Does the $F_{10.7}$ index correctly describe solar EUV flux during the deep solar minimum of 2007–2009?

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[1] This paper shows that the relationship between solar EUV flux and the $F_{10.7}$ index during the extended solar minimum (Smin) of 2007–2009 is different from that in the previous Smin. This difference is also seen in the relationship between f_oF_2 and $F_{10.7}$. We collected SOHO/SEM EUV observations and the $F_{10.7}$ index, through June 2010, to investigate solar irradiance in the recent Smin. We find that, owing to $F_{10.7}$ and solar EUV flux decreased from the last Smin to the recent one with different amplitudes (larger in EUV flux), EUV flux is significantly lower in the recent Smin than in the last one for the same $F_{10.7}$. Namely, $F_{10.7}$ does not describe solar EUV irradiance in the recent Smin as it did in the last Smin. That caused remarkable responses in ionospheric f_oF_2. For the same $F_{10.7}$, f_oF_2 in the recent Smin is lower than that in the last one; further, it is also lower than that in other previous Smins. Therefore, $F_{10.7}$ is not an ideal indicator of f_oF_2 during the recent Smin, which implies that $F_{10.7}$ is not an ideal proxy for solar EUV irradiance during this period, although it has been adequate during previous Smins. Solar irradiance models and ionospheric models will need to take this into account for solar cycle investigations.

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1. Introduction

[2] Solar activity presented by sunspot number varies over different timescales [e.g., *Frick et al.*, 1997; *Hathaway and Wilson*, 2004; *Lundstedt et al.*, 2005; *Usoskin*, 2008; *Wilson*, 1988]. The 11 year solar cycle (SC) is the most prominent variation of solar activity. Though SC variation of solar activity appears repeatedly, it varies from cycle to cycle [e.g., *Hathaway and Wilson*, 2004; *Usoskin*, 2008; *Wilson*, 1988]. The Sun is very quiet during the minimum of SCs 23/24. Sunspot counts are very low at the bottom of this solar minimum (Smin); for example, 2008 has the record (265 days) of the number of spotless days per year after 1913 (see http://users.telenet.be/j.janssens/Spotless/Spotless.html). The 3 year duration of this Smin is about a year longer than the durations of the last several Smins. That is unprecedented in the space age [*Russell et al.*, 2010]. There have been some periods of prolonged extremely low sunspot number in history, such as the Maunder Minimum [e.g., *Eddy*, 1976]. We know little about the quiet Sun and the space environment during these prolonged Smins. The recent deep Smin offers us a glimpse for understanding the quiet Sun and corresponding space environment, owing to various observations in the space age.

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[3] For understanding the effects of SC on the ionosphere, more attention has been paid to SC variations of extreme ultraviolet (EUV) irradiance that induces the vast majority of ionization in the ionosphere. EUV increases by as much as a factor of 3 over a SC [e.g., *Hinteregger et al.*, 1981; *Woods et al.*, 2005], which causes a significant SC modulation in the ionosphere [e.g., *Bilitza*, 2000; *Richards*, 2001]. There has been a lack of long-term continuous measurements of solar EUV in the past. Therefore, different indices were put forward to describe the variations of solar EUV irradiance [e.g., *Floyd et al.*, 2005; *Lean et al.*, 2001; *Liu et al.*, 2006]; and on the basis of these indices, solar EUV irradiance models, such as the EUVAC model [*Richards et al.*, 1994], the SOLAR2000 model [*Tobiska et al.*, 2000], etc., were developed for aeronomic calculations. Among these indices, $F_{10.7}$ (solar 10.7 cm radio flux) is widely used. Some solar EUV irradiance models were constructed on the basis of the postulation that the relationship between solar EUV and $F_{10.7}$ is invariant over different SCs. $F_{10.7}$ is also usually used as the solar activity proxy to develop ionospheric and thermospheric models, such as the IRI model [*Bilitza*, 2001] and the NRLMSISE-00 model [*Picone et al.*, 2002].

[4] *Gibson et al.* [2009] found that sunspot numbers in recent two Smins do not provide sufficient information to gauge solar and heliospheric magnetic complexity and its effects at the Earth, and they pointed out the importance of considering the variation of the Sun between Smins in analyzing and predicting space weather during solar quiet intervals. Namely, solar-terrestrial condition during the

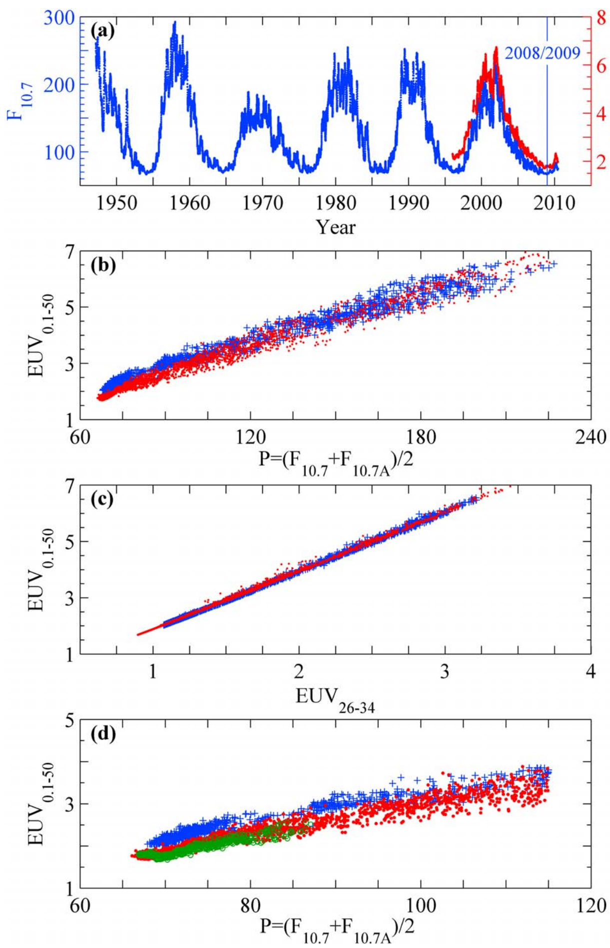

Figure 1. (a) The 27 day averages of daily $F_{10.7}$ (in units of 10^{-22} W/m^2/Hz) and SOHO/SEM 0.1–50 nm EUV flux (in units of 10^{14} photons/m^2/s). (b) SOHO/SEM 0.1–50 nm flux versus $P = (F_{10.7} + F_{10.7A})/2$ in SC 23; crosses show the ascending cycle, and dots show the descending cycle till December 2008. (c) Same as Figure 1b but for SOHO/SEM 0.1–50 nm flux versus 26–34 nm flux (in units of 10^{14} photons/m^2/s). (d) Same as Figure 1b but with circles showing the observations since 2009.

recent deep Smin differs from that during the latest one. Recently, *Didkovsky et al.* [2010] and *Solomon et al.* [2010] reported that solar EUV irradiance in the recent Smin is significantly lower than that in the previous Smin. Then, does $F_{10.7}$ describe solar EUV flux during the recent Smin as it did during the previous Smin? This paper will deal with this question. We also will discuss whether the relationship between solar EUV and $F_{10.7}$ in the recent Smin is unusual from the view of ionospheric responses.

2. Solar EUV Irradiance and $F_{10.7}$ in SC 23

[5] The Solar EUV Monitor (SEM) aboard the Solar Heliospheric Observatory (SOHO) satellite [*Judge et al.*, 1998] has continuously monitored the solar EUV fluxes in 26–34 nm and 0.1–50 nm wave bands since 1996. SOHO/SEM EUV observations provide a very good data set of solar EUV irradiance; there was no comparable continuous record in history [*Kane*, 2003]. Daily SOHO/SEM EUV fluxes are available at http://www.usc.edu/dept/space_science/semdatafolder/long/. Daily $F_{10.7}$ has been routinely observed since 1947; it is available from the SPIDR Web site. We collected SOHO/SEM EUV fluxes in two wave bands and $F_{10.7}$, through June 2010, to investigate SC variations of EUV irradiance and $F_{10.7}$ in SC 23.

[6] Figure 1a shows the series of 27 day averaged $F_{10.7}$ and SOHO/SEM 0.1–50 nm EUV flux. There are strong SC variations in $F_{10.7}$ and solar EUV. Both $F_{10.7}$ and EUV flux decreased from the last Smin to the recent one, however, the decrease amplitudes of them are different. $F_{10.7}$ is slightly lower (about 5%) in the recent Smin than in the last one, while SEM EUV flux is ~15% lower in the recent Smin than in the last one. It should be noted that the potential degradation of the SOHO/SEM instrument could cause a drift of solar measurement, which possibly overestimates the decrease of EUV irradiance. Based on the calibrations with other EUV measurements, *Didkovsky et al.* [2010] and *Solomon et al.* [2010] suggested that this effect is not dominant. We cannot conclude whether larger decrease of EUV is particular just according to the phenomenon itself, because EUV flux and $F_{10.7}$ are not in direct proportion to each other, though EUV flux approximately varies linearly with $F_{10.7}$ at lower solar activity levels [*Liu et al.*, 2006]. Thus, we need further investigate the relationship between solar EUV flux and $F_{10.7}$ during the recent and the last Smins.

[7] $P = (F_{10.7} + F_{10.7A})/2$ can better present the variations of solar EUV irradiance [e.g., *Liu et al.*, 2006; *Richards et al.*, 1994], $F_{10.7A}$ is the 81 day average of daily $F_{10.7}$. Here we use P index to present SC variation of $F_{10.7}$. Figure 1b illustrates SOHO/SEM 0.1–50 nm flux versus P in the ascending and descending phases of SC 23. For the same $F_{10.7}$ level, EUV flux in the recent Smin is significantly lower than that in the last Smin. Figure 1c, however, indicates that SOHO/SEM EUV fluxes in two wave bands (0.1–50 nm and 26–34 nm) are still linearly correlated during the recent Smin, in the same way as that during the last Smin. Namely, solar EUV and radio flux vary with solar activity in the recent Smin with modes differing from those in the last Smin. Therefore, the relationship between solar EUV flux and $F_{10.7}$ is different in the latest two Smins, and $F_{10.7}$ does not describe solar EUV flux in the recent Smin as it did in the last Smin.

[8] $F_{10.7}$ has slightly increased since the beginning of 2009 (see Figure 1a). That seems to indicate that the Sun has been recovering from the deeply quiet minimum. We are interested in whether solar EUV irradiance has been recovering from the deep Smin condition, or the phenomenon shown in Figure 1b is usual during a SC (if that is true, for the same $F_{10.7}$, solar EUV irradiance should recover to the levels of the ascending phase of SC 23). Figure 1d shows SOHO/SEM 0.1–50 nm flux versus P since 2009. It indicates that solar EUV has not recovered till June 2010, and it seems to keep at slightly lower levels than in the descending phase of SC 23 since 2009. Will solar EUV irradiance recover? When will it recover? Or is this a longer-term (longer than the 11 year period) variation of solar EUV? These questions cannot be answered at present.

3. Ionospheric f_oF_2 in the Recent Deep Smin

[9] It cannot be inferred which level of solar EUV irradiance during the latest two Smins is anomalous, or whether

Table 1. Information of the Ionosonde Data Used in This Work

Station Name	Geographic Parameters		Geomagnetic Parameters		Data Source
	Latitude	Longitude	Latitude	Dip	
Wakkanai	45.4	141.7	35.8	59.5	NICT
Kokubunji	35.7	139.5	25.9	48.8	NICT
Okinawa	26.3	127.8	15.8	36.6	NICT
Vanimo	−2.7	141.3	−12.6	−21.6	IPS
Townsville	−19.6	146.9	−28.4	−48.9	IPS
Norfolk Is.	−29.0	168.0	−34.8	−56.4	IPS

the difference between them is normal, from SOHO/SEM data alone. We may discuss this topic from ionospheric and thermospheric records. *Emmert et al.* [2010] and *Solomon et al.* [2010] reported that thermospheric density is significantly lower in the recent Smin than in previous ones, and *Solomon et al.* [2010] thought this is mainly induced by the lower EUV irradiance in the recent Smin. We collected the f_oF_2 (critical frequency of the F_2 layer) observations at the East Asia/Australia stations (see Table 1) to investigate the response of ionospheric F_2 layer to the lower EUV irradiance in the recent Smin. Japanese stations' data (Okinawa, Kokubunji, and Wakkanai) are downloaded from the NICT Web site (http://wdc.nict.go.jp/cgi-bin/print/manual_src/m_wrk/m_wrk), and the other stations' data are downloaded from the IPS Web site (http://www.ips.gov.au/World_Data_Centre).

[10] Figure 2 shows that 12 month mean f_oF_2 has a remarkable solar cycle variation. As we expected, f_oF_2 is lower in the recent Smin than in previous ones, especially at the equatorial ionization anomaly (EIA) crest latitude (Okinawa), owing to the lower EUV irradiance in the recent Smin. *Liu et al.* [2011] presented similar results by analyzing the ionosonde data of global 31 stations. We estimated the f_oF_2 values at the bottoms of the latest two Smins. Table 2 shows the ratios between these f_oF_2 values for each station. The N_mF_2 (maximum electron density of the F_2 layer) rations are also derived from the f_oF_2 rations. The ratios indicate that the decrease amplitude of f_oF_2 (N_mF_2) for the latest two Smins depends on geomagnetic latitudes of the stations. The decrease amplitude is larger at the EIA crest latitude. It is notable that the decrease amplitude of N_mF_2 is nearly equivalent to that of EUV flux at geomagnetic midlatitudes, but the former is obviously larger than the latter at Okinawa.

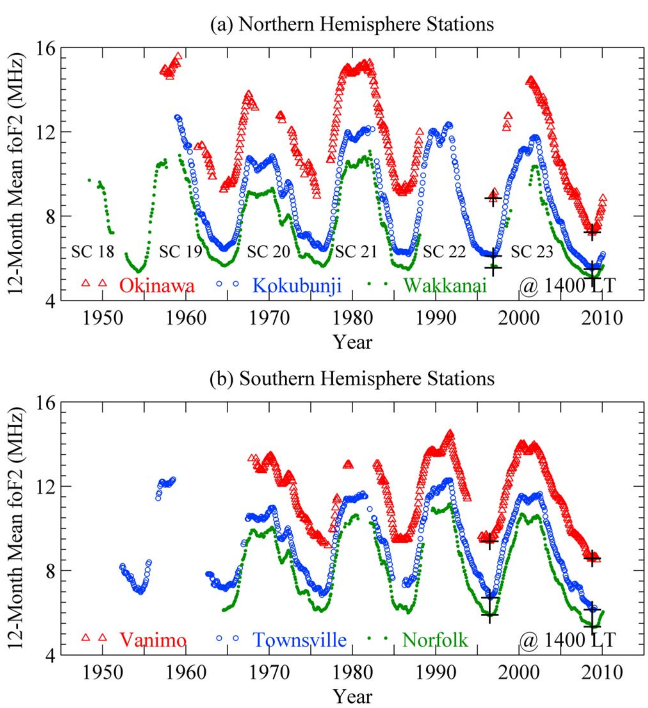

Figure 2. The 12 month means of the f_oF_2 at (a) Northern Hemisphere stations and (b) Southern Hemisphere stations. Crosses show the estimations of the lowest f_oF_2 at the bottoms of the minima of SCs 22/23 and SCs 23/24.

[11] $F_{10.7}$ does not describe EUV irradiance in the recent Smin in the same way as that in the last Smin, therefore, it is necessary to investigate whether $F_{10.7}$ still indicates f_oF_2 in the recent Smin as it did in previous Smins. This is essential for ionosphere modeling. Figure 3 shows f_oF_2 versus P in different SCs. Take the case of Kokubunji observations in the latest two Smins, f_oF_2 is lower in the recent Smin than in the last one for the same $F_{10.7}$ level, which is consistent with the difference in EUV flux versus P during the recent and the last Smins. Furthermore, f_oF_2 is also lower in the recent Smin than in other previous Smins for the same $F_{10.7}$ level, and the amplitude of the discrepancy depends on latitudes. The discrepancy is more remarkable at EIA crest latitudes, which is consistent with the latitudinal feature of solar activity dependence of f_oF_2 [e.g., *Chen and Liu*, 2010]. Linear fits are used to capture the variation trends of f_oF_2 versus P. For previous SCs they represent the relationship between f_oF_2 and P very well, but they give values that are generally higher than observed f_oF_2 during the bottom of the recent Smin. These results show that $F_{10.7}$ does not indicate f_oF_2 in the recent Smin as it did in previous Smins. Therefore, special attention should be paid to this when developing ionospheric models. In fact, some works [e.g., *Bruinsma and Forbes*, 2010; *Coley et al.*, 2010; *Lühr and Xiong*, 2010] have pointed out that some ionospheric and thermospheric models driven by $F_{10.7}$ overestimate electron concentration and neutral density during the recent Smin.

4. Discussion

[12] The lowest f_oF_2 and lower f_oF_2 versus $F_{10.7}$ in the recent Smin are understandable in terms of the dependence of ionospheric electron density on solar EUV irradiance; but the changes in other factors, such as neutral winds, thermospheric composition, the equatorial vertical $\mathbf{E} \times \mathbf{B}$ drift, etc., possibly enhance or counteract the direct effect of the

Table 2. Estimated Ratios of the Lowest f_oF_2 (N_mF_2) at the Bottom of the Minimum of SCs 22/23 to That of SCs 23/24

Station Name	f_oF_2 Ratio	N_mF_2 Ratio
Wakkanai	0.91	0.83
Kokubunji	0.90	0.81
Okinawa	0.82	0.67
Vanimo	0.91	0.83
Townsville	0.92	0.85
Norfolk Is.	0.91	0.83

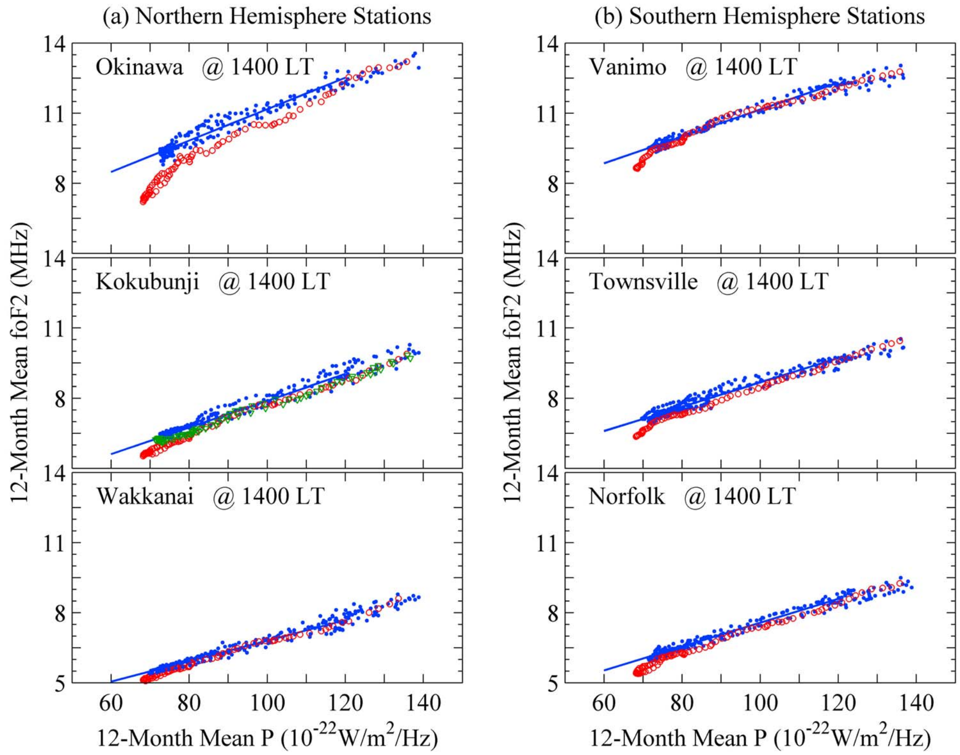

Figure 3. Plots of f_oF_2 versus $P = (F_{10.7} + F_{10.7A})/2$ at (a) Northern Hemisphere stations and (b) Southern Hemisphere stations. Dots show observations before the maximum of SC 23, except that triangles in Kokubunji show observations during the minimum of SCs 22/23, and circles show observations after that; the solid line is the linear fit of dots (only for $P < 120$), except that it is the linear fit of dots and triangles in Kokubunji.

lower EUV irradiance. The f_oF_2 discrepancy between the recent Smin and previous ones appears to increase toward the EIA crest; especially, the decrease amplitude of N_mF_2 is significantly larger than that of EUV at Okinawa. These suggest that the lower solar EUV may have both direct and indirect effects. For example, the lower EUV may exaggerate the effect of waves and tides from the lower atmosphere. A lower *E* region density could affect the strength of equatorial electric fields then enhance the f_oF_2 decrease at the EIA crest latitude. These needs to be further studied in the future. The decrease amplitudes of N_mF_2 are similar to that of solar EUV at midlatitude stations, so these stations are good indications of the direct effect of the lower solar EUV.

[13] The results of f_oF_2 potentially indicate that EUV irradiance is lowest and the relationship between EUV irradiance and $F_{10.7}$ is unusual in the recent deep Smin. However, long-term changes of f_oF_2 possibly depress or enhance f_oF_2 in the recent Smin. If effects of long-term changes are insignificant, it can be deduced that solar EUV flux is lower in the recent Smin than in all previous Smins that f_oF_2 data cover, and so is solar EUV flux versus $F_{10.7}$. Thus, effects of long-term changes must be estimated first. Long-term trends of f_oF_2 are mainly controlled by geomagnetic activity and greenhouse effect, according to prevailing interpretations for long-term trends. The long-term trend from geomagnetic control is anticorrelated with geomagnetic activity trend at midlatitudes and dominant in f_oF_2 long-term trends [e.g., *Mikhailov*, 2006]; while the long-term trend induced by greenhouse effect is negative and relatively smaller [e.g., *Qian et al.*, 2008, 2009; *Rishbeth and Roble*, 1992]. Some scientists also maintain that, owing to weaker trend in geomagnetic activity and a continuous increase of greenhouse gases, geomagnetic control was decreasing toward the end of the 20th century, while greenhouse gases control was increasing [e.g., *Laštovička*, 2005].

[14] Simulations of *Qian et al.* [2008] suggested a minor 4.5% decrease in f_oF_2 (they showed a 9% decrease in N_mF_2) at Smin for doubled CO_2 case, from 365 ppmv to 730 ppmv. This doubled increase far exceeds the CO_2 increase from the preindustrial value of about 280 ppmv to 379 ppmv at the beginning of this century, 2005 [*Intergovernmental Panel on Climate Change*, 2007]. Therefore, long-term changes from greenhouse effect cannot be responsible for the obvious decreases of f_oF_2 shown in Figure 3. Contributions from geomagnetic activity also should be investigated. Figure 4a illustrates percentage distributions of geomagnetic index *Ap* in Smins. Geomagnetic activity is significantly quieter in the recent Smin than in previous ones, which should cause a positive change of f_oF_2 from previous Smins to the recent one at midlatitudes according to *Mikhailov* [2006]. This can be proved from Kokubunji f_oF_2 versus SOHO/SEM EUV flux in SC 23 shown in Figure 4. Here *R* (see equation (1)) is the average deviation of observed f_oF_2 (f_{obs}) from linearly fitted f_oF_2 (f_{fit}) at low solar activity level; it is calculated for

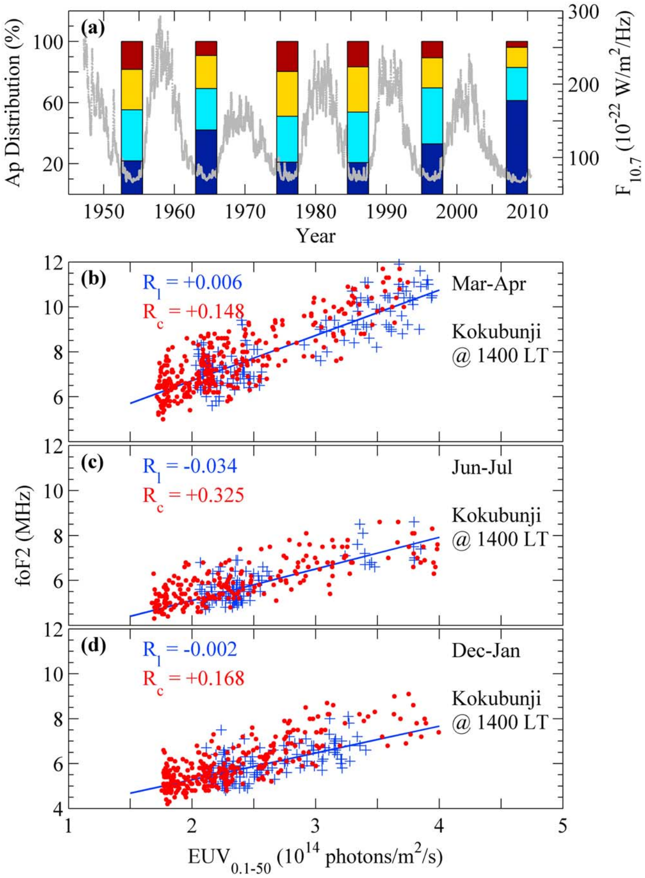

Figure 4. (a) Dots show temporal series of $F_{10.7}$, and bars show percentage distributions of *Ap* during Smins ($F_{10.7} < 80$); four segments, from top to bottom, of each bar for $Ap > 20$, $10 < Ap \leq 20$, $5 < Ap \leq 10$, and $Ap \leq 5$, respectively. (b–d) Kokubunji f_oF_2 versus SOHO/SEM 0.1–50 nm flux in March–April, June–July, and December–January, respectively. Crosses show the ascending phase of SC 23, and dots show the descending phase; the solid line is the linear fit of crosses.

EUV flux less than 2.5 (in units of 10^{14} photons/m^2/s). R_l is for the last Smin, and R_c is for the recent one:

$$R = \sum_{i=1}^{n} (f^i_{obs} - f^i_{fit})/n. \qquad (1)$$

R is used to qualitatively estimate the long-term change of f_oF_2 from the last to the recent Smin. f_oF_2 appears to have positive long-term changes, and the seasonal feature (larger in summer) of the long-term change is consistent with that of *Danilov and Mikhailov* [1999], who subsequently interpreted long-term trends in a geomagnetic control framework. This indicates geomagnetic activity induced a dominant positive long-term change, since the trend from greenhouse effect is negative. Therefore, for the same $F_{10.7}$ level, lower f_oF_2 in the recent Smin than in previous ones mainly originates from lower EUV irradiance, while long-term changes even maybe weaken this trend at midlatitudes. That is to say, solar EUV flux in the recent Smin is lowest since the middle of the last century, and the relationship between EUV flux and $F_{10.7}$ is unusual in the recent deep Smin.

5. Conclusions

[15] SOHO/SEM EUV observations and $F_{10.7}$ index were collected to investigate solar irradiance in the recent deep Smin. As revealed by *Solomon et al.* [2010], solar EUV irradiance is lower in the recent Smin than in the last one. However, what is particular is that $F_{10.7}$ and solar EUV flux decrease from the last Smin to the recent one with different amplitudes. The decreases are ~5% in $F_{10.7}$ and ~15% in 0.1–50 nm EUV flux. As a result, EUV flux is significantly lower in the recent Smin than in the last one for the same $F_{10.7}$ level, and this trend is continuing as $F_{10.7}$ begins to increase since the minimizing in late 2008; while SOHO/SEM EUV fluxes in two wave bands (0.1–50 nm and 26–34 nm) are still linearly correlated during the recent Smin in the same way as that during the last Smin. Therefore, $F_{10.7}$ does not describe EUV flux in the recent Smin as it did in the last Smin.

[16] f_oF_2 data were collected to investigate ionospheric responses to the lower EUV irradiance. f_oF_2 reached the lowest values of its historical records in the recent Smin. From the last Smin to the recent one, the decrease amplitude of N_mF_2 is nearly equivalent to that of EUV flux at higher geomagnetic latitudes (Kokubunji, Wakkanai, Townsville, and Norfolk), but they are obviously different at EIA crest latitude (Okinawa). This possibly indicates that lower EUV produces the primary effect at the midlatitude stations, while other factors, such as the change of the equatorial vertical drift, also play important roles at the equatorial low-latitude stations. For the same $F_{10.7}$, f_oF_2 is lower in the recent Smin than in previous ones, especially at EIA crest latitudes. Therefore, $F_{10.7}$ is not an ideal indicator of f_oF_2 during the recent Smin. We should pay attention to this when developing ionospheric models. Owing to long-term changes of f_oF_2 cannot be responsible for the obviously lower f_oF_2 for the same $F_{10.7}$ in the recent Smin, it indicates, for the same $F_{10.7}$, solar EUV irradiance is lower in the recent Smin than in previous ones that f_oF_2 data cover. Thus, $F_{10.7}$ does not ideally describe solar EUV flux in the recent Smin as it did in previous Smins, namely, the relationship between solar EUV flux and $F_{10.7}$ is unusual in the recent deep Smin. This also should draw our attention when developing solar EUV irradiance models for aeronomic calculations.

[17] **Acknowledgments.** The SOHO/SEM data are provided by Space Sciences Center of University of Southern California; $F_{10.7}$ and *Ap* data are taken from the SPIDR (Space Physics Interactive Data Resource) Web site; and the ionosonde data are provided by the NICT (National Institute of Information and Communications Technology) Web site and the IPS (Ionospheric Prediction Service) Web site. This research was supported by National Natural Science Foundation of China (41004068, 41074112, and 40725014), National Important Basic Research Project of China (2011CB811405), China Postdoctoral Science Foundation Funded Project (20090460509), and the Specialized Research Fund for State Key Laboratories.

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