974 and in 1982, $\Delta_27 F_{10.7}$ had large NSDs. There were significant year-to-year variations in the NSD of $\Delta_27 Ap$. These year-to-year

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**Figure 6.** Yearly averaged normalized standard deviations of band-pass-filtered $\Delta F_{10.7}$, $\Delta Ap$, and $\Delta N_m F_2$ (averaged over 11 stations) and geomagnetic latitude distributions of 18 year averaged, normalized standard deviation of band-pass-filtered $\Delta N_m F_2$. 

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variations, however, did not appear to have a strong solar cycle signature, although previous studies [Echer et al., 2004, and references therein] showed that there is a strong 11 year solar cycle variation in \( A_p \). The exact cause of this lack of solar cycle change of the 27 day variation of \( A_p \) is clearly an interesting topic for further investigation. However, during the declining phase and near solar minimum of a solar cycle, recurrent geomagnetic activity is mainly driven by CIRs and thus has a strong 27 day variation, whereas near solar maximum geomagnetic storms are caused primarily by CMEs, which are more or less sporadic, as compared with the case of CIRs. Thus, the 27 day variation of geomagnetic activity may not be as strong as the geomagnetic activity itself near solar maximum. The 18 year averaged NSD of the 27 day variation of \( D_{27}NmF_2 \) was about 9%, and the averaged NSD of the 27 day variation of \( D_{27}Ap \) was about 31%. The bottom left-hand panel of Figure 6 gives the year-to-year variations of the NSDs (averaged over 11 stations) of midday \( D_{27}NmF_2 \) and midnight \( D_{27}NmF_2 \). The NSD of \( D_{27}NmF_2 \) had a large peak between 1972 and 1974 and appeared to be slightly greater during solar maximum. Midday \( D_{27}NmF_2 \) and midnight \( D_{27}NmF_2 \) showed similar year-to-year trends, but the midnight NSD was larger than the midday one. The averaged midday variation of \( D_{27}NmF_2 \) (averaged over 18 years and 11 stations) was about 8%, as compared with 10% at the midnight.

Figure 7. Results of multiple linear regression analysis at Magadan (Mlat: 53.2°N) for 1972, 1974, and 1975. The black lines are the band-pass-filtered \( D_{27}NmF_2 \), the red lines are calculated using \( a_0 + a_1 \Delta_{27}F_{10.7}(i) + a_2 \Delta_{27}Ap(i) \), the green lines show results of \( a_1 \Delta_{27}F_{10.7}(i) \), while the blue lines are those of \( a_2 \Delta_{27}Ap(i) \). (top) Results for midday and (bottom) results for midnight.

3.3. Relative Contributions of Solar Radiation and Geomagnetic Activity to \( \sim 27 \) Day Variations of Ionospheric Peak Densities

[22] As has been demonstrated clearly in previous sections, both solar radiation and geomagnetic activity had significant \( \sim 27 \) day variations that can lead to the observed \( \sim 27 \) day variations in ionospheric peak densities. Few attempts, however, have been made so far to separate the relative contributions of the \( \sim 27 \) day variations of solar radiation and geomagnetic activity to ionospheric peak density variations at the same frequency.

[23] To quantitatively determine these relative contributions, we used the following multiple linear regression analysis to perform least squares fitting of \( \Delta_{27}NmF_2 \):

\[
\Delta_{27}NmF_2(i) = a_0 + a_1 \Delta_{27}F_{10.7}(i - \tau_1) + a_2 \Delta_{27}Ap(i - \tau_2),
\]  

where \( \tau_1 \) and \( \tau_2 \) are the time delays of \( \Delta_{27}NmF_2 \) relative to \( \Delta_{27}F_{10.7} \) and \( \Delta_{27}Ap \), \( a_0, a_1, \) and \( a_2 \) are the regression coefficients, and \( i \) is the time (day) in the time series. We applied an 81 day window in our fitting, and the window moves by
9 days each time. In this work we carried out regression analysis by changing $t_1$ and $t_2$ between 0 and 4 days, which corresponds to the time delay of the response of the ionosphere to the ~27 day variations of $F_{10.7}$ and geomagnetic activity [e.g., Oinats et al., 2008; Afraimovich et al., 2008; Min et al., 2009]. From a total of 25 groups of regression analysis, we chose the one that gave the minimum residuals and used these regression coefficients and optimal delay times $t_{1m}$ and $t_{2m}$, which were typically about 2 days, to calculate the normalized standard deviations of $\Delta_{27}N_mF_2$, which are the band-pass-filtered data at time (day) $i$. $a_1\Delta_{27}F_{10.7}(i - t_{1m})$ and $a_2\Delta_{27}Ap(i - t_{2m})$ are the contributions of solar EUV radiation and geomagnetic activity to the ~27 day variations of $\Delta_{27}N_mF_2$, respectively.

As an example, Figure 7 shows the results of multiple regression analysis at Magadan (magnetic latitude (Mlat): 53.2°N) for 1972, 1974, and 1975. Compared with the observed ionospheric peak density deviations (band-pass-filtered $\Delta_{27}N_mF_2$, black lines), the regression analysis (red lines) reproduced reasonably well the magnitude as well as the temporal variation of the observed changes for both midday and midnight. The almost identical curves of black and red lines suggest that most of the observed ~27 day variations were related to solar rotation, which caused ~27 day variations in solar radiation (green lines) and geomagnetic activity (blue lines). In some time periods, solar radiation was the main driver for the ~27 day variations in the ionosphere, such as between days 10 and 150, and days 250 and 350 for midday $\Delta_{27}N_mF_2$ in 1972; at other times, geomagnetic activity was the primary process, such as during the second half of 1974 and between days 250 and 350 in 1975 for both midday and midnight. In addition, there were also time periods during which both solar radiation and geomagnetic activity contributed to the ~27 day variations in $\Delta_{27}N_mF_2$. This situation occurred from day 82 to day 150 in 1974, when the ~27 day variations of $\Delta_{27}N_mF_2$ induced by solar radiation and by geomagnetic activity were in phase, thus resulting in very strong ~27 day variations in $\Delta_{27}N_mF_2$, whereas from day 175 to day 250 in 1972, ~27 day changes induced by solar radiation and geomagnetic activity were in opposite phases, which weakened the ~27 day variation of $\Delta_{27}N_mF_2$. Similar results are also obtained at other stations. This is consistent with the results of Oinats et al. [2008], which showed that geomagnetic activity can depress the effect of ~27 day variation of solar radiation on ionospheric parameters.

Figure 8 gives normalized standard deviations of the midday ~27 day variations at five stations from 1969 to 1986.
1977, and 1978. Nevertheless, the magnitudes of NSDs of these two terms were roughly the same, suggesting that, overall, they contributed almost equally to the \( \sim 27 \) day variations in ionospheric peak densities. The midnight case has the same characteristics as the midday one, although there were slight differences in the details. Thus, we do not show the midnight results here.

Figure 9 gives magnetic latitude distributions of the yearly averaged normalized standard deviations of midday \( \sim 27 \) day variations of the two terms, \( a_1 \Delta_27 \text{F}_{10.7}(i - \tau_{10m}) \) and \( a_2 \Delta_27 \text{Ap}(i - \tau_{20}) \). We can see that at different latitudes and years the magnitudes of the NSDs were evidently different. For example, in 1969 and 1972, at all latitudes (stations), the NSDs caused by solar radiation (\( \text{F}_{10.7} \)) were clearly larger than those caused by geomagnetic activity (\( \text{Ap} \)); thus, the \( \sim 27 \) day variation in solar radiation was the major process producing the \( \sim 27 \) day variation in \( N_m F_2 \) in these years. On the other hand, in almost all other years studied, these two terms had roughly the same magnitudes. There were also differences between the two hemispheres in the NSDs of these two terms. In 1974, the contribution of solar radiation was larger than that of geomagnetic activity in the Southern Hemisphere, whereas in the Northern Hemisphere the situation was the opposite. In 1979, 1981, and 1984, at higher latitudes, the NSDs from geomagnetic activity were almost always larger than those from solar radiation.

The top row in Figure 10 gives latitudinal distributions of 18 year averaged normalized standard deviations of \( N_m F_2 \) and fitted (red lines) \( \Delta_27 N_m F_2 \), which shows that the total NSDs from the fitting procedure were very close to that of the observed ones. The ratios between the NSDs from the fitting procedure and those from the observations (black lines on the third row) were larger than 85%. This suggests that solar radiation and geomagnetic activity were the primary causes of the \( \sim 27 \) day variations in ionospheric peak densities. The red lines on the second and third rows show that at magnetically low latitudes the contribution of geomagnetic activity to \( \Delta_27 N_m F_2 \) was slightly less than that of solar radiation. The overall contribution of geomagnetic activity to \( \Delta_27 N_m F_2 \) was about 75% of that of solar radiation. At magnetically higher latitudes, the contribution of geomagnetic activity became larger and surpassed that of solar radiation. This is more evident at midnight. In addition, fitting coefficients \( a_1 \) (black lines, bottom row in Figure 10) were positive at all latitudes, indicating that \( \Delta_27 N_m F_2 \) was positively correlated with solar radiation. On the other hand, fitting coefficients \( a_2 \) were greater than zero at magnetically lower latitudes but became negative at magnetically higher latitudes. This suggests that the correlation between geomagnetic activity and the \( \sim 27 \) day variation of \( N_m F_2 \) was positive at low latitudes and negative at higher latitudes.

4. Discussion

Solar EUV radiation has significant \( \sim 27 \) day variations because of solar rotation. The NSD of its \( \sim 27 \) day variations, using the \( \text{F}_{10.7} \) index as a proxy, was about 9% between 1969 and 1986. Solar rotation also causes \( \sim 27 \) day periodic variations in geomagnetic activity. The NSDs of the \( \sim 27 \) day variations of the \( \text{Ap} \) index were about 31% from 1969 to 1986. In this paper, we showed that at magnetically low latitudes the contribution of the \( \sim 27 \) day variation of geomagnetic activity to \( N_m F_2 \) variations was about 75% of the contribution from solar radiation variation. At higher latitudes, the contribution of geomagnetic activity became more significant and was even larger than that of solar radiation. This trend was more evident at midnight. Thus, the contribution of the \( \sim 27 \) day variation of geomagnetic activity to the variations of ionospheric peak electron densities cannot be neglected. The results that geomagnetic activity effects become more significant at higher latitudes.
are consistent with the response of the ionosphere to geomagnetic perturbations [Prölss, 1995; Danilov, 2001; Rishbeth, 1998], as energy and momentum deposition occur mostly at high latitudes during enhanced geomagnetic activity periods.

[29] Our analyses of \( N_mF_2 \) data from 11 ionosonde stations in the East Asian-Australian sector between 1969 and 1986 showed that the averaged NSDs of the \(~27\) day variation of ionospheric peak densities were 8% in midday and 10% at the midnight. Thus, the \(~27\) day variation of \( N_mF_2 \) is a significant component of the day-to-day variability of the ionosphere. A full understanding of the cause of this \(~27\) day variation and its relationship with solar rotation has potentially significant values for \( N_mF_2 \) forecasting. Our results are consistent with other studies. For instance, Liang et al. [2008] analyzed ionospheric electron density profiles retrieved from FORMOSAT-3/COSMOC radio occultation observations and found that at 2.5\(^\circ\)N and 355 km the \(~27\) day signal of electron density had a peak-to-peak variation of about 10\%–25\%, corresponding to a NSD of \( \sim 3.5\%–8.8\% \).

[30] There have been studies showing that solar rotation can also lead to \(~27\) day variations in the lower ionosphere and middle atmosphere [Forbes et al., 1996; Rhoden et al., 2000; Pancheva et al., 1991]. These variations may introduce variations in the ionospheric \( F_2 \) region by dynamic and electrodynamic coupling. The \(~27\) day variation of the ionospheric \( F_2 \) peak electron density studied in this paper may also include this effect. In addition, lower atmosphere large-scale wave activity may also have effect on the

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**Figure 10.** Latitudinal distribution of 18 year averaged normalized standard deviations of observed (black lines) and fitted (red lines) \( \Delta_{27}N_mF_2 \) (first row); contributions from solar radiation (black lines) and geomagnetic activity (red lines) to the fitted \(~27\) day variations (second row); the ratio between normalized standard deviations (third row); and fitting coefficients (fourth row).
ionospheric ~27 day variation [Pancheva et al., 2002], albeit no determinant connection between these two has been established.

[31] Borries and Hoffmann [2010] showed that solar variability accounts for up to 50% of the $F_2$ layer ionospheric oscillations with periods between 2 and 30 days, with the rest probably being caused by large-scale lower atmospheric waves. In their analysis, however, no attempts were made to separate the variability caused by ~27 day solar rotation from that caused by lower atmospheric planetary waves. Our analyses showed that the combined effect of the ~27 day variations in solar EUV and geomagnetic activity, on average, could account for about 85% of the variations seen in ionospheric peak electron densities. At higher latitudes, this percentage became larger and approached 95%. Thus, these two processes are the main driver of the ~27 day variability in $N_{m}F_2$. Note here that this result is the average of many years. It is possible that at a particular location and time period, other processes, as discussed above, may have larger effects. A comprehensive study, using data from both lower atmosphere to the ionosphere and physics-based modeling, is needed in future studies to fully understand the mechanisms for the ~27 day variations in $N_{m}F_2$.

[32] The positive correlation between ~27 day variations of $N_{m}F_2$ and solar $F_{10.7}$ is a direct consequence of the solar EUV photoionization process. The effect of geomagnetic activity on ionospheric peak electron densities, however, is controlled by both dynamical and chemical processes. At middle and high latitudes, joule heating and the upwelling of molecular rich air during magnetically active periods appear to be the more dominant processes in causing a depletion of $F$ region electron densities (or negative storm effect). At lower latitudes the downwelling of atomic oxygen rich air and the uplifting of the ionosphere by penetration electric fields and neutral winds tend to produce a more positive response, i.e., increased $F$ region electron densities, in the ionosphere [Prölls, 1995; Danilov, 2001; Rishbeth, 1998; Rishbeth and Mendillo, 2001; Lei et al., 2008a; Wang et al., 2010]. The averaged latitudinal distribution of fitting coefficient $a_2$ is consistent with these theories.

5. Summary

[33] We employed a number of data analysis methods, Fourier transform, band-pass filtering, and multiple linear regression analysis, to investigate the effect of solar rotation on the ~27 day variations of ionospheric peak densities in the East Asian-Australian sector. The data used were from 11 ionosonde stations and between 1969 and 1986. Our results are as follows.

1. Solar rotation produces evident ~27 day (22–32 day) variations in solar EUV radiation and recurrent geomagnetic activity of the same period. The ~27 day variation was the dominant component of solar EUV radiation ($F_{10.7}$). The averaged normalized standard deviation of $F_{10.7}$ was about 9% between 1969 and 1986. There were also large-amplitude ~27 day variations in geomagnetic activity. The averaged normalized standard deviation between 1969 and 1986 for $Ap$ was about 31%.

2. The ~27 day variations of solar radiation and geomagnetic activity were the primary cause of the ~27 day variation of $N_{m}F_2$. They contributed to about 85% of the $N_{m}F_2$ variations seen in the data. This contribution became larger at higher latitudes, approaching 95%.

3. The 18 year averaged, normalized standard deviations of the ~27 day variation were about 8% at midday and 10% at midnight. The latitude changes of this variation were different for midday and midnight. The midday variation was smaller in the magnetic equatorial regions and increased with latitude. On the other hand, the midnight variation had maxima in the equatorial anomaly regions and minima at the magnetic equator and at middle latitudes around ±40° in both hemispheres and became larger again at higher latitudes.

4. In magnetically low-latitude regions, the contribution of solar EUV to the ~27 day variation of $N_{m}F_2$ was slightly larger than that of geomagnetic activity. At higher latitudes, the contribution of geomagnetic activity became larger than that of solar radiation. Therefore, solar radiation and geomagnetic activity both are important sources of the ~27 day variation of the $F$ region ionosphere.

5. The correlation between the ~27 day variations of solar EUV and $N_{m}F_2$ was positive at all latitudes. The correlation between the ~27 day variations of $N_{m}F_2$ and geomagnetic activity was positive at geomagnetically low latitudes but became negative at higher latitudes.

6. There are no consistent seasonal and solar cycle patterns for the ~27 day variations of $N_{m}F_2$. There were, however, large ~27 day variations of $N_{m}F_2$ during the declining phase of the solar cycle (1972–1974 and 1981). Large differences between the two hemispheres are also seen in these variations.

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