SOLAR EUV AND IONOSPHERIC PARAMETERS: A BRIEF ASSESSMENT.

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ABSTRACT: Percentage changes in Nm, i.e., in $(foF2)^2$ should be the same as percentage changes in solar EUV. If there is a mismatch, it would be attributed to the contributions to Nm of other factors like neutral density, temperature, composition, neutral winds and electric fields, all of which vary with solar EUV. For the AE-E data of 1977-1981, the $(foF2)^2$ values at several locations increased from 1.0 (base level for January 1978) to a peak value ratio of ~2.0 in 1980, while the integrated flux for 18-910 Å appropriate for foF2 changes was ~2.00, just enough for causing the observed foF2 changes. Thus, during 1978-1980, the contribution from other factors must be small, though for the longer interval 1976-1980, *Richards* [2001] reported substantial contribution from other factors. Since 1996, SEM/SOHO has made EUV measurements in the 260-340 Å range. From the solar minimum in 1996 to the solar maximum in 2000, this EUV increased by a factor of only 2.4, but the $(foF2)^2$ at several locations have increased by a factor of 3.0 or more. Thus, in cycle 23, the contribution of other factors to Nm increase must have been substantial. In 27-day sequences of EUV, $(foF2)^2$ did not always show similar fluctuations.

1. Introduction

The Sun emits a wide variety of radiations, originating in different parts (photosphere, chromosphere, chromosphere-transition region, corona) of the solar atmosphere. Solar ultraviolet (UV) irradiance (1150-4200 Å) plays a dominant role in the temperature distribution, photochemistry, and overall momentum balance in the stratosphere, mesosphere, and lower thermosphere. The solar EUV flux, particularly below 130 nm (1300 Å) originates in the chromosphere, in the chromosphere-corona transition region, and in the solar corona [*Donnelly et al*., 1986]. It is the primary cause of ion production in the ionosphere and contributes to the heating of the thermosphere. However, except for some brief periods, there have been very few solar EUV measurements on a daily basis.

Data of solar fluxes (daily values) for several months continuously were obtained by the AE-E satellite from 1977 through 1981. In recent times (1996 onwards), there are SEM/SOHO measurements of EUV in the 1-500 Å band [*Judge et al.* 1998]. Ion production in the terrestrial ionosphere is proportional to the EUV flux, which can be related to the ambient electron density. The loss rate is quadratic for the E region and linear for the F region. Hence productions in the E and F regions are proportional to $(foE)^4$ and $(foF2)^2$ respectively. However, ionization by direct solar flux is not the sole cause of NmF2 changes. Changes can also occur because of changes in neutral density, temperature, composition, neutral winds and electric fields, all of which vary with solar EUV and their relationship with NmF2 may not be linear. Hence, direct proportionality between solar flux and NmF2 is not preserved.

In the past, several workers have examined the correlationships between the variations of solar indices and ionospheric parameters, particularly when EUV and UV data are absent. Whenever EUV fluxes are available, these are used and show high correlations with ionospheric parameters. The first extensive observations of EUV and UV were from AE-E satellite (1977-1981). Soon after the data for 15 wavelengths were published by *Hinteregger et al*. [1981], *Hedin* [1984] used these for studying their relationship with thermospheric density and temperature and found that thermospheric density correlated well with F10.7 cm (2800 MHz), slightly better with the AE-E EUV data *in* *general*, and best with the 255-300 Å band. Thus, a *qualitative* comparison was the main emphasis.

Ionospheric variations can be considered in time scales of (a) Day-to-day, including 27-day, (b) Semiannual, (c) Annual, (d) Solar cycle. In the present communication, examination is made only of the long-term (solar cycle) and short-term (27-day) variations of EUV indices and ionospheric parameters during two major satellite EUV data intervals, namely AE-E data (1977-1981), and recent SEM/SOHO data (1996 onwards, up to date).

2. Data

Most of the data were obtained from the NOAA websites ftp://ftp.ngdc.noaa.gov/STP/ SOLAR_DATA/ and http://spidr.ngdc.noaa.gov/spidr/. For ionospheric data, hourly values were available. However, picking out the noontime values from the 24 hourly values was laborious. Also, the noontime values were not always the maximum, and the maxima often shifted to nearby hours (11-14 LT). On the other hand, daily means (average of 24 hourly values) were easily accessible. A plot of the near-noon (1200 UT to 1400 LT) foF2 and daily average foF2 at the location Grahamstown (33S, 27E) for the interval March-April, 1992 (near peak sunspot activity of cycle 22) showed large day-to-day variations and the correlation between the two series was only ~+0.4. However, when moving averages over 5 consecutive days were calculated, the correlation was very high, ~+0.90. Since for short-term variations, the emphasis will be on 27-day sequences, the 5-day moving averages would smooth the data series and would still be useful to study the 27-day oscillations. Hence, only the daily average values (24-hourly means) and their 5-day moving averages are considered here for short-term studies. For long-term changes, the annual values in 1992 (sunspot maximum) for Grahamstown, when compared to the values in 1996 (sunspot minimum) were 1.61 times (61% above) the 1996 values for noontime foF2 and 1.56 times (56% above) the 1996 values for daily average foF2. Thus, the percentage long-term changes of near-noon foF2 and daily average foF2 are similar within ~5%, justifying the use of daily averages even for quantitative comparisons.

3. EUV from AE-E data (1977-1981)

The AE-E data are in 15 wavelength groups of flux ratios F/F_{ref}, where F is the measured flux for a particular day and wavelength group, while F_{ref} refers to the sunspot minimum reference period July 13-28, 1976 [*Hinteregger et al*., 1981]. The wavelength groups are: 168-190 Å, 190-206 Å, 206-255 Å, 255-300 Å, 304 Å, 510-580 Å, 584 Å, 590-660 Å, 1026 Å, 335 Å, 284 Å, 200-204 Å, 178-183 Å, 169-173 Å, 1216 Å. It was noticed that the daily values of these 15 groups were very highly inter-correlated (correlations exceeding +0.95). Recently, some accurate EUV measurements from sounding rockets during solar cycle 22 (1992-1994) indicated that the irradiances based on the AE-E data could be *underestimates by as much as a factor of 2* at some wavelengths [*Woods et al.,* 2000; *Bailey et. al.,* 2000; *Soloman et al*., 2001]. *Rishbeth* [1993] was aware of these problems, but since his study was limited to a period of two months and dealt only with day-to-day variations, the long-term calibration was not of great concern. For ionospheric studies, a serious problem is the seasonal variation of the various parameters, which is unrelated to solar EUV as such. However, since the study of seasonal variation as such is not envisaged in the present communication, a simple way would be to eliminate the seasonal fluctuations by calculating 12-month moving averages and use these for long-term studies of their association with EUV. In the present analysis of long-term trends, 12-month moving averages of the ionospheric parameters are used, and for uniformity, the EUV values are also subjected to 12-month moving averages.

3.1 Long-term variations

The AE-E data cover the period 1 July 1977 to 10 June 1981 as listed in the file SC#21OBS of *Hinteregger et al*. [1981], and are expressed as *ratios to the reference values* measured in the sunspot minimum period 13-28 July 1976 (beginning of solar cycle 21). Hence, uncertainties in absolute values are of no consequence, but errors due to instrumental drifts may still be there. Figure 1 (upper panel) shows a plot of the fifteen EUV and UV indices. In the procedure of calculating 12-month moving averages, data for 6-7 months in the beginning and in the end are lost. Hence EUV data start centered on January 1978 and end in the end part of 1980. The ratios of the peak values in 1980 to the beginning values of January 1978 are indicated by numbers in parentheses. As can be seen, the ratios are ~1.50 (increases of ~50%), except for EUV in the ranges 190-206 Å, 206-255 Å, 255-300 Å, where the ratios are ~2.0 (increases of ~100%). In the case of some individual lines, the ratios were much higher (2.89 for 284 Å, 3.60 for 335 Å). If the data are not erroneous, these large ratios indicate that at least some lines have much larger variations as compared to the background. Incidentally, the line 304 Å shows only a moderate ratio (1.47).

Figure 1 (middle panel) shows the plots for $(foF2)^2$ for the locations Slough (52N, 1W), Boulder (40N, 105W), Wallops Island (38N, 75W), Ahmedabad (23N, 73E), Kodaikanal (10N, 78E), Grahamstown (33S, 27E) and Port Stanley (52S, 58W). The ratios of the peak value in 1980 to the value of Jan. 1978, are between 1.83 and 2.13, i.e., ~2 for all locations except Kodaikanal near the equator, where the ratio is 1.64 and the peak is in the middle of 1979. Comparing with EUV, it seems that EUV in the narrow wavelength band 190-300 Å has a magnitude of increase (~2) comparable to that of the observed $(foF2)^2$ increases in low and middle latitudes. Considering the possibility that other factors might have contributed to Nm changes, it seems that the contribution of the other factors was not substantial during 1978-1980.

The lower panel of Figure 1 shows the plot of $(foE)^4$ for the location Slough. The ratio with respect to January 1978 is only 1.67. The bottommost plot is for soft X-rays (1-8 Å), and the ratio is very high, 2.82, and the peak of X-rays was much later, in June 1981. For the E region, the relevant X-ray band is 10-200 Å for which data are not available for this interval, but the characteristics would probably be similar to those of 1-8 Å X-rays. Thus, the foE behaviour does not seem to be guided completely by X-rays, qualitatively or quantitatively.

3.2 Short-term variations

For short-term studies, a major problem is lack of continuous data of daily values. Almost every second or third value, or often, data for several days may be missing. For the AE-E data, *Donnelly et al.* [1986] studied the interval November 1979 to February 1980 when AE-E data were found to be comparatively more complete than in previous intervals. Using similarity considerations, the EUV data were grouped into three ranges 168-204 Å, 206-335 Å, 516-660 Å, Lyman beta and Lyman alpha were considered separately, and missing values were interpolated whenever reasonably possible. All these are plotted as the first five top plots in Figure 2. As can be seen, there are three major peaks and a minor peak (all marked by dots) near days 15, 49, 76, 102. The percentage magnitudes of the successive rises and falls are indicated by numbers. The largest magnitudes were for the 206-335 range (e.g., a fall of 108% from day 15 to day 36, and a rise of 75% from day 36 to day 49). In the long-term changes shown in Figure 1, this same wavelength range had the largest magnitude of percentage change, as compared to the other wavelength ranges. The sixth plot in the top panel is for soft X-rays (3-day moving averages) and shows only one very prominent peak near day 15.

The other plots in the middle and lower panels of Figure 2 are for the ionospheric parameters (percentage deviations from mean), for $(foF2)^2$ at Slough, Boulder, Wallops Island, Huancayo (12S, 75W), Kodaikanal, Grahamstown, and Port Stanley, and $(foE)^4$ for Slough. All these have a general, slow decrease from October 1979 to February 1980, indicating the seasonal change, but there are other, much larger changes. The day-to-day fluctuations are large and erratic, the very low values indicating erroneous data. The thick superposed lines are 5-day moving averages. These show some distinct peaks (marked by dots), and the percentage changes from peak to trough and trough to peak are substantial (~50%) in most of the cases. However, these peaks do not always match with the peaks in EUV and UV. Exceptions are $(foF2)^2$ and $(foE)^4$ at Slough, though Slough $(foE)^4$ has one extra peak near day 40. Thus, a matching of the 27-day peaks is seen only at the northern high latitude of Slough (52N) but not at the southern high latitude of Port Stanley (52S). In low latitudes, there are displaced peaks and more in number, with spacings lesser than 27 days. Some of these could be due to the middle-atmospheric planetary waves of tropospheric origin, as was found in the E- and F2-regions above Huancayo (Peru) by *Forbes and Leveroni* [1992], who point out that free Rosby (resonant mode) oscillations with periods 2, 5, 10 and 16 days may regularly penetrate from the stratosphere into the ionosphere/thermosphere. Also, during geomagnetic disturbances, there are ionospheric disturbances with amplitudes of foF2 deviations strongly depending on the velocity of Coronal Mass Ejections [*Scheiner*, 2001] which may or may not have a 27-day oscillation.

4. EUV from SEM/SOHO

The Solar EUV Monitor (SEM) solar extreme ultraviolet (EUV) spectrometer aboard the SOlar and Heliospheric Observatory (SOHO) has been providing the first long-term solar EUV data using a spectrometer specifically designed to be highly stable throughout an extended mission [Judge et al., 1998]). Data are available from December 16, 1995 in two wavelength ranges, 260-340 Å and 1-500 Å.

4.1 Long-term variations

Solar cycle 23 started in 1996 and seems to have peaked in 2000. Figure 3 shows a plot of the 12-month moving averages of the two EUV ranges 260-340 Å and 1-500 Å obtained from SEM/SOHO. The top plot is for the wavelength range 260-340 Å and, compared to the base level of 1.0 in 1996, the value for 2000 (centered on June) shows an increase of 140%. The second plot is for the wider range 1-500 Å and shows a slightly larger increase of 153 %. Thus, some range outside the 260-340 Å range should have percentage increases larger than 153%. It is not possible to identify such a range, as the data are for the whole ranges as such without finer classification. The third plot is for Composite Lyman alpha and shows an increase of only 49%. The fourth plot is for X-rays and shows an enormous increase (20 times, 2000% or more), and the peak occurred earlier, in the end of 1998. These two plots are shown not because these are relevant for the foF2 changes but only for comparison of these solar indices which may affect the E region.

The other plots in Figure 3 are for 12-month moving averages of $(foF2)^2$ at Sofia (43N, 23E), Boulder, Wallops Island, Darwin (12S, 131E), Grahamstown, Hobart (43S, 147E) and Port Stanley. The increase from 1996 to middle of 2000 is ~200 % or more. Thus, the 150% increase of EUV is lesser than the ionospheric $(foF2)^2$ increase. In Figure 1, the largest increases were obtained for 190-300 Å. This range is included in 1-500 Å range, but the percentages might have been diluted by ranges outside the 190-300 Å range. In the absence of data for finer ranges, this problem cannot be resolved. However, there is an indication here that Nm changes (increases) might have had a substantial contribution from the other factors.

4.2 Short-term variations

During the SEM/SOHO data interval 1996-2000, there were several intervals of 27-day sequences, but all had ranges lesser than ~40%. Figure 4 shows the plots of daily values for the interval Mar. 23-July 13, 1999. In the top plots for 260-340 Å and 1-500 Å, the trough to peak percentages are 40% or less. For Lyman alpha (third plot), the percentages are 20% or less, but for X-rays (fourth plot), the percentages exceed 200%. There are four peaks (marked by dots) seen in all these plots. In the plots for $(foF2)^2$ that follow, the first three peaks are reproduced within ~5 days of the EUV peaks at most of the locations. However, the percentage ranges are much higher (40-80%) as compared to the 40% of the EUV ranges. Thus, though the 27-day sequences seem to be reflected in the $(foF2)^2$ reasonably well (better than in the events of Figure 2), the SEM/SOHO EUV magnitudes are lesser than the observed $(foF2)^2$ ranges. One may speculate that for this short interval, there is some direct solar flux influence but the Nm might have been affected by other factors too, in almost the same magnitude (40% of solar flux +40% of influence of other factors = ~80% of Nm change).

5. Conclusions

The purpose of the present study was to examine which EUV ranges of wavelength had magnitudes comparable to ionospheric changes, both long-term (solar cycle) and short-term (27-day sequences).

(a) Long-term changes:

(1) To eliminate complications due to seasonal effects, 12-month moving averages of foF2 were calculated and the resulting $(foF2)^2$ compared with 12-month moving averages of EUV.

(2) For the AE-E data of 1977-1981, the $(foF2)^2$ values at several locations increased from 1.0 (base level for January 1978) to a peak value ratio of ~2.0 in 1980. In this interval, EUV in different wavelength bands showed different ratios, but most of these were below 2.0, with the exception of the band 190-300 Å which showed a ratio of ~2.0. Some individual lines showed still higher ratios (284 Å, 2.89; 335 Å, 3.60). The integrated range 18-910 Å had a ratio of ~2.00, enough to cause long-

term ionospheric $(foF2)^2$ changes. Since Nm $(foF2)^2$ changes can occur because of the changes of other factors like neutral density, temperature, composition, neutral winds and electric fields, all of which vary with solar EUV, it seems that for 1978-1980, the contribution from these other factors was not substantial. However, for the earlier period 1976-1978, the contribution from other factors was substantial [Richards, 2001].

(3) Since 1996, SEM/SOHO has EUV measurements in the 260-340 Å range. From the solar minimum in 1996 to the solar maximum in 2000, this EUV increased by a ratio of ~2.4, but the $(foF2)^2$ at several locations have increased by a factor of 3.0 or more. Thus, the SEM/SOHO EUV changes as such were inadequate for causing the $(foF2)^2$ changes. In this case, the contribution to Nm from other factors (neutral density, temperature, and composition, neutral winds and electric fields, all of which vary with solar EUV) must have been substantial.

(b) Short-term changes:

Two sequences of daily values, each of 112 days, were examined: October 26, 1979-February 15, 1980, and March 23-July 13, 1999. In each, there were strong 27-day oscillations in the solar EUV fluxes. However, these were not well reflected in ionospheric parameters, where peaks were displaced by several days or there were more peaks with spacings less than 27 days, indicating complications due to dynamical and other factors not related to solar activity (e.g., planetary waves).

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Captions for Figures

Fig. 1: Plots of the 12-month moving averages of the EUV values (AE-E data) in different wavelength bands (upper panel), and $(foF2)^2$ (middle panel) and $(foE)^4$ (lower panel), at different locations. January 1978 values are marked with dots, and peak values (mostly in January 1980) are marked with triangles. The numbers in parentheses are the ratios of the 1980 peak values to the January 1978 values.

Fig. 2: Plots of the daily values of the percentage deviations from means, for the 112-day interval October 26, 1979-February 15, 1980. Upper panel, AE-E data series (EUV ranges 168-204 Å, 206-335 Å, 510-660 Å, Lyman beta 1026 Å, Lyman alpha 1216 Å). Middle panel, $(foF2)^2$ at several locations and lower panel, $(foE)^4$ at Slough. The numbers indicate percentage ranges of successive peaks to troughs and troughs to peaks (watch the different vertical scales).

Fig. 3: Plots of the 12-month moving averages of the EUV values (SEM/SOHO EUV, 260-340 Å and 1-500 Å), Composite Lyman alpha (1216 Å**),** X-rays (upper half), and $(foF2)^2$ at different locations (lower half). The numbers indicate percentage variations from 1996 to 2000.

Fig. 4: Plots of the daily values of the percentage deviations from means, for the 112-day interval March 23-July 13, 1999. Upper half, SEM/SOHO EUV (260-340 Å and 1-500 Å), Lyman alpha (1216 Å) and X-rays (1-8 Å). Lower half, $(foF2)^2$ at several locations. The numbers indicate percentage ranges of successive peaks to troughs and troughs to peaks (watch the different vertical scales).