Statistical analysis of solar EUV and X-ray flux enhancements induced by solar flares and its implication to upper atmosphere

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[1] The 0.1–0.8 nm X-ray flux data and 26–34 nm EUV flux data are used to statistically analyze the relationship between enhancement in X-ray flux and that in EUV flux during solar flares in 1996–2006. The EUV enhancement does not linearly increase with X-ray flux from C-class to X-class flares. Its uprising amplitude decreases with X-ray flux. The correlation coefficients between enhancements in EUV and X-ray flux for X, M and C-class flares are only 0.66, 0.58 and 0.54, respectively, which suggests that X-ray flux is not a good index for EUV flux during solar flares. Thus, for studying more accurately solar flare effect on the ionosphere/thermosphere system, one needs to use directly EUV flux measurements. One of important reasons for depressing relationship between X-ray and EUV is that the central meridian distance (CMD) of flare location can significantly affect EUV flux variation particularly for X-class flares: the larger value of CMD results in the smaller EUV enhancement. However, there are much smaller CMD effects on EUV enhancement for M and C-class flares. The solar disc images from SOHO/EIT are utilized to estimate the percentage contribution to total EUV enhancement from the flare region and from other region. The results show the larger percentage contribution from other region for the weaker flares, which would reduce the loss of EUV radiation due to limb location of flare and then weaken the CMD effect for weaker flares like M and C-class.

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1. Introduction

[2] Solar extreme ultraviolet (EUV) and X-ray photons are the primary energy source of the ionosphere and thermosphere of the Earth [*Mitra*, 1974; *Liu et al.*, 2011]. The solar flare is a sudden eruption solar phenomenon, associated with significant enhancements in EUV and X-ray radiations, with larger enhancements in X-rays and short wavelength EUV and relatively smaller enhancements in long wavelength EUV. These enhanced emissions would cause sudden and intense ionization at various levels in the Earth's ionosphere [e.g., *Afraimovich*, 2000; *Leonovich et al.*, 2002; *Liu et al.*, 2004, 2006; *Tsurutani et al.*, 2005; *Wan et al.*, 2005; *Zhang et al.*, 2002; *Zhang and Xiao*, 2005; *Le et al.*, 2007] and also cause relatively slow and weak responses in the thermosphere [e.g., *Sutton et al.*, 2006; *Liu et al.*, 2007; *Pawlowski and Ridley*, 2008].

[3] As mentioned above, solar EUV irradiance is one of the most important ionization and heating sources for the ionosphere and the thermosphere. Thus its change would directly cause variations in electron density and temperature, and neutral gas density and temperature. Generally speaking, there should be larger increase in solar EUV emission for solar flares with larger enhancements in X-ray emission; whereas for the EUV flux reaching the Earth, the situation is not always the same. For convenience, if not specified, the solar EUV radiation in the following text is referred to the solar EUV radiation observed on the earth, not the initial EUV emission from the Sun. Some previous studies present that flare location on the solar disc may be an important factor to affect the variation of solar EUV flux reaching the Earth.

[4] *Donnelly* [1976] has reported that the solar flare EUV spectra have strong center-to-limb effects, while there is essentially none for X-rays. He argued that solar EUV is produced in the lower solar atmosphere, thus the further the flare site is away from solar disc center, the greater the EUV solar absorption. By using the data of the X-ray flux from GOES satellite of solar flares from 1997 to 1999 and total electron content (TEC) derived from GPS receivers, *Zhang et al.* [2002] analyzed the correlation of flare's location on solar disc with the value of sudden increase of total electron content (SITEC) and found that for the same strength flares, the smaller the central meridian distance (CMD) of flares, the stronger the ionospheric response, which indirectly show solar EUV enhancement during flares correlate with the CMD value because the SITEC is mostly contributed to by

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the solar EUV enhancement. By using the SOHO Solar EUV Monitor (SEM) 26.0–34.0 nm 15 s resolution data and the GPS TEC data, *Tsurutani et al.* [2005] found that although the November 4, 2003 X28 solar flare have much larger X-ray flux than the October 28, 2003 X17.2 solar flare, it has much less EUV flux and also induces the much less response of the ionosphere. They ascribed this phenomenon to the limb effect of flare location on the solar disc because the CMD value is 83 degree for the November 4 solar flare and it is only 8 degree for the October 28 solar flare. In addition, *Sutton et al.* [2006] also observed the larger response of neutral gas density of the October 28 solar flare than that of the Nov 4 solar flare by using the neutral gas data from both Gravity Recovery And Climate Experiment (GRACE) satellite and CHAllenging Minisatellite Payload (CHAMP) satellite. By calculating the increases in TEC during 24 M2.0-M5.7 solar flares, *Leonovich et al.* [2010] also presented the dependence of the ionospheric TEC response amplitude to solar flares on the flare distance to the central solar meridian (CMD): the increase in TEC decreases with increasing distance from the central solar meridian.

[5] By using the X-ray data from GOES-10 and EUV data from SEM/SOHO during X-class flares in solar cycle 23, *Mahajan et al.* [2010] found a poor correlation between X-ray fluxes and EUV fluxes. However, if X-ray fluxes are adjusted for the CMD factor, they would have a higher correlation with the EUV fluxes. Thus they can be a good proxy for the EUV flux. These results show again that the variation in EUV flux is much related to the flare site on the solar disc.

[6] Updates there are a few case studies like mentioned above, which mostly studied some large X-class flares. But there are few statistical studies, especially for more flares including M-class and C-class flares. Actually, there are, on average, one X-class flare per month, one M-class solar flare every three days and much more C-class solar flares during a solar cycle. For example, the number of C-class, M-class, and X-class flares during solar cycle 23 are about 13049, 1428, and 126, respectively. These abundant solar flare events and sustained observations of solar X-ray flux from GOES and solar EUV from SOHO since 1996, provide us a unique opportunity to statistically analyze the relationship between the enhancement in X-ray flux and that in EUV flux, and the CMD effect on the enhancement in EUV flux during different class flares. The investigation of variation in X-ray flux and EUV flux and their relationship during solar flares would be helpful for the estimation and prediction of variation in the ionosphere and thermosphere during solar flares.

2. Data Source

[7] The primary parameters of solar flares, including start time, peak time, end time, flare intensity, and flare site (central meridian distance, CMD), can be obtained from website: ftp://ftp.ngdc.noaa.gov/stp/solar_data/solar_flares/. In this study, we focus on the variation of solar EUV flux, its relationship with X-ray flux variation, and the effects of flare site on solar disc on solar EUV flux during solar flares. Thus the continuous and high time solution data of EUV and X-ray flux are needed.

[8] The data of EUV flux are obtained from the SEM/SOHO experiment, which measures EUV and XUV fluxes integrated in the wavelength bands 26–34 nm and 0.1–50 nm, respectively. These are the major wavelengths which are responsible for the creation of ionization in the upper ionosphere [e.g., *Rishbeth and Garriott*, 1969]. Because the 0.1–50 nm band has a lot of contribution from X-rays in it, we only used the 26–34 nm band EUV data in this study. The daily values of the SEM/SOHO EUV fluxes are available from 1996 until now. In our analysis, for the sake of observation of solar flares, we used the high temporal resolution data, the 15-s average SEM/SOHO fluxes, which can be downloaded at the Website: http://www.usc.edu/dept/space_science/semdatafolder/. For each solar flare, the 60-min median of the EUV flux before solar flare commence is set as reference value, and then the absolute increases in EUV flux (ΔF_{EUV}) during the solar flare can be calculated. Figure 1 shows the samples of time series of 26–34 nm EUV flux during some X, M, and C class solar flares. As shown in Figure 1, X-class flares have significant enhancements in 26–34 nm EUV; Compared to X-class flares, M and C-class flares have much lower but still clear enhancement. But parts of the M and C-class flares do not have a clear increase in 26–34 nm EUV and part of them has very complicate variation in 26–34 nm EUV, so that it is difficult to calculate the values of ΔF_{EUV} for these flares. Thus these flares are excluded in this study. In addition, there are no measurements of SEM/SOHO during some solar flares including X, M, and C-class flares. The number of X, M, and C-class flares during solar cycle 23 are about 126, 1428, and13049, respectively. Finally, their numbers are reduced to 112, 1215, and 10454, respectively.

[9] The solar X-ray fluxes are being continuously measured above the Earth's atmosphere by SOLRAD series of satellites and then by the GOES series of satellites from 1975 to present. In this study, we used the 1 min averaged X-ray data observed by GOES satellites in the wavelength band 0.1 to 0.8 nm, which can be downloaded freely at the Website: http://www.ngdc.noaa.gov/stp/GOES/. For each solar flare, the 60-min median of the X-ray flux before solar flare commence is set as reference value, and then the absolute increases in X-ray flux (ΔF_{Xray}) during the solar flare can be calculated. It should be noted that the greatest solar flare ever recorded on November 4, 2003 is not considered in this analysis study because we do not know the exact peak flux of 0.1–0.8 nm X-ray due to that X-ray flux remained a saturated value of 1.84×10^{-3} W/m^2 for 13 min during this solar flare. Although a magnitude of 2.8×10^{-3} W/m^2 has been extrapolated from those data before and after the saturated period and this flare is named class X28. It is still difficult to get an accurate peak flux because of so long saturation of 13 min. *Thomson et al.* [2004] have argued from VLF phase change measurements that the November 4 event magnitude was perhaps as large as X45 ± 5. Also using riometer measurements at 20.1 MHz, *Brodrick et al.* [2005] suggested that X38 seems to be more suitable class for this flare.

3. Results

[10] Figure 2a show the plots of peak enhancements in X-ray of 0.1–0.8 nm versus peak enhancements in EUV flux

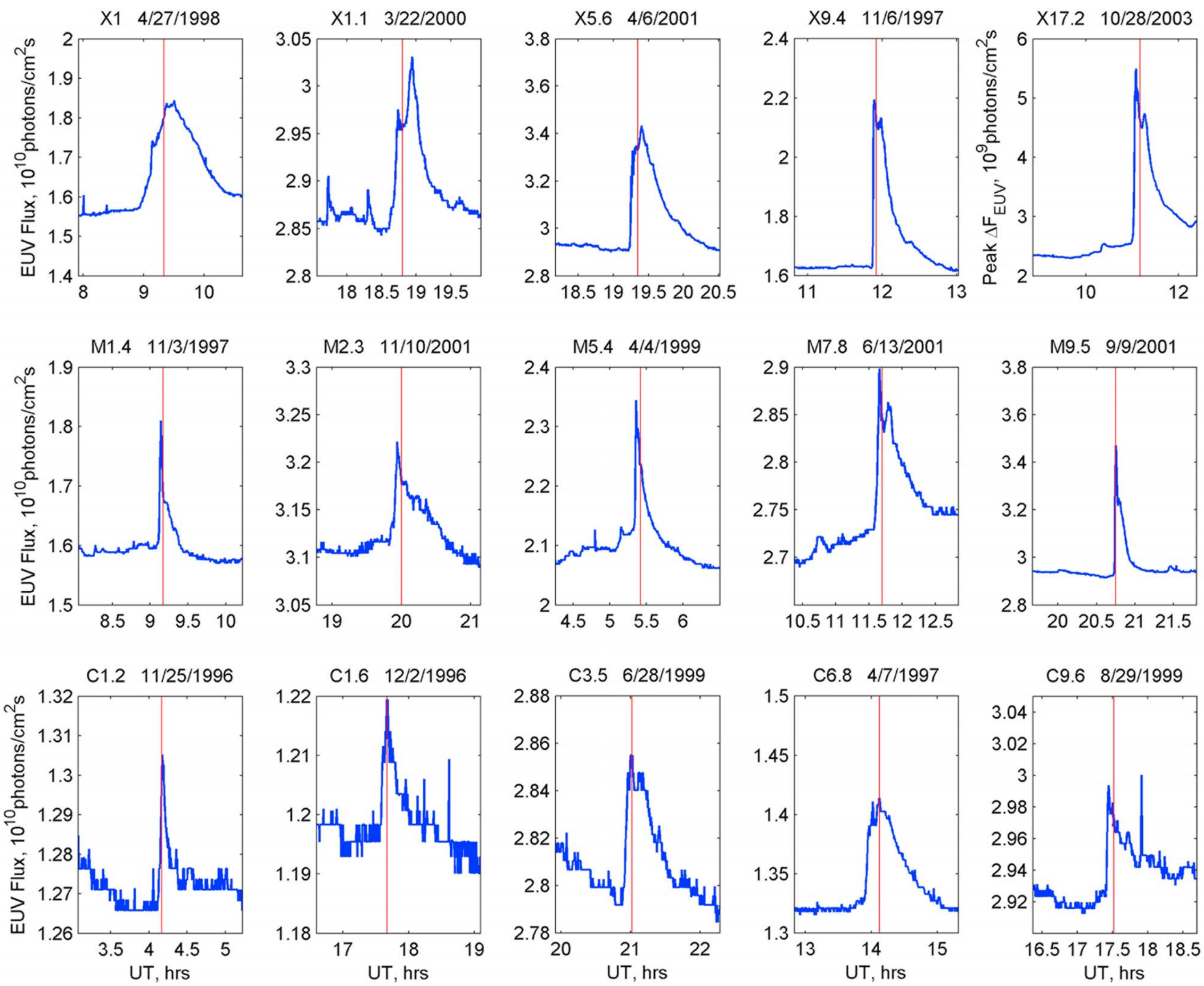

Figure 1. Sample time series of EUV fluxes during some X, M, and C class solar flares.

of 26–34 nm for X-class solar flares during 1996–2006. The corresponding correlation coefficients between them are also marked in the panel. As shown in the figure, the correlation coefficients are not impressive, only reaching 0.66. As mentioned above, the flare location on solar disc may be an important factor to affect the variation in EUV flux during a solar flare. *Mahajan et al.* [2010] has shown that, when correction for the flare location is applied by multiplying the X-ray flux by Cos(CMD), the correlation would have a major improvement. Therefore, to check the CMD effect, we also plot peak enhancements in X-ray multiplied by Cos(CMD) against peak enhancements in EUV Figure 2b, and calculate the correlation between them. The results show that the correlation coefficient jumps from 0.66 to 0.90 as a result of the CMD effect correction. That is to say, our statistical results verify again that the amplitude of enhancement in EUV flux during X-class solar flares is probably related to the flare location on solar disc (or the value of CMD) and it decreases with increasing CMD values.

[11] As discussed above, the relative strength of impulsive EUV emission for X-class solar flares has a significant CMD effect. We can approximately forecast the enhancement in EUV flux via the variation in X-ray flux coupling with the CMD effect (multiply the enhancement in X-ray flux by Cos(CMD)). Then a question arises as to whether there is a CMD effect to the same extent for other smaller flares such as M-class and C-class flares, and whether it is possible to get a higher relationship between the peak ΔF_{EUV} and the CMD modified peak ΔF_{Xray} by Cos(CMD). The number of M-class and C-class flares is more than 1200 and 10000, which is much more than that of X-class flares. The plenty data sample provide us a more sufficient condition to examine the relationship between the peak ΔF_{EUV} and peak ΔF_{Xray} for M-class flares and C-class flares, which is shown in Figures 2c–2f. The correlation coefficient between peak ΔF_{Xray} and peak ΔF_{EUV} for M-class (0.58) and C-class (0.54) flares is lower that for X-class (0.66) flares. It goes from 0.58 to 0.62 for M-class flares and from 0.54 to 0.52 for C-class flares when the effect of flare location is considered by multiplying the X-ray flux by Cos(CMD) as done for X-class flares, which means that the correlation also does not have any improvement by considering the modification of Cos(CMD) in X-ray flux.

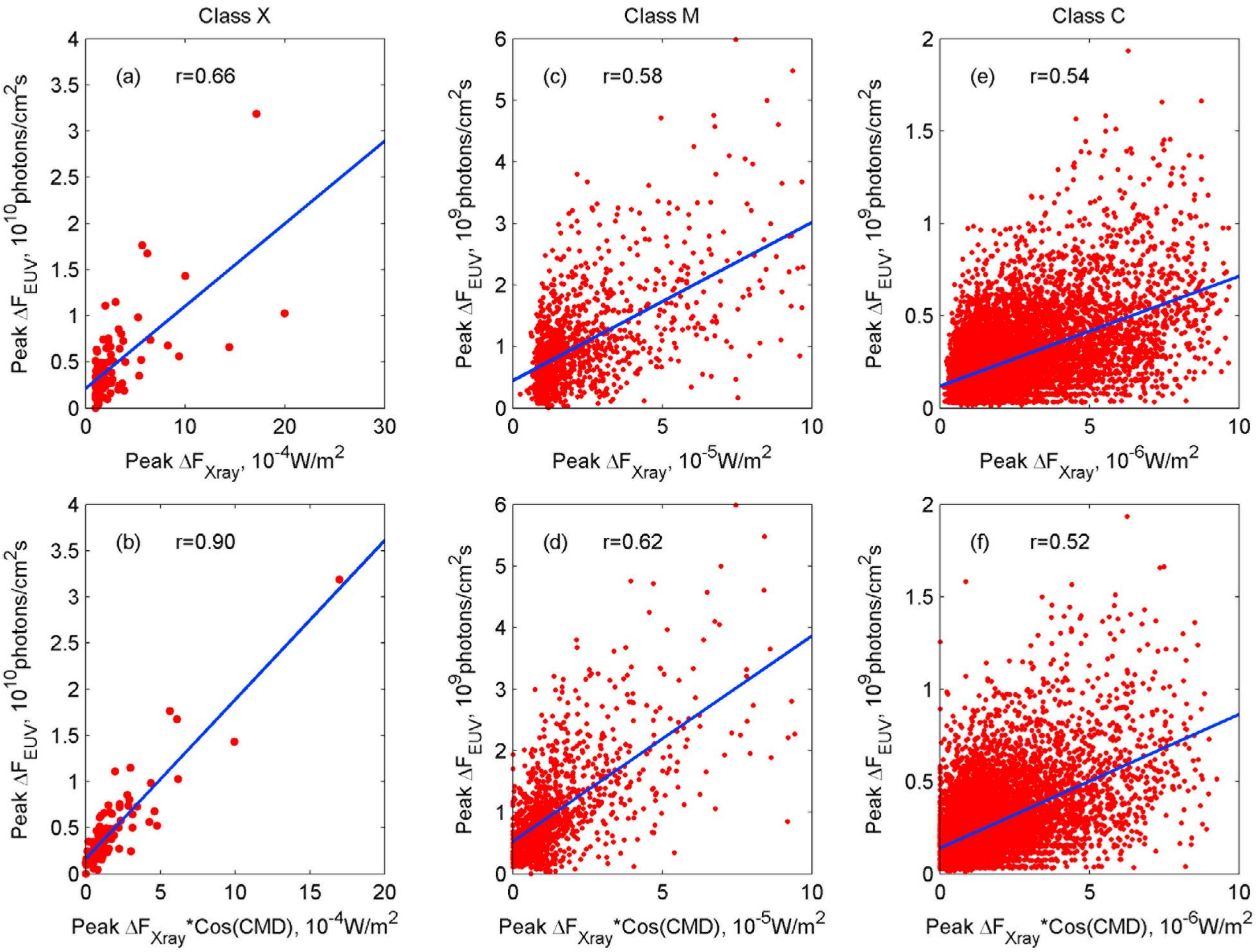

Figure 2. (a) Plots of SEM/SOHO measured peak ΔF_{EUV} of 26–34 nm versus GOES measured peak ΔF_{Xray} for 102 X-class flares from 1996 to 2006. (b) Same as top panels but for X-ray fluxes multiplied by Cos(CMD). The correlation coefficients between the two fluxes are indicated in the panels. The solid lines represent the linear fitting. (c and d) For the M-class flares. (e and f) For the C-class flares.

[12] The statistical results show that M-class and C-class flares have not the same CMD effect as X-class flares have. The modification for X-ray flux with Cos(CMD) cannot improve the correlation between EUV flux and X-ray flux. At the same time, the results do not bring us to the conclusion that M- and C-class flares do not have any CMD effect for the EUV enhancement. From the results as shown in Figures 2c–2f, we only can say that the modification factor of Cos(CMD) is wrong or not suitable for M- and C-class flares.

[13] To further check the dependence of EUV flux on the location of flares on the solar disc, we plotted the peak ΔF_{EUV} against the CMD values of flares for X, M, and C-class flares in Figures 3, 4, and 5, respectively. *Mahajan et al.* [2010] also examined the dependence of EUV flux on the location of flares by plotting the EUV flux versus CMD value for all X-class flares of X1–X28. By doing so, they only obtained an approximate result for CMD effect. Actually, different level flares may have a different extent of CMD effect. Thus, to obtain the more accuracy results, we separate X-class flares into following pieces: X1 ~ 2, X2 ~ 4, and X4 ~ 7 (as shown in Figure 2). The greater flares than X7 class cannot be statistically analyzed because of few flare samples. As shown in Figures 4 and 5, we also separate M-class flares in following pieces: M1 ~ 2, M2 ~ 3, M3 ~ 5, M5 ~ 7, and M7 ~ 10, and also separate C-class flares in the same way.

[14] For each level flares such as M1 ~ 2, we calculated the correlation coefficient (r) between peak enhancement in EUV fluxes and the CMD values and linearly fitted the data. Then through the fitted line, we calculated the ratio of peak ΔF_{EUV} of limb flares (CMD = 90°) to that of central flares (CMD = 0°), which is noted as R_f. Values of R_f represent strength of CMD effect on EUV flux. The smaller the value of R_f, the stronger the strength of CMD effect. As shown in Figure 3, the values of r are −0.53 of X1 ~ 2, −0.76 of X2 ~ 4, and −0.82 of X4 ~ 7, respectively. The values of R_f are 0.28 of X1 ~ 2, 0.15 of X2 ~ 4, and 0.08 of X4 ~ 7. These results show that the correlation between enhancement in EUV flux and CMD value increases with increasing flare strength and the CMD effect also becomes stronger with increasing flare strength.

[15] Then let us continue to see the situation for M-class and C-class flares from Figures 4 and 5. The values of r and

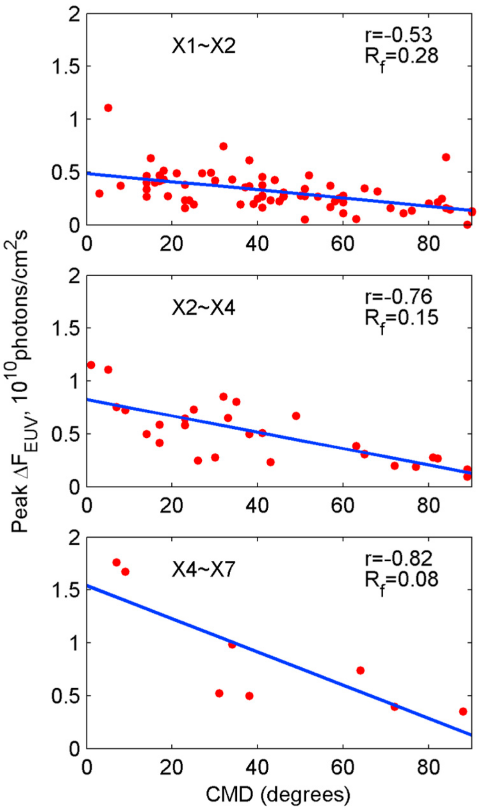

Figure 3. Dependence of the enhancement EUV flux on the values of CMD which represent the location of flares on the solar disc for X-class flares of 1996–2006. X-class flares are separated into following pieces: X1 ~ X2, X2 ~ X4, and X4 ~ X7, respectively. The solid lines represent the linear fitting. The correlation coefficient (r) and the ratio of peak ΔF_{EUV} at CMD = 90° to that at CMD = 0° (R_f) are also marked in panels.

R_f show there a similar trend of the correlation and the CMD effect for both M-class and C-class flares as that for X-class flares. Take M-class flares for example. The absolute value of r increases from 0.25 at M1 ~ 2 to 0.44 at M7 ~ 10; the value of R_f decreases from 0.55 at M1 ~ 2 to 0.41 at M7 ~ 10. To further analyze the variation of the correlation and the CMD effect for all flares from C- to X-class, the values of r and R_f from C1 ~ 2 to X4 ~ 7 are listed in Table 1. Seeing from Table 1, one can clearly find that the correlation between enhancement in EUV and CMD generally increases and the CMD effect on solar EUV flux also increases as the flare strength progresses from C-class to M-class and from M-class to X-class: for the absolute value of r, it increases from 0.13 (C1 ~ 2) to 0.82 (X4 ~ 7); for the value of R_f, it decreases from 0.72 to 0.08.

[16] To examine relationship between EUV flux and X-ray flux for all level flares from C- to X-class and further check the CMD effect for all level flares. We plot peak ΔF_{EUV} versus peak ΔF_{Xray} with CMD < 10°, CMD < 50°, and CMD < 90°, respectively, in Figure 6. The statistical results show a very high correlation of 0.92 between the two fluxes for the flares with CMD < 10°, which means that the enhancement in EUV emission is highly related to that in X-ray emission during solar flares if CMD effect is not considered. *Horan and Kreplin* [1981] also reported the highly positive correlation of soft X-ray with EUV based on simultaneous measurements of them during several X, M and C-class solar flares. For example, the 10–50 nm bands EUV have 55% enhancement for X-class, 10% enhancement for M-class, and slightly 0.5% for C-class.

[17] Figure 6 also shows that the correlation decreases when the flares with the larger CMD is considered in the statistical analysis: it decreases from 0.92 of CMD < 10° to 0.81 of CMD < 50° and 0.73 of CMD < 90°. The results suggest again the CMD effect for the EUV enhancement during solar flares. From Figure 6, one can see that the enhancement of EUV flux is not linearly related with the increase in X-ray flux and its uprising amplitude decreases with increasing X-ray flux. To better fit the data, we adjust the line segment curve-fitting to fit the data for CMD < 10°,

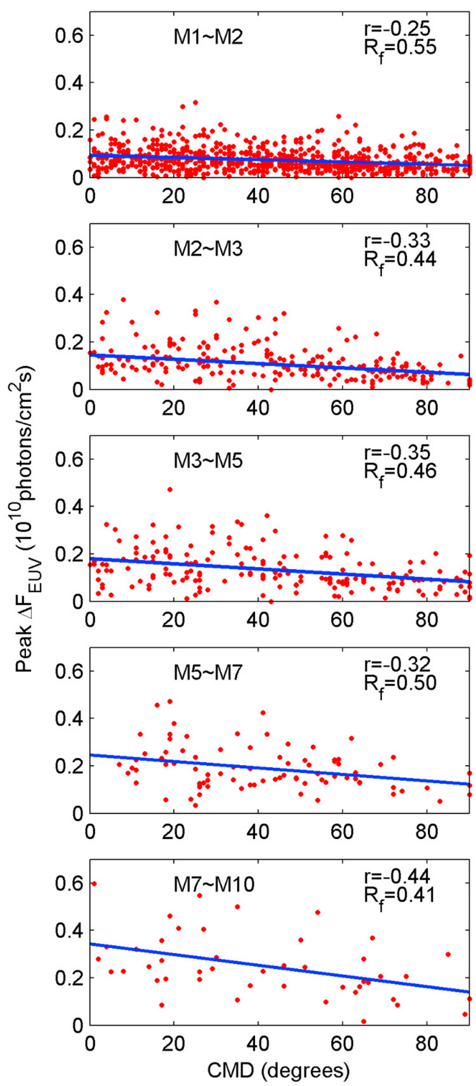

Figure 4. Same as Figure 3, but for M-class flares from 1996 to 2006. M-class flares are separated in following pieces: M1 ~ M2, M2 ~ M3, M3 ~ M5, M5 ~ M7, and M7 ~ M10, respectively.

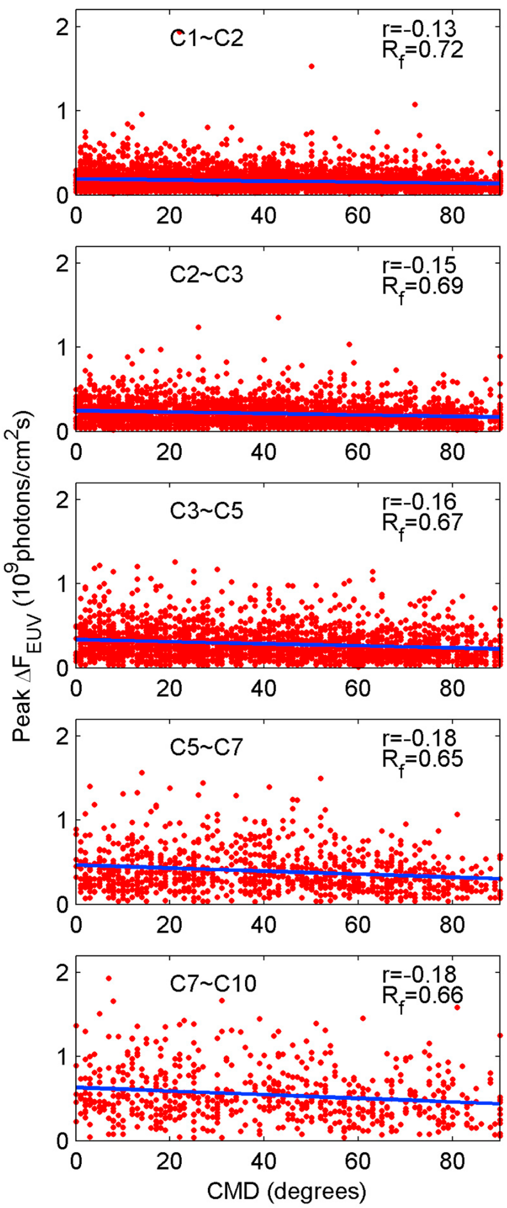

Figure 5. Same as Figure 3, but for C-class flares from 1996 to 2006. C-class flares are separated in following pieces: C1 ~ C2, C2 ~ C3, C3 ~ C5, C5 ~ C7, and C7 ~ C10, respectively.

CMD < 50°, and CMD < 90°, respectively. Formulas for regression curves as follows:

$$\Delta F_{EUV} = A + B \cdot \Delta F_{Xray}, \qquad (1)$$

where A and B are the parameters of line fitting for each X-ray segment and B represents the change rate of ΔF_{EUV} in each X-ray segment; ΔF_{EUV} and ΔF_{Xray} are measured in 10^{10}photons/cm^{2}s and 10^{-4}W/m^2. Table 2 lists the variation of A and B in different X-ray segment for solar flares with CMD < 10°, CMD < 50°, and CMD < 90°, respectively. Table 2 shows the value of B decreases with increasing X-ray flux, which means the uprising amplitude of enhancement in EUV flux decrease with increasing X-ray flux. Table 2 also shows the value of B decreases with increasing CMD, which is just due to the CMD effect on the enhancement in EUV flux.

4. Discussion

4.1. Analysis of CMD Effect

[18] The statistical results mentioned in section 3 show that the CMD effect of EUV flux has a significant dependence of solar flare class (or X-ray flux strength). The CMD effect increases with increasing solar flare class. For example, the value of R_f decreases from 0.72 of C1 ~ 2 to 0.08 of X4 ~ 7, with the corresponding correlation from −0.13 to −0.82. These results show the EUV flux has significant CMD effect for X-class flares; whereas there is much weaker CMD effect for M- and C-class flares particularly for C-class flares. This is the reason why there is not any improvement or even a drop for the correlation of EUV flux with modified X-ray flux by multiplying Cos(CMD) for M- and C-class flares (as shown in Figures 2c–2f).

[19] As mentioned above, previous studies show that the EUV radiation has a significant limb effect. Those studies mainly focused on some great X-class flare events. *Leonovich et al.* [2010] found the average amplitude of the TEC response depends on the flare distance to the central solar meridian (CMD). Except for the X-class flares, they also found the similar CMD effect of ionospheric response for M-class as well as C-class flares. But they only used 6 X2.0–5.7 flares, 24 M2.0–7.4 flares, and 8 C3–10 flares to illustrate the dependence of the TEC response amplitude on the values of CMD for X-class, M-class, and C-class, respectively. Thus their result is only a qualitative analysis for the CMD effect, which does not show any discrimination among the X, M, and C class. In this study, our statistical results based on lots of flare events give out a more accurate and quantitative analysis for X, M and C-class flares. The statistical results show a great CMD effect for X-class flares and a much weaker CMD effect of M-class and C-class flares. As it is known, the CMD effect of EUV radiation is caused by the larger absorption for the limb flare because it needs to travel longer distance from solar low-lying atmosphere to the surface. But why the CMD effect is related with solar flare strength and what cause the CMD effect decreases with solar flare strength? As we know, the Sun is

Table 1. List of Values of r and R_f of C-class, M-class, and X-class Flares for 26–34 nm

	26–34 nm	
Flare Class	r	Df
C1 ~ 2	−0.13	0.72
C2 ~ 3	−0.15	0.69
C3 ~ 5	−0.16	0.67
C5 ~ 7	−0.18	0.65
C7 ~ 10	−0.18	0.66
M1 ~ 2	−0.25	0.55
M2 ~ 3	−0.33	0.44
M3 ~ 5	−0.35	0.46
M5 ~ 7	−0.32	0.50
M7 ~ 10	−0.44	0.41
X1 ~ 2	−0.53	0.28
X2 ~ 4	−0.76	0.15
X4 ~ 7	−0.82	0.08

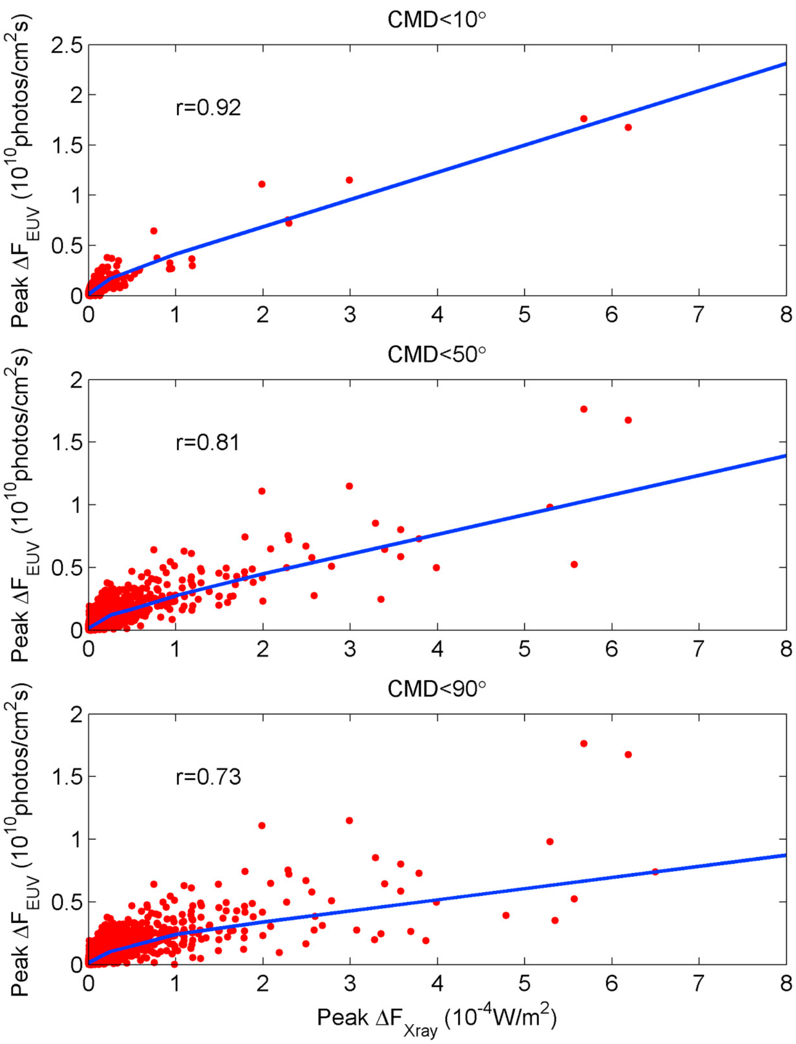

Figure 6. Plots of peak ΔF_{EUV} versus peak ΔF_{Xray} for solar flares with CMD < 10°, CMD < 50°, and CMD < 90°, respectively. Solid lines are the line segment curve-fitting of the two fluxes. Their correlation coefficients are also marked in the figure.

very active during solar flares and there are more than one solar activity regions in solar disc. Thus the enhancements in EUV radiation during a solar flare come not only from the flare region, but also from other region. Furthermore, the greater the other region's contribution, the EUV enhancement absorbed due to limb effect would be smaller and the left EUV enhancement would be larger, which means a weaker CMD effect. Take a limb solar flare for example. If total EUV enhancement comes from the flare region, the EUV enhancement is assumed to be 10% of that of a central solar flare (CMD = 0°). Then if 70% (60%, 50%) of EUV enhancement comes from the flare region and the left 30% (40%, 50%) of that comes from central region of the solar disc, the EUV enhancement would reach 37% (46%, 55%) of a central solar flare.

[20] Therefore, we suspect that the contribution from the flare region is greater for the greater solar flares. In other words, there would be greater contribution from other region for the weaker class solar flares, which would cause a weaker CMD effect. That is to say, the CMD effect of M-class solar flares would be weaker than that of X-class solar flares and the CMD effect of C-class solar flares would also be weaker than that of M-class solar flares, as illustrated in Figures 3–5.

[21] In this study, we selected the solar EUV image data from the SOHO's Extreme ultraviolet Imaging Telescope (EIT) to check the idea mentioned above. The SOHO EIT is able to image the solar transition region and inner corona in four selected band passes in the extreme ultraviolet (EUV):

Table 2. Line Segment Curve-Fitting Parameters, A and B, for Solar Flares With CMD < 10°, CMD < 50°, and CMD < 90°, Respectively

		Segment of ΔF_{Xray} (10^{-4}W/M^2)			
	CMD	0–0.25	0.25–1.0	1.0–4.0	4.0–8.0
A	<10°	0.0137	0.0889	0.1444	0.1444
	<50°	0.0148	0.0664	0.1148	0.1331
	<90°	0.0141	0.0579	0.1481	0.1590
B	<10°	0.6217	0.3264	0.2708	0.2708
	<50°	0.4144	0.2083	0.1598	0.1574
	<90°	0.3560	0.1807	0.0905	0.0891

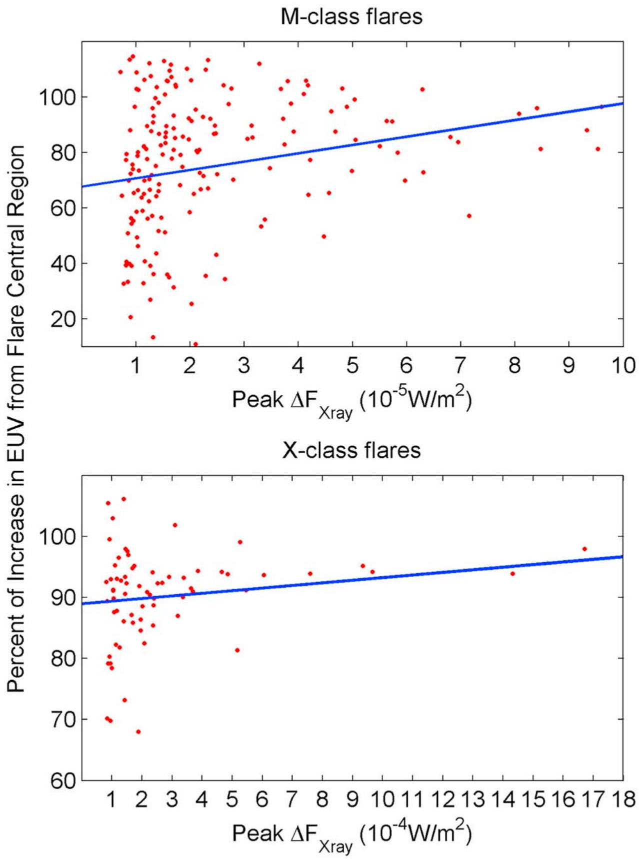

Figure 7. The dependences of percent of increase in EUV from flare central region on the strength of solar flares for both the M-class flares and the X-class flares. The solid lines represent the linear fitting.

Fe IX/X, 171 Å; Fe XII, 195 Å; Fe XV, 284 Å; He II, 304 Å. The pixel scale of the EIT instrument is 1024 × 1024 2.6-arc second pixels. There are most images of EUV emission at the line of 195 Å, thus we used the EIT data at this line.

[22] For each solar flare event, to measure the EUV flux variation induced by the solar flare, an image just before the solar flare erupts and an image near the peak time of solar flare are needed. The time between the two images is no more than 24 min. The rotation angle of the Sun within this period is no more than 0.22 degree, which means that there is almost no change in the location for all pixels on the solar disc and there are some changes in the strength for some pixels. By comparing directly these two images, we can calculate the EUV change in each pixel on the solar disc. But not all flare events have the satisfied measurements just before the solar flare erupts and an image near the peak time of solar flare. For the X-class solar flares, about 70 flares have the satisfied images. For the M-class solar flares, we selected the solar flares during 2002–2003 for the study and about 180 flares have the satisfied images. When the EUV change in each pixel on the solar disc is calculated, we then can calculate the percent of increase in EUV from the flare region and that from other regions. The flare region is defined as the region within 30 degree from the flare location.

[23] The dependences of percent of increase in EUV from flare region on the strength of solar flares for both the M-class flares and the X-class flares are illustrated in Figure 7. For the M-class flares, the percent decreases from about 95% for peak $\Delta F_{Xray} = 1.0 \times 10^{-4} W/m^2$ to about 70% for peak $\Delta F_{Xray} = 1.0 \times 10^{-5} W/m^2$. For the X-class flares, the percent decreases from about 97% for peak $\Delta F_{Xray} = 1.8 \times 10^{-3} W/m^2$ to about 90% for peak $\Delta F_{Xray} = 1.0 \times 10^{-4} W/m^2$. In addition, the results also show that the lowest value of the percent reaches 20% for the M-class flares and it reaches 70% for the X-class flares. These results show the percent from the flare region decreases with decreasing flare strength. On the contrary, the percent from other region increases with decreasing flare strength, which would cause a weaker CMD effect for M-class and C-class flares, compared with X-class flares (as shown in Figures 3–5).

4.2. Implication to Upper Atmosphere

[24] During solar flare events the abrupt enhancements in solar irradiance can significantly changes the density, temperature, and composition in Earth's upper atmosphere, which is an important aspect of space weather studies that are relevant to space-based communication/navigation systems and astronaut safety. During a solar flare, the shorter the wavelength of solar irradiance, the greater its enhancement is. For example, the results based on measurements from the Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) satellite show that the ratios of the flare irradiance spectrum to the pre-flare spectrum for the large X-class flares indicate more than a factor of 50 increase in the X-ray region and are less than a factor of 2 for the EUV region [*Woods and Eparvier*, 2006]. Although the enhancement in X-ray region is much higher than that in EUV region, the upper atmosphere is controlled mainly by EUV irradiance not by X-ray irradiance. As is known, the most important source of external forcing to the ionosphere and thermosphere is solar extreme ultraviolet (EUV) irradiation which is absorbed by the upper atmosphere from roughly 90 km to 200 km and causes the large enhancement in ionization rate and heating rate in the ionosphere and thermosphere. *Zhang et al.* [2011] also show the relationship between TEC enhancement and the EUV flux increases in 26–34 nm EUV flux during a flare is more correlative than that in 0.1–0.8 nm soft X-ray flux.

[25] In the past, researchers often took the intensity of X-ray flux as an index of the EUV flux to study the ionospheric response to solar flares. But some resent studies show that the ionospheric responses have not a one-to-one relationship with the intensity of X-ray flux [e.g., *Liu et al.*, 2006; *Tsurutani et al.*, 2005; *Mahajan et al.*, 2010; *Zhang et al.*, 2002, 2011]. In contrast, their correlation coefficient is far from unity, which shows the change in X-ray flux is not suitable to be used to predict or scale the ionospheric response to a solar flare and also indirectly shows X-ray flux cannot be used an index of EUV flux during a solar flare. In this study, based on the sufficient measurements of both X-ray and EUV flux during lots of solar flares, we obtain the similar results with previous studies: even for the X-class solar flare, their correlation coefficient is only 0.66. As mentioned above, one of the main reasons is the CMD effect: the larger value of CMD results in the smaller EUV enhancement. Our statistical results show the modified X-ray

flux with Cos(CMD) have a much improvement relationship with the EUV flux for X-class flares; however, there is not any improvement for M and C-class flares. In addition, *Zhang et al.* [2011] also show that the different ionospheric response exists even for the flares with the same value of CMD and the same X-ray class. That also illustrates the variability of the irradiation spectrum of flare to flare. Therefore, during solar flares X-ray flux cannot be used as an index of EUV flux and for studying more accurately the ionospheric and thermospheric responses to solar flares, one needs to use directly measured EUV flux. In addition, it should be noted that compared with X-class flares, most of M-class and all C class flares have rather small enhancement in EUV (mostly between 5×10^8 to 1.5×10^9 photons cm^{-2}s for 26–34 nm EUV); therefore these solar flares do not produce any detectable effect on the sluggish ionosphere and thermosphere system.

5. Summary and Conclusion

[26] There are about 13049 C-class flares, 1314 M-class flares, and 126 X-class flares during solar cycle 23. At the same time, there are also sustained observations of solar X-ray flux from GOES satellites and solar EUV from SOHO satellites since 1996. In this study, we used the 0.1–0.8 nm X-ray flux data and 26–34 nm EUV flux data during these solar flare events to statistically analyze the relationship between the enhancement in X-ray flux and that in EUV flux. The CMD effects on the enhancement in EUV flux are also specially studied during different flares from C-class to X-class. The results also show that the enhancement of EUV flux does not linearly increase with increasing X-ray flux for solar flares from C-class to M-class and to X-class, and its uprising amplitude decreases with increasing X-ray flux. The correlation coefficients between enhancements in EUV and X-ray flux for X, M and C-class flares are only 0.66, 0.58 and 0.54, respectively, which suggests that X-ray flux cannot be used as an index of EUV flux during solar flares. Thus, for studying more accurately solar flare effect on the ionosphere and thermosphere, one needs to use directly EUV flux measurements which are much plenty than before.

[27] The statistical analysis for the X-class flares show the significant limb effect or CMD effect on the EUV flux. This result is consistent with previous studies. In addition, the statistical analysis for the weaker flares including M-class and C-class are carried out. The comparisons among the X-class, M-class, and C-class flares suggest that the CMD effect on the EUV flux decreases with decreasing flare strength; the correlation coefficient (r) between the EUV flux enhancement and values of CMD also decreases with decreasing flare strength.

[28] To check what causes the significant difference of the CMD effect for different class flares. We selected the solar disc images of 19.5nm EUV emission during solar flares from SOHO/EIT. Comparing an image just before the solar flare erupts and an image near the peak time of solar flare, we calculated the percentage contribution to total EUV enhancement from the flare region and from other region. The statistical results show the percentage contribution from other region increases with decreasing flare strength, which might be the main reason for would a weaker CMD effect for the weaker flares, such as M-class and C-class flares.

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