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SOLAR ACTIVITY DURING SOLAR CYCLE 23 MONITORED BY GOME

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ABSTRACT

The daily solar spectral measurements by the Global Ozone Monitoring Experiment (GOME) aboard ERS2 are well suited to track solar activity by looking at irradiance changes in the center of selected Fraunhofer lines. The major modulation of the irradiance changes contain periodicity of about 27-28 days, corresponding to the mean solar rotation period, and eleven years due to solar activity associated with the 22-year magnetic cycle of the sun.

The MgII doublet at 280nm and the CaII K line at around 395nm have been analysed to derive a proxy solar activity indicator time series from GOME starting in July 1995 near the end of the declining phase of solar cycle 22. GOME is currently observing the onset of solar cycle 23. An excellent correlation with solar observations provided by the UARS instrument SUSIM (Solar Ultraviolet Spectral Irradiance Monitor) has been achieved after removing instrumental artefacts such as UV degradation and etaloning from the GOME level-1 spectra. An estimate of solar UV irradiance variability with a change in the GOME MgII index is given.

1. INTRODUCTION

At solar maximum during the 11-yr cycle an increased number of sun spots in the photosphere are observed. Areas with hot plages and faculae in the above lying chromosphere produce an emission core in the center of many Fraunhofer absorption lines. In an earlier paper, it was demonstrated that the Global Ozone Monitoring Experiment's (GOME) solar observations can be used to observe irradiance changes in the center of some Fraunhofer lines, from which a proxy solar activity indicator for UV irradiance changes can be derived (1). Since UV spectral measurements from space usually suffer from UV degradation and drifts in the instrumental response function, the use of proxy solar activity indicators, for instance the MgII core-to-wing ratio, which is more insensitive to longterm drifts, are used to represent solar UV irradiance variability. In the first part of this paper, observations of solar activity by GOME during the inclining phase of solar cycle 23 are reported. The definition of the GOME MgII proxy solar variability index Version 2.0 is also provided.

In order to obtain a statistically significant correlation of atmospheric variability with solar activity a longterm time series is needed covering several solar cycles. The lifetime of a single space instrument, however is generally on the order of five to six years and, therefore, a longterm time series has to be constructed from different satellite experiments. The large data set on MgII indices from different satellite instruments (SBUV Nimbus-7, SBUV2 NOAA-9 and NOAA-11, SUSIM UARS, and GOME ERS2) have been combined to obtain a homogeneous MgII index record starting in 1978 and covering about two solar cycles (2, 3, 4). Since GOME has not yet observed under solar maximum condition yet, SOLSTICE UARS irradiance data (5) have been used to estimate solar variability in the spectral range of 120–400 nm in terms of a 1% increase of the GOME MgII index. Since GOME and SOLSTICE have similar spectral resolution (0.2 nm) in the near UV, the SOLSTICE irradiance changes are expected to be representative of that of GOME (6) and SCIAMACHY (7). This data can be used to model solar output as a function of solar activity.

Solar variability in the 100–300 nm region has among others a significant impact on the ozone and oxygen photochemistry in the upper atmosphere and the energy budget in stratosphere and mesosphere. Correlation of atmospheric parameters with solar activity has provided important insights into the links between solar UV variability and fluctuations observed in the terrestrial atmosphere, for instance total ozone and cloud cover, and climate change (8, 9, 10, 11).

2. SOLAR OBSERVATIONS BY GOME

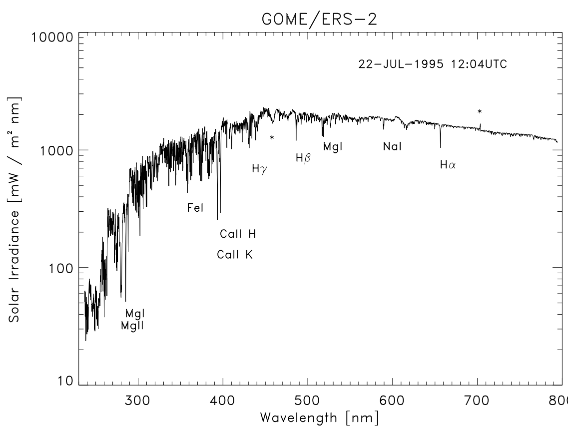

Figure 1: *GOME solar irradiance spectrum from 22 July 1995 (1).*

Once a day and every fourteenth orbit GOME solar irradiance measurements are carried out when the ERS2 satellite crosses the terminator in the North polar region coming from the night side. Since GOME is not equipped to actively track the sun, viewing of the full solar disc via the diffuser plate is only possible for a time span of about

30–50 sec. Integration times are 0.75 sec for all channels, except for the UV channel, where the integration time is doubled. A mean solar spectrum is constructed from the series of measurements during full disc solar viewing. A solar mean GOME irradiance spectrum recorded on 22 July 1995 is shown in Fig. 1. The spectral resolution varies between 0.2 nm in the UV and 0.4 nm in the visible (6). The boundaries between the four spectral channels are near 315 nm, 400 nm, and 600 nm and the asterisks marks an instrumental artefact, for instance the Wood anomaly in channel 4 (600–800nm). Some of the prominent Fraunhofer lines are marked in Fig. 1.

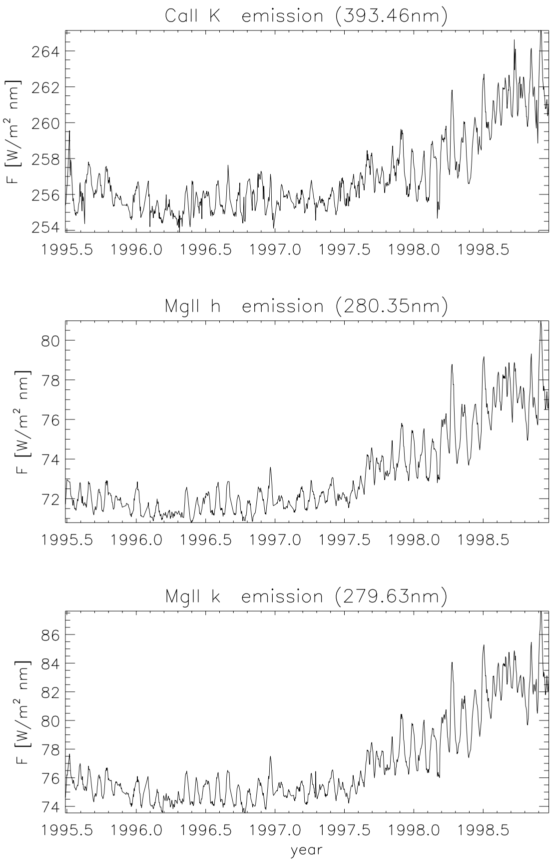

Figure 2: *Irradiance time series of the emission peaks of the CaII K (393.46nm), Mg II k and h Fraunhofer absorption line centres (279.63nm and 280.35nm) during the period between 28 June 1995 and 22 December 1998.*

3. SOLAR IRRADIANCE CHANGES OBSERVED BY GOME

In Fig. 2 the GOME time series of the peak emission of the MgII k and h peaks at 279.63 nm and 280.35 nm, respectively, and the CaII K peak at 393.46 nm are shown. The intensity time series shows a modulation with periodicity of about 27 days, which corresponds to the disc averaged solar rotation period. This can be explained by the lighthouse effect, where active regions are moved in and out of the field of view of the satellite and earth. As the solar activity started to increase after summer 1996 the Fraunhofer line center emission has increased until the end of December 1998 by about 6 $W/m^2 \cdot nm$ from 255 $W/m^2 \cdot nm$ in the case of CaII k and 10 and 6 $W/m^2 \cdot nm$ for the k and h lines of MgII from an average of 74 and 72 $W/m^2 \cdot nm$, respectively, during solar minimum. Although the emission peaks of these three Fraunhofer lines can not be resolved in the GOME spectrum, the emission in the core of some of the solar Fraunhofer lines are clearly detectable.

Since no dynamic inflight calibration of the GOME spectral irradiance data (GOME Level-1 data) for instrument drifts and UV degradation has been introduced yet, an indirect recalibration procedure has been applied to remove these artefacts from the time series. One has to keep in mind that the primary purpose of GOME is the derivation of atmospheric trace species concentrations from the sun-normalised radiance spectra, where some of the instrumental effects are cancelled by ratioing the earthshine radiance by the extraterrestrial irradiance. The most important instrumental effects are in the order of importance, first, the shifting etalon patterns with some sudden abrupt changes, particularly after accidental cooler switching in the detector arrays, and the longterm UV degradation due to extended exposure to the harmful radiation in space, from which many UV measuring space borne sensors suffer. These corrections are described in the following Section.

4. UV DEGRADATION AND ETALON CORRECTION

The absolute radiometrically calibrated average solar irradiance spectrum from the Shuttle SBUV (SSBUV8) experiment in January 1997 (12) has been used to determine a GOME UV degradation correction factor from the SSBUV8/GOME irradiance ratio (see Fig. 3).

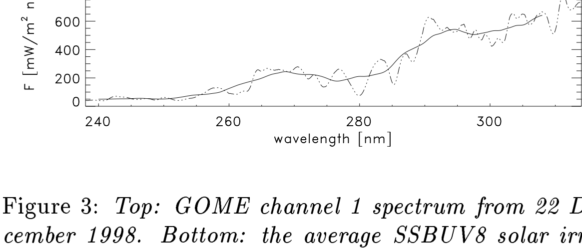

Figure 3: *Top: GOME channel 1 spectrum from 22 December 1998. Bottom: the average SSBUV8 solar irradiance recorded at a spectral resolution of ≈1 nm. Both spectra have been smoothed with a 10 nm wide boxcar (solid lines) to remove differences due to the instrument response functions and to smear out the natural variability in the narrow centres of the Fraunhofer lines.*

A polynomial fitted to the low resolution SSBUV8/GOME irradiance ratio provides the GOME UV degradation correction factor as a function of wavelength. A UV degradation of 55% at 240 nm and 17% at 280 nm has been observed during the 2-year period between January 1997 and December 1998 (see Fig. 4, top).

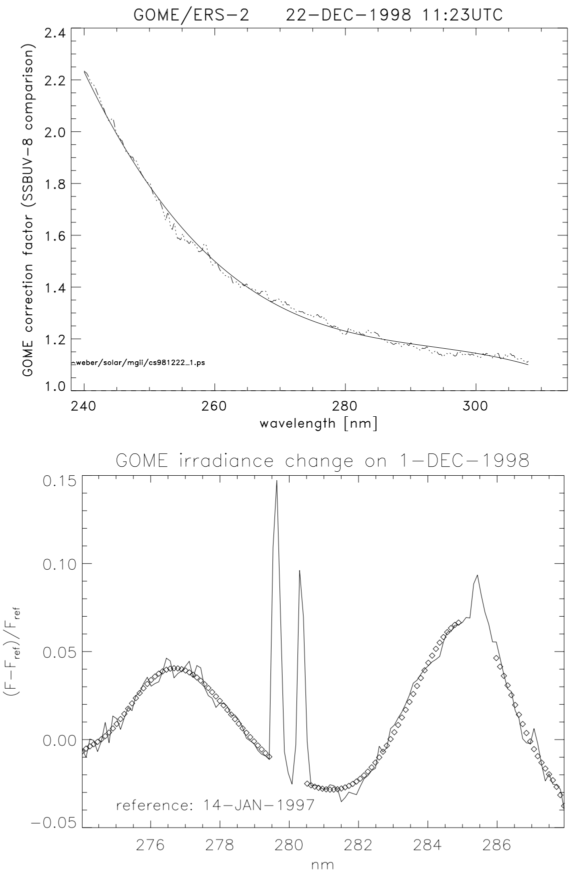

Figure 4: *Top: A polynomial (solid curve) fitted to the GOME/SSBUV8 low resolution ratio (dashed curve) determines the GOME UV degradation correction factor. Bottom: Spurious etalon patterns with periods corresponding to the thickness of the SiO_2 coating of the detector array appear in the GOME irradiance ratios. The fitted polynomial (diamonds) provides the etalon correction. Small intervals surrounding the Fraunhofer line centres (280nm and 285nm) are excluded from the fit. F_{ref} is the GOME irradiance from 14 January 1997.*

In the SSBUV8/GOME solar irradiance ratio, etalon fringes have been detected. From solar irradiance ratios of successive GOME measurements fringe amplitudes of several percent can be found. Particularly after accidental turn off of the Peltier elements which cool the detector array, sudden shifts in amplitudes and wavelengths of the etalon fringes were frequently observed. The fringes show periodicities corresponding to that of a 3μm Fabry-Perot etalon. The SiO_2 coating on the detector arrays is a possible candidate with the required thickness. After cooler switching and a subsequent warm-up a small ice layer may condense on the coating which may change the finesse of the Fabry-Perot (alteration of the internal reflectivity and changes in the fringe amplitudes). The observed fringes have been fitted to a polynomial, which then provides the etalon correction. The maximum degree of the polynomial is selected such that adding a term in the fitted polynomial does not improve the standard deviation of the multivariate regression by more than 10% (see Fig. 4 bottom). Without the etalon correction sharp discontinuities would appear in the time series such as shown in Fig. 2.

The solar irradiance correction procedure is done in consecutive steps, the UV degradation correction is applied first followed by the etalon correction. At the moment this instrument correction should not be viewed as an absolute calibration procedure, but it proves that is suffices to obtain an internal consistent data set, such as the peak emission (Fig. 2) or MgII index (next Section) over an extended time period.

5. GOME MGII SOLAR ACTIVITY INDEX

The MgII index Version 2.0 is derived from the daily mean solar spectrum (GOME Channel 1), which is part of the official GOME level-1 data product. At 280nm the GOME spectral resolution is about 0.17nm (sampling interval of 0.11nm). A UV degradation and etalon fringe corrections has been applied before deriving the MgII core-to-wing ratio (see Section 4).

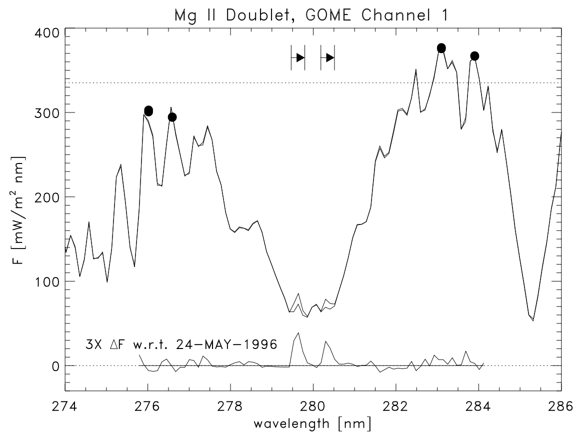

Figure 5: *The MgII doublet at 280nm recorded by GOME on 24 May 1996 (solar minimum) and on 1 December 1998 (inclining phase of solar cycle 23). The difference between the two spectra is shown scaled in the bottom and clearly shows the enhanced line center emission of the doublet peaks in early December 1998. The reference background line as determined from the average of the four wing values and the two micro windows at the centre of the two peaks are also indicated.*

The wing value or background reference is defined as the mean of the maxima of four parabolas fitted thru the data pixels 335-339 (275.79-276.23nm), 340-344 (276.34-276.79nm), 400-403 (282.92-283.25nm), and 407-411 (283.69-284.12nm) as shown in Fig. 5. The core value is given by the sum of the integrated intensities of the emission core line profile of the h and k doublet peaks. First, the centre wavelength of the k line profile is determined by finding the maximum of the cubic spline interpolant. The integrated intensity is derived by integrating the spline around this centre plus and minus the FWHM of the instrumental response function which is 1.5 times the sampling interval. The centre of the h emission core is determined by adding 0.7175nm to the k line centre. The ratio of the core (sum of integrated emission intensities) to the wing value (continuum) then defines the MgII index. The Version 2.0 definition is more similar to Version 10 of SOLSTICE (13) and Version 19r3 of SUSIM (4) and leads to a slightly improved signal-to-noise ratio and better wavelength stability.

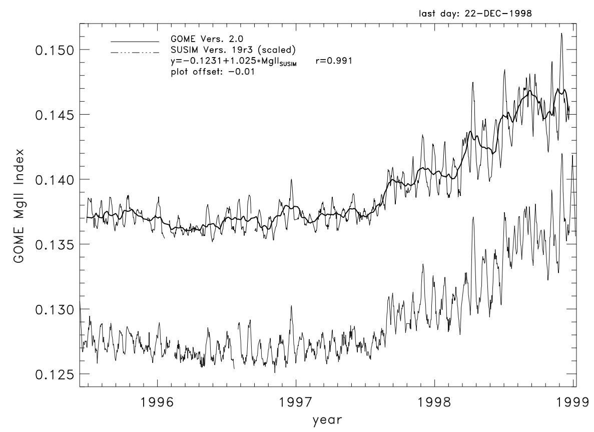

Figure 6: *The GOME MgII Index Version 2.0 time series starting 28 June 1995. The smooth solid line is a 27 day running average. The corresponding MgII core-to-wing ratio Version 19r3 derived from the SUSIM/UARS experiment, which has been scaled to the GOME value range, is shown with an offset in the bottom for comparison (4).*

In Fig. 6 the GOME MgII index time series starting end of June 1995, three months after launch of ERS2 is depicted. GOME was launched at the very end of the declining phase of solar cycle 22 and is now observing the increasing solar activity of solar cycle 23 which is documented by the increase in the MgII index. In the bottom of Fig. 6 the scaled SUSIM UARS Version 19r3 MgII index is shown (plotted with an offset for better clarity). The correlation coefficient between both time series is 0.991 and can be considered excellent. Since the MgII index is a relative index (core-to-wing ratio), its value is strongly dependent on the instrumental resolution and the definition of the core-to-wing ratio. The scaling of the SUSIM Version 19r3 MgII index can be achieved with the following relation $y = -0.1231(11) + 1.0246(43) \cdot \mathrm{MgII}_{SUSIM}$, where the digits in the brackets are the uncertainty in the last two digits of the linear regression coefficients. The high correlation between SUSIM and GOME demonstrate that GOME can be used in conjunction with other space instruments to provide a continuous longterm time series. It also justifies the simple calibration correction applied as described in the previous section.

6. SOLAR CYCLE UV IRRADIANCE VARIATION

Although the GOME observations have been limited to three and a half year (about a third of a typical solar cycle length), the high correlation between the GOME and SUSIM MgII index shows already great promises that GOME and the next generation of European space sensors such as SCIAMACHY and GOME Metop will be able to continue solar observations well in the coming two decades and complement other dedicated solar observation platforms planned in the near future. In Fig. 7 a composite MgII index has been constructed by successive scaling time series from a series of space experiments to that of GOME (2). This time series covers almost two complete solar cycles and shows what GOME might have measured if it had been in operation for twenty years. From solar minimum to solar maximum the GOME MgII index would be expected to increase by about 20% if the coming solar cycle has the intensity of solar cycle 22. Currently the actual index has climbed 12% and is approximately halfway to the next solar maximum expected to peak in 2001.

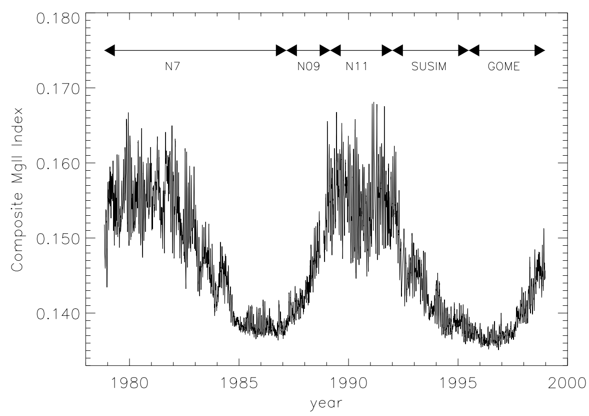

Figure 7: *Combining the MgII index time series from SBUV/Nimbus7 (N7), SBUV2/NOAA9 (N9), SBUV2/NOAA11 (N11), and SUSIM/UARS a composite MgII index spanning more than two solar cycles has been constructed (see text for details).*

In the following the matching and scaling procedure for the SBUV Nimbus7, SBUV2 NOAA9 and NOAA11 discrete mode V2.0, and SUSIM UARS V. 19r3 and GOME V. 2.0 index time series (14, 3, 4) into a composite GOME MgII index is described. The longest time series has been provided by the SBUV2 NOAA9, which starts in May 1986 and whose latest processed data set Version 2.0x lasts until September 1997. This data covers an entire solar cycle (from minimum to minimum). For this reason the low resolution instrument time series from SBUV, SBUV2, and SUSIM (spectral resolution of about 1 nm) were first scaled to the value range from the NOAA9 instrument by linear regression. In their respective overlap regions the correlation coefficient between these time series and NOAA9 are 0.887, 0.994, and 0.984, respectively. The low correlation between Nimbus7 and NOAA9 is explained by the short overlap available for the regression, which was during solar minimum following solar cycle 21 (May 1986–March 1987), where the variability is smallest and the correlation weaker.

The various scaled data sets were joined into the

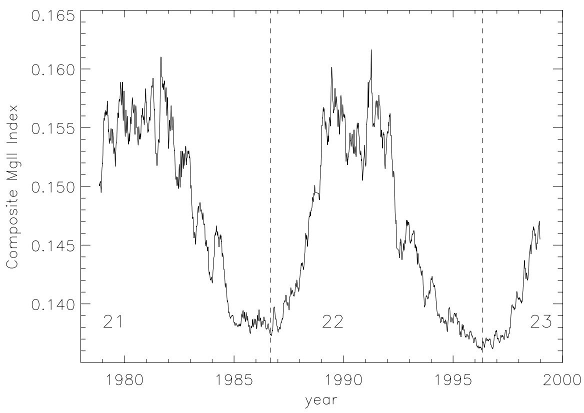

Figure 8: *The composite Mg II index smoothed with a 27 day running average. Solar cycles 22 and 23 started in September 1986 and May 1996, respectively, where the number of sunspots in a 13-month smoothed time series reaches its minimum value (see http://www.dxlc.com/solar/cyclcomp.html).*

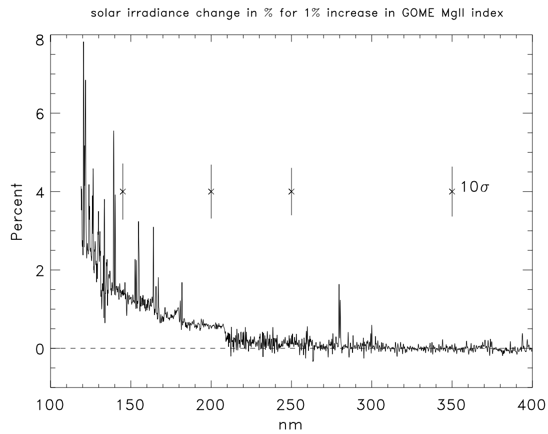

Figure 9: *Wavelength dependent UV irradiance changes in percent for a 1% change in the composite MgII index as derived from SOLSTICE UARS solar data (5). The 10σ error is indicated by the error bars, which have been plotted with an offset for better clarity. The irradiance changes in the near UV are representative of those expected for GOME and SCIAMACHY, since they have similar spectral resolution.*

composite index set as follows: 7 November 1978 - 28 February 1987 (Nimbus 7), 1 March 1987 - 28 February 1989 (NOAA9), 1 March 1989 - 31 December 1991 (NOAA11), 1 January 1992 - 27 June 1995 (SUSIM), and 28 June 1995 - 22-DEC-1998 (GOME). The final scaling of the low resolution composite index was done by linear regression of the NOAA9 scaled SUSIM time series to the high resolution GOME time series. In Fig. 8 the composite MgII index smoothed with a 27-day running average is shown.

Figure 9 depicts the wavelength dependent UV irradiance variation for a 1% change in the GOME MgII V. 2.0 index. Since GOME has not measured under solar maximum condition, the SOLSTICE irradiance data (5) from four representative days (2-FEB-1992 MgII=0.1624, 29-MAR-1992 0.1511, 15-APR-1993 0.1418, 2-JAN-1995 0.1373) covering various phases of the solar cycle from maximum to minimum have been fitted to a straight line as a function of the composite MgII index value. The slope provides the ratio of solar irradiance change at a given wavelength to a change in the MgII index. Since GOME and SCIAMACHY have similar spectral resolution in the near UV than SOLSTICE (≈0.24 nm), the irradiance changes in Fig. 9 are representative of expected changes in the GOME and SCIAMACHY spectral irradiancea. The SOLSTICE data also provides information in the 120–240nm region not covered by GOME and SCIAMACHY.

7. CONCLUSION

This work has demonstrated that despite a lack of an absolute inflight recalibration the GOME solar observations can be utilised to derive a time series of a proxy solar activity indicator for longterm studies of solar-terrestrial interaction studies. The series of European sensors starting with GOME, SCIAMACHY ENVISAT (launch in 2000) and the second generation GOME2 (launch in 2003) and GOME3 (2008) aboard the METOP series will provide continuation in observation in solar activity throughout the entire solar cycle 23 and the beginning of solar cycle 24. However, sufficient overlap between different space missions are a prerequisite in establishing a longterm record of solar variability by cross correlation, which exceeds the lifetime of a single space instrument.

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