Contents

Chapter 3
Investigation of solar irradiance variations and their impact on middle atmospheric ozone

M. Weber, J. Pagaran, S. Dikty, C. von Savigny, J. P. Burrows, M. DeLand, L. E. Floyd, J. W. Harder, M. G. Mlynczak, H. Schmidt

Abstract The satellite spectrometer SCIAMACHY aboard ENVISAT is a unique instrument that covers at a moderately high spectral resolution the entire optical range from the near UV (230 nm) to the near IR (2.4μm) with some gaps above 1.7μ. This broad spectral range allows not only the retrieval of several atmospheric trace gases (among them ozone), cloud and aerosol parameters, but also regular daily measurements of the spectral solar irradiance (SSI) with an unprecedented spectral coverage. The following studies were carried out with irradiance and ozone data from SCIAMACHY: a) SCIAMACHY SSI was compared to other solar data from space and ground as well as with SIM/SORCE (Solar Irradiance Monitor, the only other satellite instrument daily measuring the visible and near IR, in order to verify the quality of the SCIAMACHY measurements, b) an empirical solar proxy model, in short the SCIA proxy model, was developed that permits expressing the SCIA-

---

Mark Weber, Joseph Pagaran, Sebastian Dikty, Christian von Savigny, and John P. Burrows
Institute of Environmental Physics, University of Bremen FB1, PO Box 330 440, D-28334 Bremen, Germany e-mail: weber@uni-bremen.de

Matt T. DeLand
Science System and Applications, Inc (SSAI), 10210 Greenbelt Road, Suite 600, Lanham, MD 20706 e-mail: matthew.deland@ssaihq.com

Jerry W. Harder,
Laboratory for Atmospheric and Space Physics (LASP), University of Colorado, 1234 Innovation Drive, Boulder, CO 80303, USA e-mail: jerry.harder@lasp.colorado.edu

Linton E. Floyd
Interferometrics Inc., 13454 Sunrise Valley Drive, Herndon, Virginia, VA 20171, USA e-mail: linton4@gmail.com

Martin G. Mlynczak
NASA Langley Research Center, Hampton, VA 23681-2199, USA e-mail: m.g.mlynczak@nasa.gov

Hauke Schmidt
Max-Planck-Institute for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany e-mail: hauke.schmidt@zmaw.de

MACHY SSI variations by fitting solar proxies for faculae brightening and sunspot darkening, which then allows investigation of solar variability on time scales beyond the instrument life time, e.g. 11-year solar cycle, c) solar cycle SSI variations derived from empirical models (Lean2000, SATIRE, SCIA proxy) and different observations (SBUV composite, SUSIM) were compared for the three most recent solar cycles 21-23, and d) SCIAMACHY ozone limb profiles were analysed to derive signatures of the 27-day solar rotation on stratospheric ozone. Our studies were complemented by investigations of daytime variations in mesospheric ozone (here data from SABER/TIMED), which were compared to results from the HAMMONIA chemistry climate model.

3.1 Introduction

Regular daily space-borne satellite SSI monitoring started in 1978. The wavelength coverage of early SSI measurements from different satellite instruments was generally limited to below 400 nm (UV), where the largest variations occur over an 11-year solar cycle (*Rottman et al.*, 2004). A limiting factor for many space spectrometers measuring in the UV is the optical degradation due to hard radiation that makes it challenging to maintain the accuracy over the instrument lifetime which rarely extends to more than a decade (*DeLand et al.*, 2004). In order to derive estimates for SSI variations over an entire 11-year solar cycle or more one needs to rely on a SSI timeseries composed of different instruments (UV composite) as done for the UV spectral range (*DeLand and Cebula*, 2008) or use solar proxies, like the Mg II index, that are well correlated with irradiance changes over a large spectral range to extrapolate beyond the instrumental lifetime (*DeLand and Cebula*, 1993; *Viereck et al.*, 2001).

Daily observations of the visible and near-IR started with the three channel SPM (Sun Photometer) of VIRGO/SOHO (1996-2010) at selected wavelength bands (*Fröhlich et al.*, 1997) and were continued with GOME/ERS-2 (Global Ozone Monitoring Experiment) since 1995, covering 240–800 nm (*Weber et al.*, 1998; *Burrows et al.*, 1999), SCIAMACHY/ENVISAT (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) since 2002, covering 220nm - 2.4μm (*Bovensmann et al.*, 1999), and SIM/SORCE (Solar Irradiance Monitor) since 2003, 240nm–3μm (*Harder et al.*, 2005a,b). In Fig. 3.1 a sample SCIAMACHY solar irradiance spectrum is shown. Compared to the UV region, daily irradiance measurements simultaneously covering the UV, visible, and the near IR do not cover yet a complete solar cycle. One of the important scientific question is what are the irradiance changes in the visible and near IR during 27-day solar rotations and can we use this information to extrapolate to changes during the 11-year solar cycle.

SCIAMACHY is primarily an atmospheric sounder measuring several trace gases in nadir (column amounts) and limb viewing geometry (vertical profiles) (*Bovensmann et al.*, 2011). Global vertical profiles are measured by SCIAMACHY and cover the altitude range from the tropopause to about 70 km altitude (*von Savi-

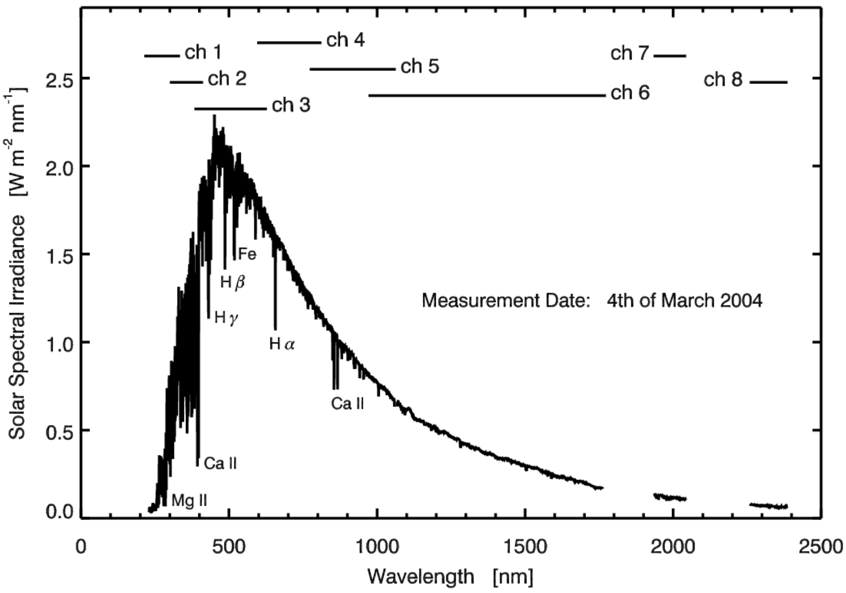

Fig. 3.1 SCIAMACHY full disc solar spectrum measured on March 4, 2004. The eight spectral channels varying in spectral resolution from 0.2 nm to 1.5 nm are indicated. The gaps near 1850 nm as well as 2200 nm are not measured by SCIAMACHY since terrestrial water vapor absorption saturates in the atmospheric observation mode. From *Pagaran et al.* (2009). Reproduced by permission of the AAS.

gny et al., 2005; *Sonkaew et al.*, 2009). The influence of irradiance variations related to the 27-day mean solar rotation period on upper stratosphere ozone can be investigated using SCIAMACHY ozone data. The upper stratosphere above 30 km is chemically controlled and an immediate radiative influence on the photochemistry is expected (e.g. *Gruzdev et al.*, 2009; *Fioletov*, 2009). In this study for the first time a wavelet analysis was applied to study the 27-day signature in ozone. This permits the investigation of the time-varying frequency content of the ozone signal.

The non-polar orbit of the TIMED satellite (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) carrying the SABER instrument (Sounding of the Atmosphere using Broadband Emission Radiometry) (*Russell III et al.*, 1999) permits the study of daytime variations in mesospheric ozone that are significantly larger than the 27-day and solar cycle related changes observed in the upper stratosphere (*Huang et al.*, 2008). In this study the daytime variation of mesospheric ozone were compared for the first time with the output of a chemistry climate model (*Dikty et al.*, 2010a).

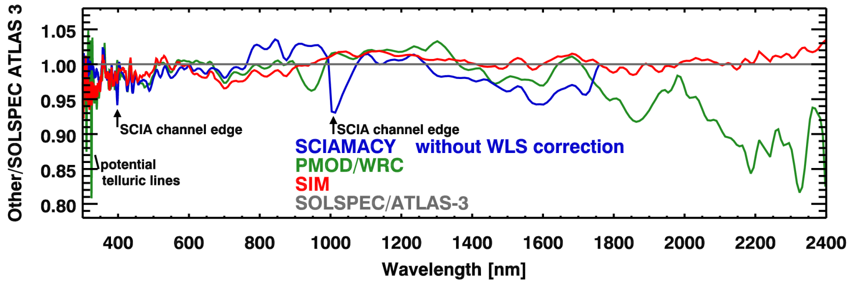

Fig. 3.2 SSI ratios of SCIAMACHY, SIM (*Harder et al.*, 2010), and PMOD/WRC (WRC85) composite (*Wehrli*, 1985) with respect to the SOLSPEC/ATLAS-3 shuttle experiment data (*Thuillier et al.*, 2004). Close to the channel boundaries of the SCIAMACHY instrument larger deviations are observed due to instrumental artifacts. From *Pagaran et al.* (2011a). Reproduced with permission ©ESO.

3.2 SCIAMACHY spectral solar irradiance

SCIAMACHY is a passive remote sensing double spectrometer combining a predispersing prism and eight gratings in separate channels. Silicon and InGaAs detectors are used as linear arrays with 1024 pixels each in Channels 1-5 (UV/visible) and Channels 6-8 (near IR), respectively. A detailed description of SCIAMACHY can be found in *Bovensmann et al.* (1999) and *Pagaran et al.* (2009).

Radiometrically calibrated SSI has been measured by SCIAMACHY since July 2002 once a day. A sample spectrum from March 2004 is shown in Fig. 3.1. The SCIAMACHY SSI has been compared with solar data from other satellites and measurements from the ground (*Skupin et al.*, 2005a,b; *Pagaran et al.*, 2011a). Figure 3.2 shows the comparison of SCIAMACHY with SIM (*Harder et al.*, 2010), the SOLSPEC/ATLAS-3 shuttle experiment (*Thuillier et al.*, 2004), and the PMOD/WRC (WRC85) composite (*Wehrli*, 1985). The PMOD/WRC composite (200 nm –10 μm) was derived from various spectra obtained from aircraft, rocket, and balloon experiments as well as ground data from *Neckel and Labs* (1984). SCIAMACHY agrees to within 5% (SIM within 4%) with the SOLSPEC data from 300 to 1600 nm (*Pagaran et al.*, 2011a). The theoretical precision is usually in the range of 2-3% based upon radiometric standards (*Bovensmann et al.*, 1999). A more comprehensive comparison also to other solar data can be found in *Pagaran et al.* (2011a).

In later years of the SCIAMACHY mission the optical degradation in the UV due to the hard radiation environment in space is evident. The agreement of SCIAMACHY with other solar data can be improved when using the white light lamp (WLS) source as a degradation correction, however, the corrections are too strong since WLS itself is optically degrading and therefore this type of correction cannot be applied to the more recent SCIAMACHY data (*Pagaran et al.*, 2011a). Further investigations are underway to improve upon the in-flight radiometric calibration. For atmospheric studies this is generally not a problem since the degradation cancels out in the sun-normalized earth radiances used in most atmospheric retrievals.

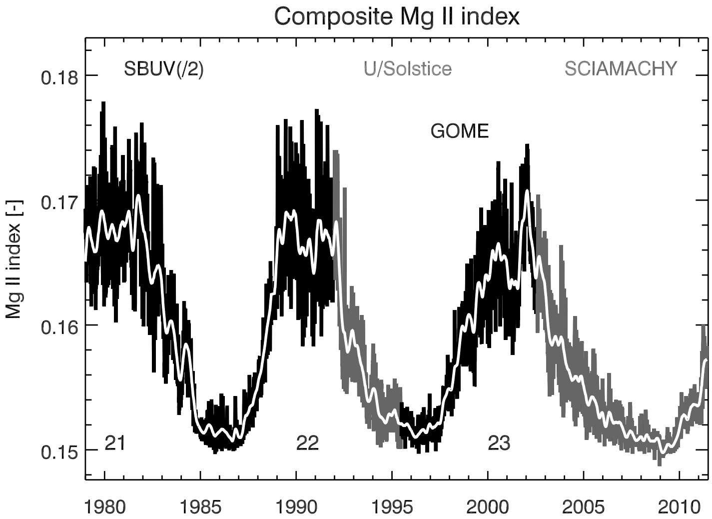

Fig. 3.3 Composite Mg II index measured near 280 nm derived from multiple satellite data and extending from solar cycle 21 to 24. In addition to SBUV(/2), UARS/Solstice, GOME, and SCIAMACHY as indicated here, other data such as SUSIM, the more recent SBUV/2 instruments from NOAA-16 to NOAA-18 as well as SORCE/Solstice have been used to fill daily gaps. The smooth white line shows the low-pass filtered time series by applying a 55-day triangular filter to remove the 27-day solar rotation signature.

The Mg II core to wing ratio derived from the Mg II Fraunhofer lines at 280 nm (Fig. 3.1) is an index that has been proven to correlate well with UV irradiance changes down to 30 nm (*DeLand and Cebula*, 1993; *Viereck et al.*, 2001). It is a measure for the chromospheric activity of the sun and describes the plage and faculae brightening responsible for the UV increase. The Mg II index, defined as a ratio, is insensitive to instrumental degradation and has been derived from many different instruments to provide a long-term time series going back to the late 1970s (*DeLand and Cebula*, 1993; *Viereck and Puga*, 1999; *Viereck et al.*, 2004). An updated composite Mg II index by adding the GOME (*Weber et al.*, 1998; *Weber*, 1999) and recent SCIAMACHY data is shown in Fig. 3.3. It seems that the Mg II index was lower during the recent solar minimum in 2008 than the two solar minima before, but this is not statistically significant. A potential lower solar minimum value could be expected from the very low thermospheric density observed in 2008 (*Emmert et al.*, 2010). Solar irradiance at extreme ultraviolet (EUV) wavelengths heats the thermosphere, causing it to expand. Low EUV irradiance contracts the thermosphere and decreases the density at a given altitude. The cooling of the upper atmosphere due to increases of greenhouse gases can only explain part of the recent contraction observed (*Emmert et al.*, 2010; *Solomon et al.*, 2011).

3.3 Irradiance variations from solar rotations to several solar cycles

In order to estimate SSI irradiance variations beyond the instrument lifetime and covering several decades a model was developed that uses solar proxies scaled to SCIAMACHY SSI observations. The underlying assumption is that irradiance variations are mainly caused by solar surface magnetic activity (*Fligge et al.*, 2000) and can be expressed in terms of faculae brightening as represented by the Mg II index and sunspot darkening as expressed by the photometric sunspot index (PSI), here taken from *Balmaceda et al.* (2009). The SSI can then be written as a time series as follows

$$I_\lambda(t) = I_\lambda(t_o) + a_\lambda\,[P_a(t) - P_a(t_o)] + b_\lambda[P_b(t) - P_b(t_o)] + p_\lambda(t), \tag{3.1}$$

where $P_a(t)$ and $P_b(t)$ are the Mg II index and PSI time series, respectively. A similar approach was used to model UV irradiance variations derived from UARS/Solstice (*Lean et al.*, 1997).

A multivariate linear regression is performed to determine the regression coefficients of the solar proxies. In addition to the two solar proxy terms piecewise polynomials, $p_\lambda(t)$, are used to correct for instrument degradation and small jumps following instrument and satellite platform anomalies (*Pagaran et al.*, 2009). The regression was applied to SCIAMACHY SSI time series over several solar rotations during 2003 and 2004. Regression coefficients, a_λ and b_λ, were determined from 240 nm to 1750 nm (SCIAMACHY channels 1 to 6) in steps of 10 nm (*Pagaran et al.*, 2009). As a solar reference spectrum, $I_\lambda(t_0)$, the SCIAMACHY SSI from March 4, 2004, (Fig. 3.1) was selected.

The modeled and observed SCIAMACHY solar irradiance change is shown as an example in Fig. 3.4 during the Halloween 2003 solar storm, where the PSI index value reached the lowest value since 1980 and substantial mesopsheric ozone loss (mainly due to solar protons) was observed by SCIAMACHY (*Rohen et al.*, 2005). The combined faculae and sunspot contributions and SCIAMACHY observations are in qualitative agreement with Figure 6 in *Lean et al.* (2005). Across the near-UV, vis, and near-IR spectral range solar irradiance dropped by 0.3% (near-IR) to 0.5% (near-UV). This is consistent with a drop of about 0.4% in the total solar irradiance (TSI) or solar constant. Below 300 nm an irradiance enhancement due to faculae activity was observed reaching +1.3% near 250 nm.

The SCIAMACHY irradiance timeseries as well as the SCIA proxy model show the dark faculae effect in the spectral region 1400–1600 nm (near opacity H^- minimum), where both sunspot and faculae contributions are negative in agreement with observations from ground indicating a darkening under enhanced solar activity conditions (*Moran et al.*, 1992). The SCIA proxy model, nevertheless, underestimates the observed irradiance depletion in this spectral region.

The SCIA proxy model can be used to reconstruct spectral irradiance changes since the late 1970s, where the Mg II index record started, covering nearly three solar cycles. From the SCIA proxy model the UV contribution below 400 nm to TSI

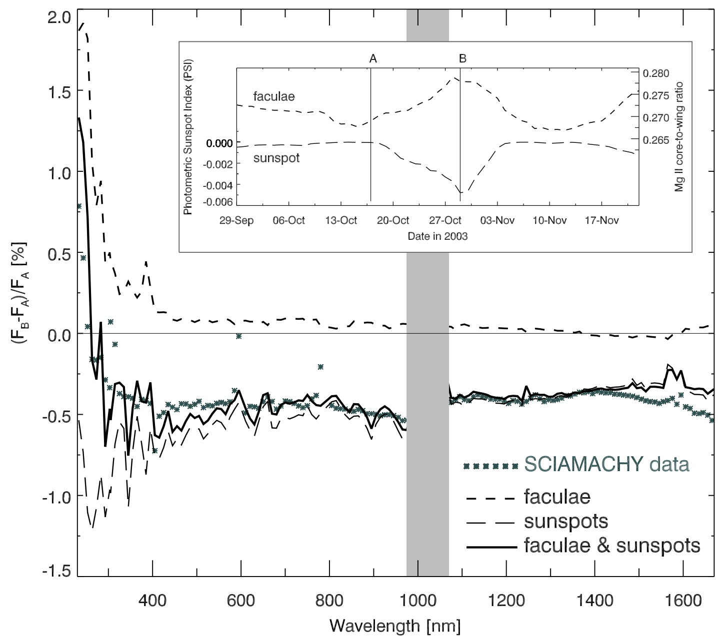

Fig. 3.4 Modeled and observed SCIAMACHY solar irradiance change during the Halloween solar storm in 2003 decomposed into faculae and sunspot contributions.The inset shows the Mg II and PSI index with labels A and B indicating dates from which irradiance differences were derived. From *Pagaran et al.* (2009). Reproduced by permission of the AAS.

changes in solar cycle 23 ($\sim$0.1%) is 55% (*Pagaran et al.*, 2009) which is higher than the 30% estimate from solar cycle 22 derived from SOLSTICE observations (*Lean et al.*, 1997) and lower than the 63% derived from the semi-empirical model SATIRE (Spectral and Total Irradiance Reconstructions) (*Krivova et al.*, 2006).

The largest TSI change contribution comes from the near UV (300-400 nm), where the irradiance solar cycle change per wavelength is well below 1% (*Pagaran et al.*, 2009). During solar cycles 21 to 23, the dominant contribution to irradiance changes in the UV from solar minimum to maximum comes from the faculae brightening. The sunspot contribution is non-negligible in the near UV and in the visible cancels within the error bars the faculae brightening (see Fig. 3.5, *Pagaran et al.* (2009, 2011b)). The dark faculae near 1400–1600 nm are again evident at solar maximum in agreement with observations by SIM and results from the SATIRE model (*Unruh et al.*, 2008).

Harder et al. (2009) reported on SIM irradiance changes during the descending phase of solar cycle 23 (April 2004 to November 2007) and found UV changes that are much larger than models like the NRLSSI irradiance model (*Lean*, 2000) indicate. This is also true when comparing to other data sets as shown in Fig. 3.6 where the comparison is extended to the SCIA proxy model, the SATIRE model (*Krivova et al.*, 2009), and the UV composite from *DeLand and Cebula* (2008) as

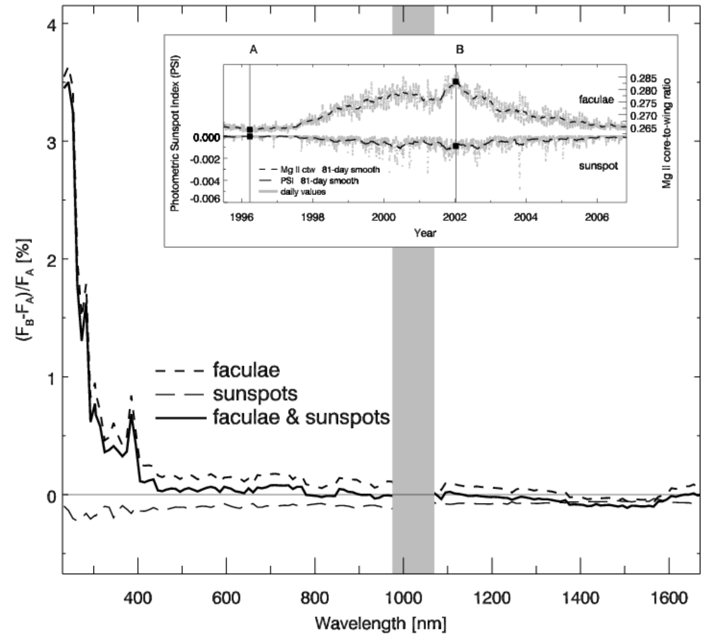

Fig. 3.5 Solar irradiance variations during solar cycle 23 as derived from SCIAMACHY observations and proxy data. Solar maximum and minimum dates were defined by the 81 day boxcar smooth of Mg II index timeseries (inset). Contributions from faculae and sunspots are indicated. From *Pagaran et al.* (2009). Reproduced by permission of the AAS.

well. Also shown in this figure are the comparison of irradiance changes during the descending phase of prior solar cycles with similar Mg II index change as in solar cycle 23 (*Pagaran et al.*, 2011b).

It appears that current models including the SCIA proxy model that assume that irradiance changes are mostly related to surface magnetic activity are underestimating solar cycle changes in the UV as compared to the SIM observations. Direct observations from SUSIM and the UV composite also see larger UV changes during solar cycle 22 than the models, but are still only about half of SIM's result for solar cycle 23. Such a large UV change as observed by SIM has strong implications on radiative forcing in the upper atmosphere (*Haigh et al.*, 2010; *Oberländer et al.*, 2012) and will remain a matter of debate.

3.4 Solar rotation (27-day) signature in stratospheric ozone

The solar variation on the 11-year time scale has been shown to cause 2-3% variability in tropical ozone at altitudes of approximately 40 km. This has been concluded from different satellite observations (e.g. *Remsberg*, 2008; *Fioletov*, 2009, and ref-

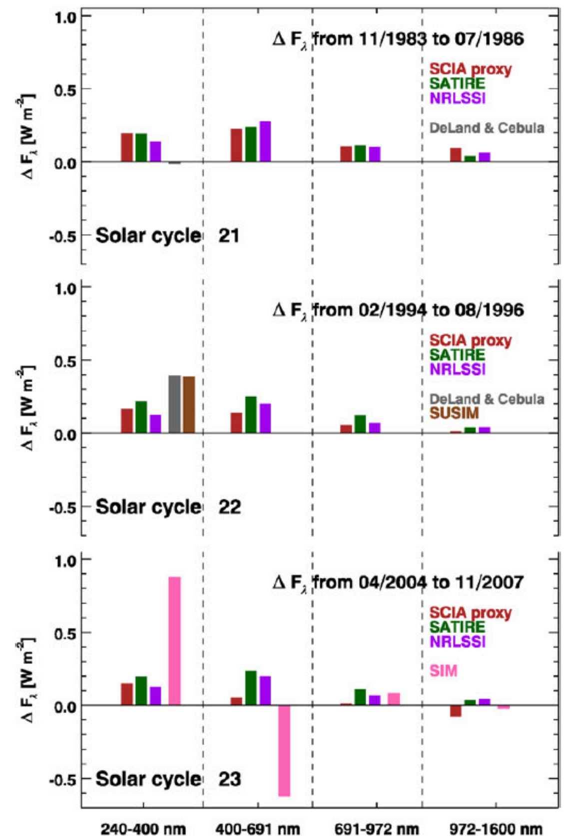

Fig. 3.6 SSI changes during part of the descending phase of solar cycles 21 to 23 (top to bottom), respectively. Dates near solar maximum and minimum are chosen in such a way that the differences between the Mg II indices are about the same in each solar cycle and correspond to that of the SIM observation period used here. NRLSSI (*Lean*, 2000), SATIRE (*Krivova et al.*, 2009) and SCIA proxy are models. SUSIM, SIM, and UV composite from *DeLand and Cebula* (2008) are direct satellite observations. From *Pagaran et al.* (2011b).

erences therein) and was confirmed by model studies (e.g. *Langematz et al.*, 2005; *Sekiyama et al.*, 2006; *Marsh et al.*, 2007). The influence of the 27-day solar rotation on ozone was first investigated by *Hood* (1986) in the 1980s using SBUV ozone measurements. He found the ozone sensitivity at 45 km to be slightly more than 0.4% per 1% change in the 205 nm flux. Further investigations with different satellite data sets and model outputs covering other time periods followed (*Gruzdev et al.*, 2009; *Fioletov*, 2009, and references therein). *Austin et al.* (2007) and *Gruzdev et al.* (2009) compared the 27-day ozone variability determined by chemistry climate models (CCM) with satellite measurements and were able to verify the observations in magnitude (0.4 to 0.5 %/%) but found the maximum ozone sensitivity slightly lower in altitude (approx. 40 km) in the model simulations.

The motivation for this study is to use the new dataset that is available from SCIAMACHY, e.g. global ozone profiles during the descending phase of solar cycle 23 (*von Savigny et al.*, 2005; *Sonkaew et al.*, 2009). Continuous wavelet transform (CWT), fast Fourier transform (FFT), and cross correlations (CC) have been applied to SCIAMACHY ozone in the tropics (<20° latitude) between 20 and 60 km altitude (*Dikty et al.*, 2010b). The maximum correlation between the Mg II index and ozone

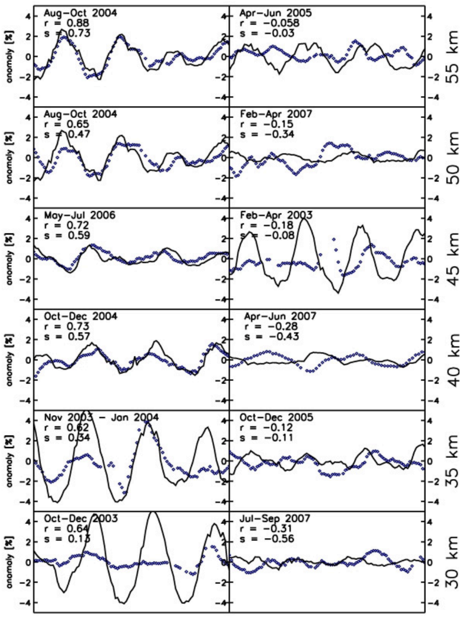

Fig. 3.7 Selected three month periods with high (left panels) and low correlation (right panels) between ozone (solid line) and Mg II index (circles). In each panel, the period, correlation (r), and ozone sensitivity (s) is indicated, the latter is defined as the ozone change per Mg II index change in units of %/%. The ozone sensitivity per unit 205 nm solar irradiance change is obtained by multiplying s with 0.61. From *Dikty et al.* (2010b). Reproduced by permission of American Geophysical Union. ©2010 American Geophysical Union.

is weaker during the maximum of solar cycle 23 ($r = 0.38$) than in the previous two solar cycles that have been investigated in earlier studies using different data sets. This is in agreement with results from *Fioletov* (2009).

The magnitude of the ozone signals is highly time dependent as revealed by the CWT analysis and may vanish for several solar rotations even close to solar maximum conditions (see Fig. 3.7). The ozone sensitivity (ozone change in percent per percent change in 205 nm solar flux) is on average about 0.2%/% above 30 km altitude and smaller by about a factor of two compared to earlier studies. For selected three month periods the sensitivity may rise beyond 0.6%/% in better agreement with earlier studies. The analysis of the 27-day solar forcing was also carried out with stratospheric temperatures from the European Centre for Medium-Range Weather Forecasts operational analysis. Although direct radiation effects on temperature are weak in the upper stratosphere, temperature signals with statistically significant periods in the 25–35 day range similar to ozone were found (*Dikty et al.*, 2010b).

3.5 Daytime variations in mesospheric ozone

In comparison with the 27-day solar rotation signal and the 11-year solar cycle response in the stratosphere, the diurnal and daytime variation of UV radiation inflicts a by far greater response in upper atmosphere ozone. The response of ozone above 60 km to variations in UV radiation is less well established. Ozone and temperature data from SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) in its version 1.07 (*Russell III et al.*, 1999) are used to study the daytime pattern of mesospheric ozone. In contrast to SCIAMACHY, SABER aboard TIMED flies in a more inclined orbit allowing measurements at different local times. In our study (*Dikty et al.*, 2010a) a specific sampling of SABER data was preformed to derive daytime pattern in tropical ozone using both the results from the 1.27μ air glow (*Mlynczak et al.*, 2007) and 9.6μm thermal emission retrieval (*Rong et al.*, 2008). Compared to the earlier study on daytime variations by *Huang et al.* (2008) more years of SABER data were used and our results were compared to HAMMONIA (Hamburg Model of the Neutral and Ionized Atmosphere) (*Schmidt et al.*, 2006).

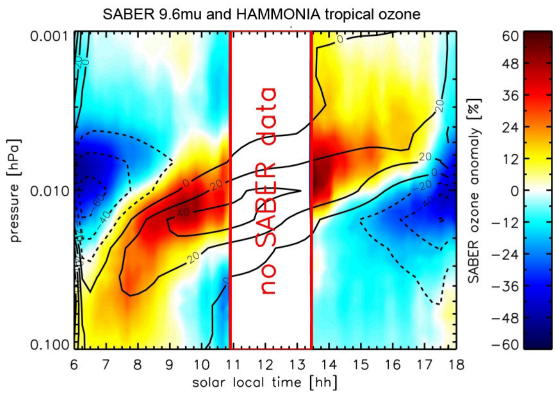

Fig. 3.8 SABER observations at 9.6μm (color) and HAMMONIA model (contour) daytime ozone variations between 0.1 and 0.001 hPa expressed as percent deviation from the daytime mean. From *Dikty et al.* (2010a).

The amplitude of daytime ozone variations is approximately 60% of the daytime mean for SABER and lower for the model (see Fig. 3.8). The agreement with HAMMONIA is generally better for the 9.6μm retrieved ozone data than for the 1.27μm air glow retrieval (*Dikty et al.*, 2010a). The maximum daytime peak anomaly observed at 0.05 hPa (~70 km) in the morning shifts its altitude to about 0.007 hPa (~80 km) in the afternoon. This daytime shift is in very good agreement with the model, however the peak anomaly reaches a maximum of 40–50% of the daytime mean, which is higher than HAMMONIA (30–40%). Negative anomalies are observed in the early morning hours at 0.007 hPa and in the late afternoon near 0.015 hPa in quite good agreement with the model. During equinox the daytime maximum ozone abundance is higher than during solstice, especially above 0.01 hPa (approx. 80 km). The seasonal variation is somewhat weaker in HAMMONIA.

In contrast to ozone, temperature data from SABER (*Remsberg et al.*, 2008) show little daytime variations between 65 and 90 km and their amplitudes are less than 1.5%, suggesting photochemistry playing a dominant role in the mesospheric ozone chemistry. *Marsh et al.* (2002) proposed that the solar diurnal tide brings down atomic oxygen for ozone production in the afternoon (>85 km). The model, however, underestimates ozone in the afternoon above approximately 0.01 hPa, so the remaining difference could be attributed to solar tides. The minimum early in the morning is caused by the direct photolysis of ozone before enough atomic oxygen is produced to counteract the ozone destruction. The ozone rise in the morning hours may also be due to tides transporting ozone rich air from below (*Marsh et al.*, 2002). The new SABER version 1.08 data will also include water vapor, which will be helpful to constrain the HO_x budget and its influence on daytime ozone.

3.6 Conclusion

SCIAMACHY was the first satellite instrument providing daily spectral solar irradiances (SSI) from the UV, visible and near infrared. The comparisons with other solar data from space and ground showed good agreement to within a few percent up to 1700 nm (*Skupin et al.*, 2005a,b; *Pagaran et al.*, 2011a). Expressing SCIAMACHY irradiance variations over several solar rotations in terms of solar proxies for sunspot darkening and faculae brightening permits the extrapolation of SCIAMACHY SSI variations to the 11-year solar cycle scales (*Pagaran et al.*, 2009, 2011b). It was shown that about half of the 0.1% change in the solar constant over solar cycle 23 has originates from the visible and IR spectral region (*Pagaran et al.*, 2009). A particular challenge is the solar cycle variation estimate for the near UV (300-400 nm), where recent SIM observations (*Harder et al.*, 2009) indicate changes during solar cycle 23 that are much higher than expected from indirect SCIAMACHY observations and other empirical models (assuming solar surface magnetic activity as primary driver for SSI variations) as well as observations from other satellite data in earlier solar cycles cycles (*Pagaran et al.*, 2011b).

SCIAMACHY limb ozone vertical profiles from 2003 to 2008 were analyzed for signatures of the 27-day solar rotation. It was found that this signature is highly variable in time and that even under solar maximum condition this signal can vanish for several months (*Dikty et al.*, 2010b). On average the sensitivity above 30 km is a 0.2% ozone change per percent change in the 205 nm solar flux (important for ozone production) near solar maximum, which is smaller than found in earlier studies and prior solar cycles.

Daytime variations in tropical mesospheric ozone yield changes of up to 60% from the daytime mean based upon SABER ozone data and peak anomalies are generally higher during equinox. SABER results were compared for the first time with an output of a chemistry climate model, here the HAMMONIA model (*Dikty et al.*, 2010a). SABER ozone from the 9.6μm retrieval agrees qualitatively very well with HAMMONIA, however, little agreement was found between modeled and SABER temperatures above 0.01 hPa. The low temperature variations of a few degree during daytime may suggest that photochemical processes are the main driver for daytime ozone variations and to a lesser degree transport related to tides.

Acknowledgements The support by the DFG research project SOLOZON (DFG WE 3647/1-1) within the German CAWSES priority program and the support by the State of Bremen is gratefully acknowledged. The authors JP, MW, LEF, and GWH were part of the International Space Studies

Institute (ISSI) team on spectral solar irradiance (http://www.issibern.ch/teams/solarspect/), whose meetings and discussions have greatly benefitted this work.

References

Austin, J., L. L. Hood, and B. E. Soukharev (2007), Solar cycle variations of stratospheric ozone and temperature in simulations of a coupled chemistry-climate model, *Atmos. Chem. Phys.*, *7*, 1693–1706.

Balmaceda, L. A., S. K. Solanki, N. A. Krivova, and S. Foster (2009), A homogeneous sunspot areas database covering more than 130 years, *J. Geophys. Res.*, *114*, A7104, doi:10.1029/2009JA014299.

Bovensmann, H., J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, and A. P. H. Goede (1999), SCIAMACHY: Mission objectives and measurement modes, *J. Atmos. Sci.*, *56*, 127–150.

Bovensmann, H., I. Aben, M. van Roozendael, S. Kühl, M. Gottwald, C. von Savigny, M. Buchwitz, A. Richter, C. Frankenberg, P. Stammes, M. de Graaf, F. Wittrock, M. Sinnhuber, B.-M. Sinnhuber, A. Schönhardt, S. Beirle, A. Gloudemans, H. Schrijver, A. Bracher, A. V. Rozanov, M. Weber, and J. P. Burrows (2011), SCHIAMACHY's view of the changing earth's environment, in *SCIAMACHY - Exploring the Changing Earth's Atmopshere*, edited by M. Gottwald and H. Bovensmann, chap. 10, Springer, Dordrecht, doi:10.1007/978-90-481-9896-2.

Burrows, J. P., M. Weber, M. Buchwitz, V. Rozanov, A. Ladstätter-Weißenmayer, A. Richter, R. Debeek, R. Hoogen, K. Bramstedt, K.-U. Eichmann, M. Eisinger, and D. Perner (1999), The Global Ozone Monitoring Experiment (GOME): Mission concept and first scientific results, *J. Atmos. Sci.*, *56*, 151–175.

DeLand, M. T., and R. P. Cebula (1993), Composite Mg II solar activity index for solar cycles 21 and 22, *J. Geophys. Res.*, *98*, 12,809–12,823.

DeLand, M. T., and R. P. Cebula (2008), Creation of a composite solar ultraviolet irradiance data set, *J. Geophys. Res.*, *113*, A11,103, doi:10.1029/2008JA013401.

DeLand, M. T., L. E. Floyd, G. J. Rottman, and J. Pap (2004), Status of UARS solar UV irradiance data, *Adv. Space Res.*, *34*, 243–250.

Dikty, S., H. Schmidt, M. Weber, C. von Savigny, and M. G. Mlynczak (2010a), Daytime ozone and temperature variations in the mesosphere: a comparison between SABER observations and HAMMONIA model, *Atmos. Chem. Phys.*, *10*, 8331–8339, doi:10.5194/acp-10-8331-2010.

Dikty, S., M. Weber, C. von Savigny, T. Sonkaew, A. Rozanov, and J. P. Burrows (2010b), Modulations of the 27-day solar cycle signal in stratospheric ozone from SCIAMACHY, *J. Geophys. Res.*, *115*, D00,115, doi:10.1029/2009JD012379.

Emmert, J. T., J. L. Lean, and J. M. Picone (2010), Record-low thermospheric density during the 2008 solar minimum, *Geophys. Res. Lett.*, *37*, L12,102, doi:10.1029/2010GL043671.

Fioletov, V. E. (2009), Estimating the 27-day and 11-year solar cycle variations in tropical upper stratospheric ozone, *J. Geophys. Res.*, *114*, D02,302, doi: 10.1029/2008JD010499.

Fligge, M., S. K. Solanki, and Y. C. Unruh (2000), Modelling irradiance variations from the surface distribution of the solar magnetic field, *Astron. Astrophys*, *353*, 380–388.

Fröhlich, C., C. A. Crommelynck, C. Wehrli, M. Anklin, S. Dewitte, A. Fichot, W. Finsterle, A. Jiménez, A. Chevalier, and H. Roth (1997), In-flight performance of the Virgo solar irradiance instruments on SOHO, *Sol. Phys.*, *175*, 267–286.

Gruzdev, A. N., H. Schmidt, and G. P. Brasseur (2009), The effect of the solar rotational irradiance variation on the middle and upper atmosphere calculated by a three-dimensional chemistry-climate model, *Atmos. Chem. Phys.*, *8*, 1113–1158.

Haigh, J. D., A. R. Winning, R. Toumi, and J. W. Harder (2010), An influence of solar spectral variations on radiative forcing of climate, *Nature*, *467*, 696–699, doi:10.1038/nature09426.

Harder, J. W., G. Lawrence, J. Fontenla, G. Rottman, and T. Woods (2005a), The Spectral Irradiance Monitor: Scientific requirements, instrument design, and operation modes, *Sol. Phys.*, *230*, 141–167, doi:10.1007/s11207-005-5007-5.

Harder, J. W., J. Fontenla, G. Lawrence, T. Woods, and G. Rottman (2005b), The Spectral Irradiance Monitor: Measurement equations and calibration, *Sol. Phys.*, *230*, 169–204, doi:10.1007/s11207-005-1528-1.

Harder, J. W., J. M. Fontenla, P. Pilewskie, E. C. Richard, and T. N. Woods (2009), Trends in solar spectral irradiance variability in the visible and infrared, *Geophys. Res. Lett.*, *36*, 7801, doi:10.1029/2008GL036797.

Harder, J. W., G. Thuillier, E. C. Richard, S. W. Brown, K. R. Lykke, M. Snow, W. E. McClintock, J. M. Fontenla, T. N. Woods, and P. Pilewskie (2010), The SORCE SIM solar spectrum: Comparison with recent observations, *Sol. Phys.*, *263*, 3–24, doi:10.1007/s11207-010-9555-y.

Hood, L. L. (1986), Coupled stratospheric ozone and temperature response to short-term changes in solar ultraviolet flux: An analysis of Nimbus 7 SBUV and SAMS data, *J. Geophys. Res.*, *91*, 5264s–5276.

Huang, F. T., H. Mayr, J. M. Russell III, M. G. Mlynczak, and C. A. Reber (2008), Ozone diurnal variations and mean profiles in the mesosphere, lower thermosphere, and stratosphere, based on measurements from SABER on TIMED, *J. Geophys. Res.*, *113*, A04,307, doi:10.1029/2007JA012739.

Krivova, N. A., S. K. Solanki, and L. Floyd (2006), Reconstruction of solar uv irradiance in cycle 23, *Astron. Astrophys*, *452*, 631–639, doi:10.1051/0004-6361:20064809.

Krivova, N. A., S. K. Solanki, T. Wenzler, and B. Podlipnik (2009), Reconstruction of solar UV irradiance since 1974, *J. Geophys. Res.*, *114*, D00I04, doi: 10.1029/2009JD012375.

Langematz, U., J. L. Grenfell, K. Matthes, P. Mieth, M. Kunze, B. Steil, and C. Brühl (2005), Chemical effects in 11-year solar cycle simulations with the Freie Universität Berlin Middle Atmospheric Model with online chemistry (FUB-CMAM-CHEM), *Geophys. Res. Lett.*, *32*(L13803), doi:10.1029/2005GL022686.

Lean, J., G. Rottman, J. Harder, and G. Kopp (2005), SORCE contributions to new understanding of global change and solar variability, *Sol. Phys.*, *230*, 27–53, doi:10.1007/s11207-005-1527-2.

Lean, J. L. (2000), Evolution of the sun's spectral irradiance since the Maunder minimum, *Geophys. Res. Lett.*, *16*, 2425–2428.

Lean, J. L., G. J. Rottman, H. L. Kyle, T. N. Woods, J. R. Hickey, and L. C. Puga (1997), Detection and parameterization of variations in solar mid- and near-ultraviolet radiation (200-400 nm), *J. Geophys. Res.*, *102*, 29,939–29,956.

Marsh, D. R., W. R. Skinner, A. R. Marshall, P. B. Hays, D. A. Ortland, and J.-H. Yee (2002), High Resolution Doppler Imager observations of ozone in the mesosphere and lower thermosphere, *J. Geophys. Res.*, *107*, 4390, doi:10.1029/2001JD001505.

Marsh, D. R., R. R. Garcia, D. E. Kinnison, B. A. Boville, F. Sassi, S. C. Solomon, and K. Matthes (2007), Modelling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, *J. Geophys. Res.*, *112*(D23306), doi:10.1029/2006JD008306.

Mlynczak, M. G., B. T. Marshall, F. J. Martin-Torres, J. M. Russel III, R. E. Thompson, E. E. Remsberg, and L. L. Gordley (2007), Sounding of the Atmosphere using Broadband Emission Radiometry observations of daytime mesospheric $O_2(^1\Delta)$ 1.27 μm emission and derivation of ozone, atomic oxygen, and solar and chemical energy deposition rates, *J. Geophys. Res.*, *112*, D15,306, doi:10.1029/2006JD008355.

Moran, T., P. Foukal, and D. Rabin (1992), A photometric study of faculae and sunspots between 1.2 and 1.6 micron, *Sol. Phys.*, *142*, 35–46.

Neckel, H., and D. Labs (1984), The solar radiation between 3300 and 12500Å, *Sol. Phys.*, *90*, 205–258.

Oberländer, S., U. Langematz, K. Matthes, M. Kunze, A. Kubin, J. Harder, N. A. Krivova, S. K. Solanki, J. Pagaran, and M. Weber (2012), The influence of spectral solar irradiance data on stratospheric heating rates during the 11 year solar cycle, *Geophys. Res. Lett.*, *39*, L01,801, doi:10.1029/2011GL049539.

Pagaran, J., M. Weber, and J. P. Burrows (2009), Solar variability from 240 to 1750 nm in terms of faculae brightening and sunspot darkening from SCIAMACHY, *Astron. J.*, *700*, 1884–1895.

Pagaran, J., G. Harder, M. Weber, L. Floyd, and J. P. Burrows (2011a), Intercomparison of SCIAMACHY and SIM vis-IR irradiance over several solar rotational timescales, *Astron. Astrophys*, *528*, A67, doi:10.1051/0004-6361/201015632.

Pagaran, J., M. Weber, M. DeLand, L. Floyd, and J. P. Burrows (2011b), Solar spectral irradiance variations in 240-1600 nm during the recent solar cycles 21-23, *Sol. Phys.*, *XX*, XX–XX.

Remsberg, E. E. (2008), On the response of Halogen Occultation Experiment (HALOE) stratospheric ozone and temperature to the 11-year solar cycle forcing, *J. Geophys. Res.*, *113*(D22304), doi:10.1029/2008JD010189.

Remsberg, E. E., B. T. Marshall, M. Garcia-Comas, D. Krueger, G. S. Lingenfelser, J. Martin-Torres, M. G. Mlynczak, J. M. Russel III, A. K. Smith, Y. Zhao, C. Brown, L. L. Gordley, M. J. Lopez-Gonzales, M. Lopez-Puertas, C.-Y. She, M. J. Taylor, and R. E. Thompson (2008), Assesment of the quality of the Version 1.07 temperature-versus-pressure profiles of the middle atmosphere from TIMED/SABER, *J. Geophys. Res.*, *113*, D17,101, doi:10.1029/2008JD010013.

Rohen, G., C. von Savigny, M. Sinnhuber, E. J. Llewellyn, J. W. Kaiser, C. H. Jackman, M.-B. Kallenrode, J. Schröter, K.-U. Eichmann, H. Bovensmann, and J. P. Burrows (2005), Ozone depletion during the solar proton events of October/November 2003 as seen by SCIAMACHY, *J. Geophys. Res.*, *110*, A09S39, doi:10.1029/2004JA010984.

Rong, P. P., J. M. Russell III, M. G. Mlynczak, E. E. Remsberg, B. T. Marshall, L. L. Gordley, and M. Lopez-Puertas (2008), Validation of TIMED/SABER v1.07 ozone at 9.6 μm in the altitude range 15-70 km, *J. Geophys. Res.*, *114*, D04,306, doi:10.1029/2008JD010073.

Rottman, G., L. Floyd, and R. Viereck (2004), Measurement of solar ultraviolet irradiance, *Geophys. Mono.*, *41*, 111–125, doi:10.10219/141GM10.

Russell III, J. M., M. G. Mlynczak, L. L. Gordley, J. J. Tansock Jr., and R. W. Esplin (1999), Overview of the SABER experiment and preliminary calibration results, *Proc. SPIE*, *3756*(277), doi:10.1117/12.366382.

Schmidt, H., G. P. Brasseur, M. Charron, E. Manzini, M. A. Giorgetta, T. Diehl, V. I. Fomichev, D. Kinnison, D. Marsh, and S. Walters (2006), The HAMMONIA Chemistry climate model: Sensitivity of the mesopause region to the 11-year solar cycle and CO_2 doubling, *J. Climate*, *19*, 3903–3931.

Sekiyama, T. T., K. Shibata, M. Deushi, K. Kodera, and J. L. Lean (2006), Stratospheric ozone variation induced by the 11-year solar cycle: Recent 22-year simulation using 3-D chemical transport model with reanalysis data, *Geophys. Res. Lett.*, *33*(L17812), doi:10.1029/2006GL026711.

Skupin, J., S. Noël, M. W. Wuttke, M. Gottwald, H. Bovensmann, M. Weber, and J. P. Burrows (2005a), SCIAMACHY solar irradiance observation in the spectral range from 240 to 2380 nm, *Adv. Space Res.*, *35*, 370–375, doi: 10.1016/j.asr.2005.03.036.

Skupin, J., M. Weber, S. Noël, H. Bovensmann, and J. P. Burrows (2005b), GOME and SCIAMACHY solar measurements: Solar spectral irradiance and Mg II solar activity proxy indicator, *Mem. Soc. Astron. Ital.*, *76*, 1038–1041.

Solomon, S. C., L. Qian, L. V. Didkovsky, R. A. Viereck, and T. N. Woods (2011), Causes of low thermospheric density during the 2007-2009 solar minimum, *J. Geophys. Res.*, *116*, doi:10.1029/2011JA016508, in press.

Sonkaew, T., V. V. Rozanov, C. von Savigny, A. Rozanov, H. Bovensmann, and J. P. Burrows (2009), Cloud sensitivity studies for stratospheric and lower mesospheric ozone profile retrievals from measurements of limb scattered solar radiation, *Atmos. Meas. Tech.*, *2*, 653–678, doi:10.5194/amt-2-653-2009.

Thuillier, G., L. Floyd, T. N. Woods, R. Cebula, E. Hilsenrath, M. Hersé, and D. Labs (2004), Solar irradiance reference spectra, in *Solar Variability and its Effects on Climate. Geophysical Monograph 141*, vol. 141, edited by J. M. Pap,

P. Fox, C. Fröhlich, J. K. H. S. Hudson, J. McCormack, G. North, W. Sprigg, and S. T. Wu, pp. 171–194.

Unruh, Y. C., N. A. Krivova, S. K. Solanki, J. W. Harder, and G. Kopp (2008), Spectral irradiance variations: comparison between observations and the SATIRE model on solar rotation time scales, *Astron. Astrophys*, *486*, 311–323, doi: 10.1051/0004-6361:20078421.

Viereck, R. A., and L. C. Puga (1999), The NOAA Mg II core-to-wing solar index: Construction of a 20-year times series of chromospheric variability from multiple satellites, *J. Geophys. Res.*, *104*, 9,995–10,005.

Viereck, R. A., L. Puga, D. McMullin, D. Judge, M. Weber, and W. K. Tobiska (2001), The Mg II index: A proxy for solar EUV, *Geophys. Res. Lett.*, *28*, 1343–1346.

Viereck, R. A., L. E. Floyd, P. C. Crane, T. Woods, B. G. Knapp, G. Rottman, M. Weber, L. C. Puga, and M. T. DeLand (2004), A composite Mg II index spanning from 1978 to 2003, *Space Weather*, *2*, S10,005.

von Savigny, C., A. Rozanov, H. Bovensmann, K.-U. Eichmann, S. Noël, V. V. Rozanov, M. Weber, J. P. Burrows, and J. W. Kaiser (2005), The ozone hole breakup in September 2002 as seen by SCIAMACHY on ENVISAT, *J. Atmos. Sci.*, *62*, 721–734.

Weber, M. (1999), Solar Activity during solar cycle 23 monitored by GOME, in *ESA-WPP 1999: European Symposium on Atmospheric Measurements from Space, Proc. ESAMS '99*, *ESA Special Publication*, vol. 161, pp. 611–616, ESA Publications Division, Nordwijk.

Weber, M., J. P. Burrows, and R. P. Cebula (1998), GOME solar uv/vis irradiance measurements between 1995 and 1997 - First results on proxy solar activity studies, *Sol. Phys.*, *177*, 63–77.

Wehrli, C. (1985), Extraterrestrial solar spectrum, *Tech. rep.*, Physikalisch-Meteorologisches Observatorium, World Radiation Center (PMO/WRC), Publication No. 615.

References

Austin, J., L. L. Hood, and B. E. Soukharev (2007), Solar cycle variations of stratospheric ozone and temperature in simulations of a coupled chemistry-climate model, *Atmos. Chem. Phys.*, *7*, 1693–1706.

Balmaceda, L. A., S. K. Solanki, N. A. Krivova, and S. Foster (2009), A homogeneous sunspot areas database covering more than 130 years, *J. Geophys. Res.*, *114*, A7104, doi:10.1029/2009JA014299.

Bovensmann, H., J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, and A. P. H. Goede (1999), SCIAMACHY: Mission objectives and measurement modes, *J. Atmos. Sci.*, *56*, 127–150.

Bovensmann, H., I. Aben, M. van Roozendael, S. Kühl, M. Gottwald, C. von Savigny, M. Buchwitz, A. Richter, C. Frankenberg, P. Stammes, M. de Graaf, F. Wittrock, M. Sinnhuber, B.-M. Sinnhuber, A. Schönhardt, S. Beirle, A. Gloudemans, H. Schrijver, A. Bracher, A. V. Rozanov, M. Weber, and J. P. Burrows (2011), SCHIAMACHY's view of the changing earth's environment, in *SCIAMACHY - Exploring the Changing Earth's Atmopshere*, edited by M. Gottwald and H. Bovensmann, chap. 10, Springer, Dordrecht, doi:10.1007/978-90-481-9896-2.

Burrows, J. P., M. Weber, M. Buchwitz, V. Rozanov, A. Ladstätter-Weißenmayer, A. Richter, R. Debeek, R. Hoogen, K. Bramstedt, K.-U. Eichmann, M. Eisinger, and D. Perner (1999), The Global Ozone Monitoring Experiment (GOME): Mission concept and first scientific results, *J. Atmos. Sci.*, *56*, 151–175.

DeLand, M. T., and R. P. Cebula (1993), Composite Mg II solar activity index for solar cycles 21 and 22, *J. Geophys. Res.*, *98*, 12,809–12,823.

DeLand, M. T., and R. P. Cebula (2008), Creation of a composite solar ultraviolet irradiance data set, *J. Geophys. Res.*, *113*, A11,103, doi:10.1029/2008JA013401.

DeLand, M. T., L. E. Floyd, G. J. Rottman, and J. Pap (2004), Status of UARS solar UV irradiance data, *Adv. Space Res.*, *34*, 243–250.

Dikty, S., H. Schmidt, M. Weber, C. von Savigny, and M. G. Mlynczak (2010a), Daytime ozone and temperature variations in the mesosphere: a comparison between SABER observations and HAMMONIA model, *Atmos. Chem. Phys.*, *10*, 8331–8339, doi:10.5194/acp-10-8331-2010.

Dikty, S., M. Weber, C. von Savigny, T. Sonkaew, A. Rozanov, and J. P. Burrows (2010b), Modulations of the 27-day solar cycle signal in stratospheric ozone from SCIAMACHY, *J. Geophys. Res.*, *115*, D00,115, doi:10.1029/2009JD012379.

Emmert, J. T., J. L. Lean, and J. M. Picone (2010), Record-low thermospheric density during the 2008 solar minimum, *Geophys. Res. Lett.*, *37*, L12,102, doi: 10.1029/2010GL043671.

Fioletov, V. E. (2009), Estimating the 27-day and 11-year solar cycle variations in tropical upper stratospheric ozone, *J. Geophys. Res.*, *114*, D02,302, doi: 10.1029/2008JD010499.

Fligge, M., S. K. Solanki, and Y. C. Unruh (2000), Modelling irradiance variations from the surface distribution of the solar magnetic field, *Astron. Astrophys*, *353*, 380–388.

Fröhlich, C., C. A. Crommelynck, C. Wehrli, M. Anklin, S. Dewitte, A. Fichot, W. Finsterle, A. Jiménez, A. Chevalier, and H. Roth (1997), In-flight performance of the Virgo solar irradiance instruments on SOHO, *Sol. Phys.*, *175*, 267–286.

Gruzdev, A. N., H. Schmidt, and G. P. Brasseur (2009), The effect of the solar rotational irradiance variation on the middle and upper atmosphere calculated by a three-dimensional chemistry-climate model, *Atmos. Chem. Phys.*, *8*, 1113–1158.

Haigh, J. D., A. R. Winning, R. Toumi, and J. W. Harder (2010), An influence of solar spectral variations on radiative forcing of climate, *Nature*, *467*, 696–699, doi:10.1038/nature09426.

Harder, J. W., G. Lawrence, J. Fontenla, G. Rottman, and T. Woods (2005a), The Spectral Irradiance Monitor: Scientific requirements, instrument design, and operation modes, *Sol. Phys.*, *230*, 141–167, doi:10.1007/s11207-005-5007-5.

Harder, J. W., J. Fontenla, G. Lawrence, T. Woods, and G. Rottman (2005b), The Spectral Irradiance Monitor: Measurement equations and calibration, *Sol. Phys.*, *230*, 169–204, doi:10.1007/s11207-005-1528-1.

Harder, J. W., J. M. Fontenla, P. Pilewskie, E. C. Richard, and T. N. Woods (2009), Trends in solar spectral irradiance variability in the visible and infrared, *Geophys. Res. Lett.*, *36*, 7801, doi:10.1029/2008GL036797.

Harder, J. W., G. Thuillier, E. C. Richard, S. W. Brown, K. R. Lykke, M. Snow, W. E. McClintock, J. M. Fontenla, T. N. Woods, and P. Pilewskie (2010), The SORCE SIM solar spectrum: Comparison with recent observations, *Sol. Phys.*, *263*, 3–24, doi:10.1007/s11207-010-9555-y.

Hood, L. L. (1986), Coupled stratospheric ozone and temperature response to short-term changes in solar ultraviolet flux: An analysis of Nimbus 7 SBUV and SAMS data, *J. Geophys. Res.*, *91*, 5264s–5276.

Huang, F. T., H. Mayr, J. M. Russell III, M. G. Mlynczak, and C. A. Reber (2008), Ozone diurnal variations and mean profiles in the mesosphere, lower thermosphere, and stratosphere, based on measurements from SABER on TIMED, *J. Geophys. Res.*, *113*, A04,307, doi:10.1029/2007JA012739.

Krivova, N. A., S. K. Solanki, and L. Floyd (2006), Reconstruction of solar uv irradiance in cycle 23, *Astron. Astrophys*, *452*, 631–639, doi:10.1051/0004-6361:20064809.

Krivova, N. A., S. K. Solanki, T. Wenzler, and B. Podlipnik (2009), Reconstruction of solar UV irradiance since 1974, *J. Geophys. Res.*, *114*, D00I04, doi:10.1029/2009JD012375.

Langematz, U., J. L. Grenfell, K. Matthes, P. Mieth, M. Kunze, B. Steil, and C. Brühl (2005), Chemical effects in 11-year solar cycle simulations with the Freie Universität Berlin Middle Atmospheric Model with online chemistry (FUB-CMAM-CHEM), *Geophys. Res. Lett.*, *32*(L13803), doi:10.1029/2005GL022686.

Lean, J., G. Rottman, J. Harder, and G. Kopp (2005), SORCE contributions to new understanding of global change and solar variability, *Sol. Phys.*, *230*, 27–53, doi:10.1007/s11207-005-1527-2.

Lean, J. L. (2000), Evolution of the sun's spectral irradiance since the Maunder minimum, *Geophys. Res. Lett.*, *16*, 2425–2428.

Lean, J. L., G. J. Rottman, H. L. Kyle, T. N. Woods, J. R. Hickey, and L. C. Puga (1997), Detection and parameterization of variations in solar mid- and near-ultraviolet radiation (200-400 nm), *J. Geophys. Res.*, *102*, 29,939–29,956.

Marsh, D. R., W. R. Skinner, A. R. Marshall, P. B. Hays, D. A. Ortland, and J.-H. Yee (2002), High Resolution Doppler Imager observations of ozone in the mesosphere and lower thermosphere, *J. Geophys. Res.*, *107*, 4390, doi: 10.1029/2001JD001505.

Marsh, D. R., R. R. Garcia, D. E. Kinnison, B. A. Boville, F. Sassi, S. C. Solomon, and K. Matthes (2007), Modelling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, *J. Geophys. Res.*, *112*(D23306), doi:10.1029/2006JD008306.

Mlynczak, M. G., B. T. Marshall, F. J. Martin-Torres, J. M. Russel III, R. E. Thompson, E. E. Remsberg, and L. L. Gordley (2007), Sounding of the Atmosphere using Broadband Emission Radiometry observations of daytime mesospheric $O_2(^1\Delta)$ 1.27 μm emission and derivation of ozone, atomic oxygen, and solar and chemical energy deposition rates, *J. Geophys. Res.*, *112*, D15,306, doi: 10.1029/2006JD008355.

Moran, T., P. Foukal, and D. Rabin (1992), A photometric study of faculae and sunspots between 1.2 and 1.6 micron, *Sol. Phys.*, *142*, 35–46.

Neckel, H., and D. Labs (1984), The solar radiation between 3300 and 12500Å, *Sol. Phys.*, *90*, 205–258.

Oberländer, S., U. Langematz, K. Matthes, M. Kunze, A. Kubin, J. Harder, N. A. Krivova, S. K. Solanki, J. Pagaran, and M. Weber (2012), The influence of spectral solar irradiance data on stratospheric heating rates during the 11 year solar cycle, *Geophys. Res. Lett.*, *39*, L01,801, doi:10.1029/2011GL049539.

Pagaran, J., M. Weber, and J. P. Burrows (2009), Solar variability from 240 to 1750 nm in terms of faculae brightening and sunspot darkening from SCIAMACHY, *Astron. J.*, *700*, 1884–1895.

Pagaran, J., G. Harder, M. Weber, L. Floyd, and J. P. Burrows (2011a), Intercomparison of SCIAMACHY and SIM vis-IR irradiance over several solar rotational timescales, *Astron. Astrophys*, *528*, A67, doi:10.1051/0004-6361/201015632.

Pagaran, J., M. Weber, M. DeLand, L. Floyd, and J. P. Burrows (2011b), Solar spectral irradiance variations in 240-1600 nm during the recent solar cycles 21-23, *Sol. Phys.*, *XX*, XX–XX.

Remsberg, E. E. (2008), On the response of Halogen Occultation Experiment (HALOE) stratospheric ozone and temperature to the 11-year solar cycle forcing, *J. Geophys. Res.*, *113*(D22304), doi:10.1029/2008JD010189.

Remsberg, E. E., B. T. Marshall, M. Garcia-Comas, D. Krueger, G. S. Lingenfelser, J. Martin-Torres, M. G. Mlynczak, J. M. Russel III, A. K. Smith, Y. Zhao, C. Brown, L. L. Gordley, M. J. Lopez-Gonzales, M. Lopez-Puertas, C.-Y. She, M. J. Taylor, and R. E. Thompson (2008), Assesment of the quality of the Version 1.07 temperature-versus-pressure profiles of the middle atmosphere from TIMED/SABER, *J. Geophys. Res.*, *113*, D17,101, doi:10.1029/2008JD010013.

Rohen, G., C. von Savigny, M. Sinnhuber, E. J. Llewellyn, J. W. Kaiser, C. H. Jackman, M.-B. Kallenrode, J. Schröter, K.-U. Eichmann, H. Bovensmann, and

J. P. Burrows (2005), Ozone depletion during the solar proton events of October/November 2003 as seen by SCIAMACHY, *J. Geophys. Res.*, *110*, A09S39, doi:10.1029/2004JA010984.

Rong, P. P., J. M. Russell III, M. G. Mlynczak, E. E. Remsberg, B. T. Marshall, L. L. Gordley, and M. Lopez-Puertas (2008), Validation of TIMED/SABER v1.07 ozone at 9.6 μm in the altitude range 15-70 km, *J. Geophys. Res.*, *114*, D04,306, doi:10.1029/2008JD010073.

Rottman, G., L. Floyd, and R. Viereck (2004), Measurement of solar ultraviolet irradiance, *Geophys. Mono.*, *41*, 111–125, doi:10.10219/141GM10.

Russell III, J. M., M. G. Mlynczak, L. L. Gordley, J. J. Tansock Jr., and R. W. Esplin (1999), Overview of the SABER experiment and preliminary calibration results, *Proc. SPIE*, *3756*(277), doi:10.1117/12.366382.

Schmidt, H., G. P. Brasseur, M. Charron, E. Manzini, M. A. Giorgetta, T. Diehl, V. I. Fomichev, D. Kinnison, D. Marsh, and S. Walters (2006), The HAMMONIA Chemistry climate model: Sensitivity of the mesopause region to the 11-year solar cycle and CO_2 doubling, *J. Climate*, *19*, 3903–3931.

Sekiyama, T. T., K. Shibata, M. Deushi, K. Kodera, and J. L. Lean (2006), Stratospheric ozone variation induced by the 11-year solar cycle: Recent 22-year simulation using 3-D chemical transport model with reanalysis data, *Geophys. Res. Lett.*, *33*(L17812), doi:10.1029/2006GL026711.

Skupin, J., S. Noël, M. W. Wuttke, M. Gottwald, H. Bovensmann, M. Weber, and J. P. Burrows (2005a), SCIAMACHY solar irradiance observation in the spectral range from 240 to 2380 nm, *Adv. Space Res.*, *35*, 370–375, doi: 10.1016/j.asr.2005.03.036.

Skupin, J., M. Weber, S. Noël, H. Bovensmann, and J. P. Burrows (2005b), GOME and SCIAMACHY solar measurements: Solar spectral irradiance and Mg II solar activity proxy indicator, *Mem. Soc. Astron. Ital.*, *76*, 1038–1041.

Solomon, S. C., L. Qian, L. V. Didkovsky, R. A. Viereck, and T. N. Woods (2011), Causes of low thermospheric density during the 2007-2009 solar minimum, *J. Geophys. Res.*, *116*, doi:10.1029/2011JA016508, in press.

Sonkaew, T., V. V. Rozanov, C. von Savigny, A. Rozanov, H. Bovensmann, and J. P. Burrows (2009), Cloud sensitivity studies for stratospheric and lower mesospheric ozone profile retrievals from measurements of limb scattered solar radiation, *Atmos. Meas. Tech.*, *2*, 653–678, doi:10.5194/amt-2-653-2009.

Thuillier, G., L. Floyd, T. N. Woods, R. Cebula, E. Hilsenrath, M. Hersé, and D. Labs (2004), Solar irradiance reference spectra, in *Solar Variability and its Effects on Climate. Geophysical Monograph 141*, vol. 141, edited by J. M. Pap, P. Fox, C. Fröhlich, J. K. H. S. Hudson, J. McCormack, G. North, W. Sprigg, and S. T. Wu, pp. 171–194.

Unruh, Y. C., N. A. Krivova, S. K. Solanki, J. W. Harder, and G. Kopp (2008), Spectral irradiance variations: comparison between observations and the SATIRE model on solar rotation time scales, *Astron. Astrophys*, *486*, 311–323, doi: 10.1051/0004-6361:20078421.

Viereck, R. A., and L. C. Puga (1999), The NOAA Mg II core-to-wing solar index: Construction of a 20-year times series of chromospheric variability from multiple satellites, *J. Geophys. Res.*, *104*, 9,995–10,005.

Viereck, R. A., L. Puga, D. McMullin, D. Judge, M. Weber, and W. K. Tobiska (2001), The Mg II index: A proxy for solar EUV, *Geophys. Res. Lett.*, *28*, 1343–1346.

Viereck, R. A., L. E. Floyd, P. C. Crane, T. Woods, B. G. Knapp, G. Rottman, M. Weber, L. C. Puga, and M. T. DeLand (2004), A composite Mg II index spanning from 1978 to 2003, *Space Weather*, *2*, S10,005.

von Savigny, C., A. Rozanov, H. Bovensmann, K.-U. Eichmann, S. Noël, V. V. Rozanov, M. Weber, J. P. Burrows, and J. W. Kaiser (2005), The ozone hole breakup in September 2002 as seen by SCIAMACHY on ENVISAT, *J. Atmos. Sci.*, *62*, 721–734.

Weber, M. (1999), Solar Activity during solar cycle 23 monitored by GOME, in *ESA-WPP 1999: European Symposium on Atmospheric Measurements from Space, Proc. ESAMS '99*, *ESA Special Publication*, vol. 161, pp. 611–616, ESA Publications Division, Nordwijk.

Weber, M., J. P. Burrows, and R. P. Cebula (1998), GOME solar uv/vis irradiance measurements between 1995 and 1997 - First results on proxy solar activity studies, *Sol. Phys.*, *177*, 63–77.

Wehrli, C. (1985), Extraterrestrial solar spectrum, *Tech. rep.*, Physikalisch-Meteorologisches Observatorium, World Radiation Center (PMO/WRC), Publication No. 615.