

Overview of the temperature response in the mesosphere and lower thermosphere to solar activity

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15 **Abstract**

The natural variability in the terrestrial mesosphere needs to be known to correctly quantify global change. The response of the thermal structure to solar activity variations is an important factor. Some of the earlier studies highly overestimated the mesospheric solar response. Modeling of the mesospheric temperature response to solar activity has evolved in recent years, and measurement techniques as well as the amount of data have improved. Recent investigations revealed much smaller solar signatures and in some case no significant solar signal at all. However, not much effort has been made to synthesize the results available so far. This article presents an overview of the energy budget of the mesosphere and lower thermosphere (MLT) and an up-to-date status of solar response in temperature structure based on recently available observational data. An objective evaluation of the data sets is attempted and important factors of uncertainty are discussed.

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1. INTRODUCTION

The study of variation in atmospheric parameters due to several natural periodic and episodic events has always been an interesting subject. It was realized recently that the perturbation of atmospheric parameters caused by various human activities is not only confined to the lower atmosphere but that it also most likely extends into the upper atmosphere [*Roble and Dickinson, 1989; Roble, 1995; Beig, 2000*]. In view of this, it has become all the more important and vital to study the variations due to natural activities in parameters affecting climate to distinguish them from perturbations induced by global change.

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Variations arising on decadal and even longer time scales may play a significant role in long-term trend estimates. One of the major sources of decadal variability in the atmosphere is the 11-year solar activity cycle (as modeled by *Brasseur and Solomon, 1986*). Electromagnetic radiation from the sun is not constant and varies mainly at shorter UV wavelengths on different time scales [*Donnelly, 1991*]. Incoming solar radiation provides the external forcing for the Earth-atmosphere system. While the total solar flux is quite constant, the UV spectral irradiance on the timescale of the 27-day and 11-year solar cycles exhibits the largest changes, up to a factor of two over a solar cycle for the solar Lyman- α flux. Studies on the changes in solar UV spectral irradiance on timescales of the 27-day and 11-year solar cycles have been attempted by many workers in the past [*Donnelly, 1991, Woods and Rottman, 1997, etc.*]. It is believed that the essentially permanent changes arising in several mesospheric parameters due to human activities are weaker whereas periodic changes due to variations in solar activity are comparatively stronger [*Beig, 2000*].

55 The study related to the influence of solar activity on the vertical structure of temperature and its separation from global change signals has been a challenge because only data sets of short length (one or two decades) were available. The analysis of systematic changes in temperature in the mesosphere and lower thermosphere has not been as comprehensive as in the lower atmosphere. It is possible to suppress or even almost avoid the effects of solar cycle on trend determination with the use of proper selection of the analyzed period combined with the use of data corrected for solar and geomagnetic activity, or by comparison with empirical models, which includes solar and geomagnetic activity, local time, season, latitude and maybe some other parameters. The solar and geomagnetic activity may have a crucial impact

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on the trend determination when data series are relatively short, or when we study trends in
65 the ionized component (ionosphere). Modeling of the mesospheric data series to extract the
solar cycle response has evolved with time, as improvements have been made in the
measurement techniques of the 11-year solar UV spectral changes. Most of the earlier
predictions overestimated the mesospheric response, since they were based on incorrect solar
70 UV-radiation derived from data of insufficient quality and/or length. This situation only
changed with the SME and UARS-missions, when the data became available to quantify the
variations since 1981. The modeling work of *Chen et al.* [1997] reported a solar cycle
response of several Kelvin in the mesopause region. The observed temperature variability at
70 km is not explicable in terms of corresponding 11-year changes in observed ozone
[*Keating et al.*, 1987]. Searches for a strong dynamical feedback and attempts to invoke a
75 strong odd hydrogen photochemical heating effect, have so far not been successful. Until
recently, different data sets showed solar-cycle responses different even in polarity. The
limited availability of data sets and the comparatively short length of data records have been
the major constraints for mesospheric analysis. Nevertheless, during the past decade, a
number of studies have been carried out and more reliable solar signals in mesospheric
80 temperatures have been reported. It was thought earlier that it would be hard to identify a
trend in the MLT region if solar response is very large in magnitude, and that we needed
longer data sets encompassing several solar cycles. Recent investigations revealed the
presence of a solar component in MLT temperature in several data sets but probably they are
not as strong as expected. In recent times, a number of studies related to 11-year periodicities
85 in temperature of the MLT region have been reported [*She and Krueger*, 2004 and references
therein].

However, the solar response in temperature, if not properly filtered out, is still one of the
major sources of variation which may interfere with the detection of human-induced
90 temperature trends for the MLT region [*Beig*, 2002] and will have strong implication in the
quantification of global change signals. In recent time, the search for the effects of the 11-yr
solar cycle on middle atmosphere temperature has not led to consistent results that were easy
to interpret. Model studies suggest an in-phase response to the UV flux, peaking in the upper
mesosphere (2 K ampl.) and at the stratopause (1 to 2 K ampl.) [e.g., *Brasseur*, 1993; *Matthes*
95 *et al.*, 2004]. However, the satellite analysis of *Scaife et al.* [2000] indicates a maximum
response at low latitude of about 0.7 K between 2 and 5 hPa (around 40 km), while that of
Hood [2004] shows a near zero response at 5 hPa but then increasing sharply to 2 K near 1

hPa. The increase of solar influence with altitude is not smooth. For example, the solar effect in the mesopause region is relatively small (according to the model by *Matthes et al.*, 2004; 100 but also according to several observations, see below), so it is easier to study long-term trends in this region. It should be clear that if one does not account properly for the solar cycle response, there can be biases for any remaining trend term. This concern is a particular problem for any data time series that is not well-calibrated, not representative of seasonal or global-scale processes, or not long enough.

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Because of the very limited data not much effort has been made to synthesize the results available in the past. Consequently, our knowledge of the quantification of solar response in the temperature based on observations and model calculations for this region has been rather poor. In view of this, it would be highly desirable that a consolidated status report for solar 110 trend in thermal structure for this region be prepared.

Before ground-based instrumentation with sensitive photoelectric registration and rocket-borne in-situ measurements became available, the search for solar cycle effects with visual airglow photometry in the 1920s, and with photographic spectrography, still dominant in the 115 1960s, is now mainly of historical interest. Reliable temperature determinations, by whatever technique, became available only a few decades ago. Only recently, the detection of solar activity effects in the upper atmosphere comes close to become a routine affair, and the length of the available data sets is the main factor determining the quality of the results. In order to arrive at a balanced overview of our present knowledge, it is therefore natural to 120 focus on the most recent results. These are also often based on the longest-duration data sets of homogeneous quality. The reader interested in the historical development can find references about early investigations of the atomic oxygen green line, which date back to the 1920s, and of subsequent Doppler temperature determinations since the mid-1950s, in *Hernandez* [1976]. Other useful references focussing on green-line intensity variations can be 125 found in *Deutsch and Hernandez* [2003].

This article reviews the present status of observational and modelling evidence on the response of the temperature structure in the region from 50 to 100 km to solar activity variations. An objective evaluation of the available data sets is briefly attempted and 130 important uncertainly factors are outlined. We also discuss the lower thermosphere briefly. For convenience, the whole region from 50-100 km is referred to as the MLT (Mesosphere

and Lower Thermosphere) region. The region from 50-80 km will be referred to as the “mesosphere” and the region 80-100 km will be referred to as the “mesopause region”. Understanding and interpreting the causes of atmospheric trends requires a fundamental understanding of the energy budget. This is essentially the focus of the entire field of tropospheric climate science, which is seeking to determine the extent to which human activities are altering the planetary energy balance through the emission of greenhouse gases and pollutants. We are just now at the point of being able to quantitatively assess the energy budget in the MLT for the first time using the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument data.

2. OVERVIEW OF THE ENERGY BUDGET OF THE MESOSPHERE AND LOWER THERMOSPHERE

Earth’s mesosphere and lower thermosphere are regions in which the transport and exchange of energy occur through subtle and complex processes. The main inputs to the system are of course provided by the Sun in the form of both photon and particulate energy. Ultraviolet (UV) radiation from 1 to 300 nm is absorbed primarily by molecular oxygen and ozone in the MLT. The variability of this portion of the spectrum with the 11-year solar cycle affects both the thermal structure (through changes in the overall amount of energy deposited) and the photochemistry of the MLT, especially the ozone abundance. Ozone is of particular importance to the MLT energy budget. Through the absorption of solar radiation and as a participant in exothermic chemical reactions ozone is responsible for up to 80% of the solar and chemical heating of the mesosphere [Mlynczak, 1997]. Here we will provide a brief overview of the energy budget of the MLT region in this section, following the corresponding presentation in *Beig et al.* [2003] where more details are given.

The critical elements of the MLT energy budget are: heating due to the absorption of solar radiation by O₂, O₃, and CO₂; cooling due to infrared emission from NO, CO₂, O₃, H₂O and O; heating due to exothermic chemical reactions involving odd-oxygen and odd-hydrogen species; energy loss due to airglow emission by O₂(¹Δ), O₂(¹Σ), CO₂(4.3 μm) and OH(ν). It is important to distinguish the energy loss due to airglow from that which is characterized as cooling. The energy in the airglow reduces the efficiency of solar or chemical reaction

165 heating – it never enters the thermal field, and hence is not acting to reduce the kinetic
temperature of the atmospheric gases. Finally, particle input, especially in the thermosphere,
is important, especially on short timescales and associated with solar flare or coronal mass
ejection (CME) events. A summary of key heating (solar and chemical) and infrared cooling
terms is given in Table 1.

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The single most significant factor in differentiating the energy balance of the MLT from the
atmosphere below is that the density in the MLT is so low that collisions cannot always
maintain the processes of absorption and emission of radiation under local thermodynamic
equilibrium (LTE). Consequently, computation of rates of solar heating and infrared cooling
175 is a much more challenging process. In the case of solar energy, not all of the absorbed
energy is thermalized locally. This fact requires a detailed accounting of all possible
pathways for the absorbed solar energy to transit prior to ending up as heat or to being
radiated from the atmosphere as airglow without ever having entered the thermal field. Thus
we say that the efficiency of solar heating is substantially less than unity due to these
180 processes, to as low as 65%. The details of the solar and chemical heating and the associated
efficiencies are reviewed by *Mlynczak and Solomon* [1993].

In the case of radiative cooling, the effective temperature at which infrared active species
radiate is not given by the local kinetic temperature. This fact requires extremely detailed
185 consideration of the exchange of energy (thermal, radiative, chemical) between the infrared
active molecules and their environment for a multitude of quantum energy states within each
molecule [e.g., *López-Puertas and Taylor*, 2002]. The key radiative cooling mechanisms in
the MLT involve several infrared active species including the molecules CO₂ and O₃ [*Curtis
and Goody*, 1956], H₂O [e.g., *Mlynczak et al.*, 1999], NO [*Kockarts*, 1980], and atomic
190 oxygen (O) [*Bates*, 1951]. Of these, the CO₂, O₃, and NO emissions exhibit substantial
departure from LTE in the MLT. The water vapor and atomic oxygen emissions correspond
to transitions in the far-infrared portion of the spectrum (wavelengths typically longer than 20
μm) that are more readily thermalized by collisions, and thus maintained in LTE.

195 The solar photon energy is the dominant source of energy into the MLT, but the solar
particulate energy is nevertheless important. While the photon energy from the Sun varies on
relatively long timescales (from the 27-day solar rotation to the 11-year sunspot cycle),

particulate energy from the Sun varies in a much more erratic (and often violent) way. Recent observations of the thermospheric and mesospheric response to variations in particle input from CME events clearly indicate the potential to alter the thermal structure and the radiative cooling mechanisms. *Seppälä et al.*, [2004] and *Rohen et al.*, [2005] have observed the destruction of ozone in response to strong solar storm events. In the stratosphere and lower mesosphere, radiative cooling by ozone is critical to the energy balance. Thus there is a direct impact on the energy balance in the stratosphere from solar particle precipitation.

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From this overview of the energy budget, it is clear that the variability of solar radiation input into the MLT region may impact the thermal structure directly (through the increase or decrease in the total amount of solar energy deposited) and indirectly, for example, by modifying the ozone abundance and thereby the heating and cooling rates. It is specifically because of the complexity of the energy budget that assessing and attributing observed changes (cyclical and secular) in the MLT is a formidable scientific challenge.

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3. TECHNIQUES AND OBJECTIVE EVALUATION OF TEMPERATURE DATA SETS

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In addition to the satellite datasets, there are a number of experimental data records from ground based or in-situ observations of mesospheric temperatures, although the mesospheric record is still small compared to what is available at lower altitudes. The same techniques and associated measuring uncertainties that are discussed by *Beig et al.* [2003] for their use in trend analyses are also relevant, to some extent, in the present context, so we can make reference to the greater detail given there.

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In addition to ground-based observations which are capable to supply long data sets at fixed geographic locations, also in-situ data from rocketsondes and global observations from satellites can be used to measure temperature suitable for the detection of solar activity effects. Details of all the data sets obtained during the past few decades and available for evaluation of temperature trend in the MLT region are also given in *Beig et al.* [2003]. Figure 1 shows most of the known ground based locations of long term temperature measurements all over the globe. The techniques applied to measure the temperature are also indicated as far as possible. As mentioned in *Beig et al.* [2003], even for standard instrumentation used for a

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long time, technical improvements can introduce uncertainties when data obtained at different times are combined into longer data sets. While this can be most serious for long-term trend detection, it can also interfere to some extent with the determination of solar activity response. Techniques capable of supplying data over an extended height range like rocket-
235 launched or lidar temperature or density soundings (from which temperature profiles can be derived) nevertheless suffer from an inevitable loss of precision at the greatest altitudes, where they often cannot compete with ground-based observations. The long time span covered by some ground-based measurements makes them particularly useful to study solar cycle variations.

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Mesopause region temperature is most often determined from line intensity measurements in hydroxyl (OH) airglow bands of the airglow, but the so-called Atmospheric band of molecular oxygen is now quite often also used. These rotational temperatures agree with kinetic temperature at the peak of the vertical airglow emission profile. According to
245 measurements with many different techniques, the OH emission comes from an emission layer at 87 km with a mean thickness of 8 km [Baker and Stair, 1988; more references are given in Beig *et al.*, 2003]. Satellite limb scans have resulted in reports on height variations by several kilometers which may be related to dynamics [e.g., Liu and Shepherd, 2006], and Nikoukar *et al.* [2007] have found recently that the bands from the upper vibrational levels 7,
250 8, and 9 come from an altitude slightly higher than the bands from the 4, 5, and 6 levels. According to these results, the difference is 1.9 ± 1.4 km, while the mean peak altitude for the latter bands (which are probably representative of the most widely used ground-based observations) is consistent with the nominal values mentioned above. The observed variability does not invalidate ground-based measurements of hydroxyl rotational
255 temperature as a useful tool to diagnose atmospheric temperature trends or solar activity effects, as long as this variability can be treated as random, or be considered as part of the phenomenon. The same holds for the O₂ Atmospheric band, with a nominal emission peak height of 95 km.

260 From OH or O₂ airglow observations, temperature precisions of a few Kelvin can be obtained with integration times not longer than a few minutes. Therefore, by averaging over a number of individual measurements, the contribution of instrumental noise to the mean temperature can easily be made negligible. Systematic errors affecting data accuracy have only an influence on trend or solar activity results if they vary with time. They are not a problem if

265 long-term stability can be assured, and one way to ensure stability is with good instrument
calibration. The discussion about this point in *Beig et al.* [2003] is mostly important in the
context of the possibility to detect small long-term trends. For detecting effects of the 11-year
solar cycle, which has a rise time of only about four years, and where responses of several
Kelvin have been reported, the instrument stability requirements are less stringent. The
270 relative calibration of the instrument response at two or more wavelengths necessary for
determining rotational temperature is not difficult.

The rotational temperatures in the mesopause region vary on time scales from a few minutes
for short-period gravity waves to the solar cycle, and beyond. Nocturnal mean temperatures
275 used as the basis for solar cycle and trend analysis are affected by the short-term variability
only as far as gravity waves and variations due to the thermal tide are not completely
cancelled out. This “geophysical noise” can be expected to be quite variable and so create
only small uncertainties on longer time scales. There is however also a day-to-day variability
from planetary waves and unknown sources which could not be avoided even if
280 measurements over complete nights were always available. This underlines the importance of
dealing with airglow temperature data sets based on the greatest possible number of nights.
The same obviously also holds for data sets from other techniques.

Apart from O₂ rotational temperatures, some data sets extend the information available above
285 the altitude of OH by using atomic line intensities from sodium or atomic oxygen as a proxy
for temperature, based on an empirical correlation between intensity and temperature (see,
e.g., *Golitsyn et al.*, [2006]). The validity of this approach is questionable and cannot be
recommended as a replacement for direct temperature measurements, be it by the
measurement of O₂ rotational temperature, of Doppler width with Fabry-Perot instruments, or
290 by laser spectroscopy with sodium lidars.

The length of the data set required for determining solar signatures may be as short as the few
years that the solar cycle takes to ascend from minimum to maximum, but may also be as
long as several cycles, if the effect is small compared to other variability (for example,
295 seasonal) , or is itself strongly variable. The data sets from different measurement techniques
vary widely not only in the number of years covered, but even more so with respect to the
uniformity of coverage and the number of individual data points available. Some airglow data
sets consist of millions of individual, statistically independent observations at a fixed site,

300 resulting in up to about 5000 nocturnal means, all referring to the same (nominal) altitude. On
the other hand, rocket soundings yield only one profile per launch, and from less than 100 to
several hundred profiles may be available from a given site, but a considerable altitude range
is covered. As pointed out before, lidar soundings (either by Rayleigh lidars covering a wide
range of altitudes similar to rocketsondes, or by sodium lidars that are limited to the
mesopause region) can easily surpass the number of profiles from rockets, being limited only
305 by clear weather requirements, and not by equipment expense. Finally, satellite observations
easily comprise millions of vertical temperature profiles, with near-global coverage, but the
number of overpasses at a given site is very much lower, refers to only slowly varying local
time, and the available long-term coverage is still small. The SCIAMACHY instrument on
Envisat is capable of measuring OH rotational temperature by limb sounding [*von Savigny et*
310 *al.*, 2004]. It was launched only in 2004, but can be expected to contribute data on solar
activity response in the near future.

315 4. OBSERVATIONS OF THE SOLAR RESPONSE IN THE MESOSPHERE

The response of temperature and the middle atmosphere species to 11-year solar UV
variations has been difficult to isolate using satellite data. This is partially due to the short
time series of satellite data sets relative to 11-year variations, to instrument drifts, and to the
320 strong longitudinal variability that makes zonal means appear quite noisy [see *Chanin*, 2006].
On this time scale the quasi coincidence of the recent major volcanic eruptions with solar
maximum [*Kerzenmacher et al.*, 2006] conditions increases the challenge while indirect
mesospheric responses were observed [*Keckhut et al.*, 1995, 1996]. This effect was caused by
changes to the wave propagation induced by the thermal forcing inside the volcanic cloud and
325 vertical stability around the tropopause [*Rind et al.*, 1992]. In the past, only rocket
temperatures have provided such long data sets in the mesosphere. However, the required
aerothermic corrections and changes of the sampling and time of measurements induce some
bias mainly in the mesosphere. More recently Rayleigh lidars that are much less expensive
and require less resources for continuous operations have replaced the rocket techniques.
330 From space, HALOE aboard UARS is the only experiment that allows mesospheric
temperature over more than a decade with a single instrument. However, while global, the

number of solar occultation does not provide such a large sampling as desirable.

335 The solar activity is also modulated by the solar rotation, and UV series exhibit strong responses with periods of 27 days and harmonics. On this scale more temperature series are available. From the ground, rockets and lidars can be used. However, lidars are more adequate to perform daily series while typical rocket sampling is close to a week. The experiments on board Nimbus 6 and 7 were used intensively to retrieve stratospheric and mesospheric temperature responses. However, these changes related to the solar rotation
340 present smaller amplitudes than the solar cycle and are highly non-stationary. In the case of the sun, the physical processes governing the evolution of active regions and the resulted variations in the solar output are, at best, only quasi-stationary over a limited time period.

On the time range of solar cycle the radio flux at 10.7 cm is used as proxy of solar activity
345 while long-term UV measurements from space are not available. On the other hand, the short-term solar UV variation is not well described by standard radio solar flux at 10.7 cm and more direct UV measurements from space at 205 nm, Lyman alpha or proxies such as Magnesium Lines Mg II are preferred to better describe daily changes of solar UV (see *Dudok de Wit et al.*, [2007] for a recent investigation of this topic). While in the middle
350 atmosphere, ozone and temperature are highly connected due to thermal ozone absorption and thermal sensitivity of the ozone dissociation, the simultaneous investigations of ozone and temperature allow for a better understanding of the middle-atmosphere response to solar activity changes. Ozone measurements on Solar Mesosphere Explorer (SME) and on Nimbus 7 were analyzed. At high latitudes, direct ozone response (and hence temperature) to solar
355 activity variations may also be overwhelmed by solar proton events. The satellite sensors for solar EUV may also occasionally be saturated by solar particles [e.g. see an example in *Scheer and Reisin*, 2007].

In photochemical models, the ozone sensitivity on the 27-day and the 11-year scale are
360 similar because the time constant of ozone is negligibly short, in comparison. However, discrepancies exist when including temperature-chemistry feedback in the model calculations. It is possible that this is indicative of an indirect dynamical component of the solar response.

365 4.1 Changes due to 27-Day UV Solar Forcing

Temperature variations are affected by a number of short-term dynamical influences independent of solar variations, and thus it is more difficult to isolate the solar signal. Temperatures are available simultaneously from the SAMS instrument on the Solar Mesosphere Explorer (SME) satellite. In the $\pm 20^\circ$ latitude band at 2 mbar a temperature variation of 1.5K for 10% ozone change is reported, which grows to 2.5K at 70 km. In contrast to the stratospheric maximum that is limited to the $\pm 20^\circ$ latitude band, this second maximum in the mesosphere is present in the $\pm 40^\circ$ latitude band. The observed temperature phase lag with 205 nm solar flux is shorter than 1 day in the mesosphere, and the altitude of maximum temperature sensitivity is close to the altitudes of maximum ozone depletion. Therefore, in addition to the HO_x effect on ozone, the temperature sensitivity can be expected to play a role through temperature feedback or as a consequence of the solar Lyman alpha heating. This mesospheric maximum was not predicted by numerical models but must be real, since *Summers et al.* [1990] conclude that the discrepancies between model and observation cannot be explained by data-related errors. At mid-latitudes, wavelet analysis of lidar time series [*Keckhut and Chanin, 1992*] shows that planetary waves tend to mask the direct solar response in temperatures since wave amplitudes are large and periods may be comparable to the solar rotation period; planetary waves exhibit periods from a few days to 30 days. On the other hand, planetary waves may be directly involved in the solar forcing (see below).

Ebel et al. [1986] have suggested that the generation of vertical wind oscillations in the 27-day period range would at least lead to the right sign of correlation (through adiabatic cooling during the upward wind phase and simultaneous transport in the direction of the vertical ozone mixing ratio gradient in the lower dynamical regime and photochemical increase at higher layers due to the temperature dependence of the ozone reaction coefficients). This effect may also be responsible for the fact that the ozone perturbations inferred from UV flux changes are better reproduced by simulations without temperature feedback than with it [*Keating et al., 1987*] due to the compensating effect of adiabatic heating.

Radiance measurements were made with the Pressure Modulated Radiometer (PMR) on board NIMBUS 6 [*Crane, 1979*]. Maximum values obtained for the 27 day periodicity were

1.5 K near the mesopause, 3.0 K in the lower mesosphere and 3.5 K in the upper stratosphere, at latitudes between about 50° and 70° [Ebel *et al.*, 1986]. Since indirect perturbations seem
400 to exceed the direct ones in amplitude, non-linear interactions of forced variations with the atmospheric system also have to be considered. Furthermore the large spatial scales of the possible solar activity effects showing up in the global and hemispheric data sets employed in this study support the view that planetary waves are an essential part of the unknown mechanisms.

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4.2 Changes on the 11-Years Solar Scale

The atmospheric temperature response to solar UV changes is expected through ozone and oxygen absorption processes in the middle atmosphere. In the stratosphere, the response
410 shows a positive correlation between the temperature and the solar activity with an effect of 1-2 Kelvin in the upper stratosphere due to ozone photolysis and solar absorption, while at higher latitude negative responses are reported [Keckhut *et al.*, 2005]. These observations confirmed by rocket series could be explained by dynamic feedbacks and more specifically by the occurrence of stratospheric warmings [Hampson *et al.*, 2005]. From this numerical
415 simulation, a positive effect is expected in the mesosphere. Because the winter response results in a dynamic feedback, the signature is expected to be non-zonal in the northern hemisphere [Hampson *et al.*, 2006]. While stratospheric warmings are associated with mesospheric cooling, it is not surprising to see these alternating patterns at mid and high latitudes [Matsuno, 1971]. In the tropical mesosphere, a response can be also expected, as
420 tropical mesospheric anomalies associated with stratospheric warmings are also reported [Sivakumar *et al.*, 2004, Shepherd *et al.*, 2007]. A summary of the solar response in the mesosphere is given in Table 2.

The search for a solar trend in the mesosphere had started in the late 70s when a few authors
425 reported solar cycle associated variability in mesosphere temperatures. Shefov [1969] reported a solar cycle variation in OH rotational temperature on the order of 20-25 K for mid-latitudes. Labitzke and Chanin [1988] using rocketsonde data at Heiss island located at 81°N reported solar cycle temperature variations on the order of 25K at 80 km. Kubicki *et al.* [2007] have reanalyzed the same set of data and deduced a negative solar response of several
430 kelvins. The time series of Russian rocketsonde measurements at four different sites

(covering low to high latitudes) revealed a substantial positive solar response in the mesosphere [Mohanakumar, 1985, 1995]. However, in recent time, results are found to be quite different. The reanalysis of the Thumba (8°N) tropical data extending to more than two solar cycles [Beig and Fadnavis, 2003] has recently also resulted in a positive solar response of temperature in the mesosphere but of much lower magnitude than reported earlier [Kokin et al., 1990]. US rockets have shown a clear solar response in the upper stratosphere [Dunkerton et al., 1998]. In the mesosphere only 2 subtropical sites allow to retrieve the solar response in the mesosphere. A positive correlation has been found with a temperature response of 2 K on a large latitude range from 50 to 70 km [Keckhut et al., 1999]. An analysis of falling sphere and rocket grenade data by Lübken [2000, 2001] revealed no statistically significant solar component for the altitude range 50-85 km, however the analysis only included data during the summer season. Remsberg and Deaver [2005] have analyzed long-term changes in temperature versus pressure given by the long time series of zonal average temperature from the Halogen Occultation Experiment HALOE on the Upper Atmosphere Research Satellite (UARS). The HALOE temperature data are being obtained using atmospheric transmission measurement from its CO₂ channel centered at 2.8 micrometers [Russell et al., 1993, Remsberg et al., 2002]. While the length of the data set is still short, they have reported a mesospheric response of 2-3 K around 70-75 km. In a more recent work Remsberg [2007] found more accurate results ranging from 0.7 to 1.6 K in the lower mesosphere and from 1.7 to 3.5 K in the upper mesosphere. In mid-latitude responses are larger and in the tropical latitude band only 0.4 to 1.1 K is reported. The long-term series of lidar data obtained at Haute Provence (44°N) has revealed a positive (in phase) solar response of 2 K/100 sfu (solar flux units) in the mesosphere up to 70 km. The response was found to fall off with height above 65 km, with a tendency towards a negative response above 80 km [Keckhut et al., 1995].

Atmospheric temperature response to the 27-days and 11-years solar cycle as function of altitude from different studies focus on tropical regions are shown in Figure 2. SAMS [Keating et al., 1987] and PMR [Ebel et al., 1986] analyses are performed on the solar rotation time scale. HALOE analyses above the ±20° latitude band [Remsberg, 2007] concern the 11-years time scale. Two different analyses [Beig and Fadnavis, 2003; Kokin et al., 1990] have been used to analyze the data of the rocket station Thumba (8.5°N, 77°E)..

465 Atmospheric temperature response to the 11-years solar cycle as a function of altitude from
different studies covering mid-latitudes are shown in Figure 3. Error bars associated with the
OHP lidar correspond to the range of seasonal changes [Keckhut *et al.*, 2005]. The hatched
area corresponds to the HALOE observations in different latitude bands [Remsberg, 2007].
The US Rocket corresponds to an average of 3 subtropical rocket stations [Keckhut *et al.*,
1999]. The Soviet rocket sites (Heiss, Volgograd and Molodezhnaya) data have been
470 analyzed by Kokin *et al.* [1990] and Golitsyn *et al.* (2006). They obtained different solar
response for different stations as shown in Figure 3.

4.3 Seasonal Variations

475 Mohanakumar [1995] shows the summer response varied in the same way with latitude
between Arctic and Antarctic but was about half the wintertime values. The Thumba results
indicate also a stronger positive solar component in winter as compared to summer for the
mesosphere, which is in agreement with mid-latitude lidar results [Keckhut *et al.*, 1995].
Hauchecorne *et al.* [1991] had already reported earlier that solar response changes sign from
480 winter to summer depending on height, using lidar data (1978-1989) at heights from 33 up to
75 km. They found about 5 K/100sfu during winter for 60-70 km altitude (where the
maximum response is observed) and for summer about 3K/100sfu. Later, Keckhut *et al.*
[1995] using data from the same lidar for an extended period reported the solar response over
a height range of 30-80 km for summer, with a negative tendency at height above 75 km. In
485 the mesopause region, the changes of the response to solar activity during the specified
intervals occur most distinctly in autumn, winter and spring. For summer, the response of the
atmosphere does not practically change, though it has the maximal value. Therefore the
dispersion of the values mentioned above is probably caused by the seasonal nature of
observation. Golitsyn *et al.* [2006] have recently analyzed the response of the monthly mean
490 temperature data on the solar activity variations for the altitudes 30-100 km. They obtained
the minimal solar response at heights ~55-70 km with a value of $+2\pm 0.4$ K/100sfu for winter
and -1 ± 0.4 K/100 sfu for summer.

495

4.4 Atmospheric Response due to Solar Flares

During major solar flare events, energetic particles penetrate down into the Earth's mesosphere and upper stratosphere. By ionizing molecules, solar proton events (SPE) are expected to produce a large enhancement of odd nitrogen at high latitudes in the mesosphere [Crutzen, 1975; Callis et al., 2002]. Odd nitrogen species play an important role in the stratospheric ozone balance through catalytic ozone destruction. In the upper stratosphere and mesosphere, ozone decreases of 20 to 40% associated with SPE have been reported [Weeks et al., 1972; Heath et al., 1977; McPeters et al., 1981; Thomas et al., 1983, McPeters and Jackman, 1985]. When a strong stable polar vortex forms, diabatic descent inside the vortex can transport NO_x rapidly downward, and may enhance the effect of ozone destruction [Hauchecorne et al., 2005]. As expected from numerical models [Reagan et al., 1981; Reid and Solomon, 1991] simultaneous cooling of around 10 K in the lower mesosphere was observed by Zadorozhny et al. [1994], in October 1989, using meteorological M-100B rockets, while NCEP temperature analyses [Jackman and Mc Peters, 1985] report no detectable temperature decrease associated with the event of July 1982.

A recent search for a response of the mesopause region to solar flares and geomagnetic storms by Scheer and Reisin [2007] in the airglow data base from El Leoncito (32°S, 69°W) revealed no convincing evidence, in spite of the coverage of very strong solar and geomagnetic events. There is however the possibility that the atmospheric response (at the relatively low latitude) is only short-lived and therefore limits detection by nocturnal observations to cases of favorable flare timing. If this is so, daytime observation techniques would be more suitable for detecting flare effects in the mesopause region.

520

5. OBSERVATIONS OF THE SOLAR CYCLE RESPONSE IN THE MESOPAUSE REGION

5.1 Annual mean response

525

The majority of the results discussed in this section are obtained from measurements of OH airglow which correspond to nominal altitudes of 87 km. Section 4 of the Beig et al. [2003]

paper contains information on some earlier solar activity studies since the 1970s, with an emphasis on OH rotational temperature, only part of which will therefore again be discussed
530 here.

Sahai et al. [1996] reported a solar activity effect of 32 K/100sfu from OH airglow temperature measurements at Calgary (51°N, 114°W) based on the comparison of two low activity years (1987, 1988) with a high activity year (1990). The solar signal found by
535 *Gavrilyeva and Ammosov* [2002] from their OH data obtained at Maimaga (63°N, 130°E) between 1997 and early 2000 was only one third as great as the result from Calgary, but is still a high-end result (11 ± 3 K/100sfu), when compared to the other solar temperature responses observed all over the globe, that were published in recent years. Both results may be considered problematic because of the short time span covered, in combination with the
540 strong seasonal variability, characteristic of medium and high latitudes. They are not automatically discredited by disagreeing with the lower values found elsewhere, because they could only be refuted by observations under the same conditions. Similar arguments can be used in favor of the strongly negative solar cycle effects in O I Doppler temperatures (ca. -30 K/100sfu) by *Hernandez* [1976] at mid- and low latitudes, and by *Nikolashkin et al.* [2001],
545 at Maimaga (ca. -15 K/100sfu), although those latter authors' result for OH temperature ($+5$ K/100sfu for eastward QBO phase, -30 K/100sfu for westward) is somewhat at odds with the more recent data by *Gavrilyeva and Ammosov* [2002] from the same site.

Figure 4 and 5 show the solar response in temperature (K/100sfu) as reported by different
550 authors using various experimental data in recent time for the Northern and Southern Hemispheres, respectively. For easier reference, the pertinent details corresponding to each result are also listed in Table 3.

Sigernes et al. [2003] found no solar signal in the time series of OH airglow data from the
555 auroral station Adventsdalen (78°N, 15°E) that span 22 years. On the other hand, in the mid-latitude Northern Hemisphere, where the greatest number of OH airglow temperature measurements is available, all studies signal a positive response to solar activity. *Espy and Stegman* [2002] have initially not reported an appreciable solar cycle effect at the height of the OH layer over Stockholm (59°N, 18°E), but after a new analysis that includes more recent
560 data, these authors find evidence for a positive effect of about 2 K/100sfu (1.6 ± 0.8

K/100sfu, in winter); [*P.J. Espy*, 2007, personal communication]. New results from Zvenigorod (56°N, 37°E), for the years 2000 – 2006 reported by *Pertsev and Perminov* [2007] indicate an annual mean response of 4.5 ± 0.5 K/100sfu, which is somewhat stronger than previous results partly derived from the same site [*Golitsyn et al.*, 2006, see below].

565 The recent analysis by *Offermann et al.* [2004] based on 21 years of OH airglow temperature data for Wuppertal (51°N, 7°E) extends up to 2002 and now covers almost two solar cycles. This long series of observations was started in 1980 with the aim to determine solar and long-term trends in the mesopause region. The authors found an effect of 3.0 ± 1.6 K/100sfu, on a monthly basis, from temperature enhancements during the maxima of two solar cycles. The
570 authors assumed a linear correlation between temperature and solar activity, ignoring possible lags. The annual mean response is 3.4 K/100sfu.

Bittner et al. [2000] analyzed the Wuppertal (51°N, 7°E) data for the period 1981-1995 with respect to temperature variability with periods of several days, but not with respect to
575 absolute temperature (as most other studies). They found positive solar correlation response for temperature oscillations with periods greater than ~30 days and negative correlation for periods less than ~10 days. In an analysis of the complete Wuppertal data set including the year 2005 [*Höppner and Bittner*, 2007] , the 11-year solar signal for the period range from 3 to 20 days had disappeared, but there was, surprisingly, evidence for a correlation with the
580 22-year heliomagnetic cycle. The authors investigated the possibility of a magnetic coupling between the solar and terrestrial magnetic fields, and indeed found a weak modulation in the Earth's rotation period with a shape similar to the observed variation of the standard deviation of OH temperature. *Lowe* [2002] has made OH layer measurements for one full solar cycle at Delaware Observatory (43°N, 81°W) in Canada and found a positive solar
585 response of 1.5 ± 1.1 K/100sfu.

Golitsyn et al. [2006] have consolidated Russian results from their earlier analysis [*Golitsyn et al.*, 1996] based on the rocket data from Volgograd (49°N) and data from different airglow emissions obtained at Abastumani (42°N) and Zvenigorod (56°N), covering two activity
590 cycles (1976-1991). Monthly and annual mean model profiles of the temperature response to the solar cycle were fitted to these data, which at the altitude of 87 km are based essentially on OH rotational temperatures. The annual mean response is about 2.7 ± 1.7 K/100sfu, with a tendency to grow with altitude.

595 An alternating negative and positive temperature response is consistently found in Northern Hemisphere mid-latitude results obtained by incoherent scatter radar, Rayleigh lidar [*Chanin et al.*, 1989], and sodium lidar [*She and Krueger*, 2004] for altitudes between 30 and (in some data sets as high as) 140 km. This suggests that dynamical coupling from the troposphere to the thermosphere is involved in solar activity induced signatures. *She and Krueger* [2004] have recently reported the impact of 11 year solar variabilities on the mesopause region temperature over Fort Collins (41°N, 105°W) using their sodium lidar data obtained between 1990 and 2001. They found no solar signal at 83 km, but a positive effect of 3 ± 2 K/100sfu at 87 km (updated numbers according to *C.-Y. She*, personal communication [2007]). The HALOE results by *Remsberg and Deaver* [2005] mentioned above also refer to the lower limit of the mesopause region. For different latitude zones, 11-yr solar cycle terms with amplitudes of 0.5 to 1.7 K were found for the middle to upper mesosphere (80 km).

Figure 5 shows the solar response in temperature for the Southern Hemisphere. *Clemesha et al.* [2005] reported the OH rotational temperature measurements made at Cachoeira Paulista (23°S, 45°W) for the period from 1987 to 2000. A simultaneous linear and 11-year sinusoidal fit resulted in a solar cycle amplitude of 6.0 ± 1.3 K with maxima in 1990 (and therefore also in 2001), well in phase with solar activity. The linear trend of 10.8 ± 1.5 K / decade agrees perfectly well with the results obtained for nearly the same time span and geographic area (El Leoncito, 32°S, 69 °W) by *Reisin and Scheer* [2002]. *Clemesha et al.* [2005] also found a positive OH intensity trend of the order of 1.9%/year, which, in view of the combined error bounds, is not considerably above the intensity trend observed by *Reisin and Scheer* (about +1%/year). However, the strong solar cycle signature found by *Clemesha et al.* [2005] (expressed as 11-year amplitude) that can be estimated to correspond to about 8-10 K/100sfu is at odds with the near-zero effect encountered by *Reisin and Scheer* [2002]. The Leoncito results are confirmed by the most recent analysis of OH (6-2) rotational temperatures and airglow brightness variations during the rise and maximum phase of solar cycle 23 [*Scheer et al.*, 2005]. No solar cycle signature was found, but when a temporal trend is allowed for, the solar effect may approach 1.4K. The disagreement with the solar response at Cachoeira Paulista may be a consequence of latitudinal differences in planetary wave activity, and therefore need not be considered contradictory.

Results about OH temperatures from Davis (69°S, 78°E) will be discussed in the next section. *Hernandez* [2003] measured the polar mesospheric temperature above South Pole (90°S) from 1991-2002 using the Doppler width of the OH line at 840 nm by means of a high-
630 reolution Fabry-Perot interferometer and deduced a solar signal as high as 13K/100sfu. This is the strongest solar temperature signal reported in recent years. From the same site, *Azeem et al.* [2007] have reported OH rotational temperatures obtained during the austral winters of 1994–2004. In spite of the temporal overlap between both data sets, the comparable coverage of data, and the expected approximate equivalence of the temperatures obtained by both
635 techniques, the solar cycle effect of 4.0 ± 1.0 K/sfu reported by *Azeem et al.* [2007] is only about one third of the result obtained by *Hernandez* [2003]. The reason for this discrepancy is unknown. Figure 6 provides the summary of the solar response in temperature for the lower thermosphere. In this height range, the results obtained by *Golitsyn et al.* [2006] depend in part on temperatures estimated from the brightness of different airglow emissions, and in part
640 on the extrapolation of OH temperature response to greater heights. Their composite profile indicates an annual mean solar response of 2.8K/100sfu and 2.3K /100 sfu for the altitudes of 92 km and 97 km respectively. *She and Krueger* [2004] have found a solar signal of 4K/100sfu between about 92 and 98 km. Above 101 km, the effect decreases quickly to zero at 103 km and becomes negative at 104 km. The mean solar cycle effect in O₂ rotational
645 temperatures measured at El Leoncito (32°S, 69°W) [*Scheer et al.*, 2005] is consistent with the range of upper limits estimated earlier [*Reisin and Scheer*, 2002]. A positive response of 3.3 ± 0.3 K/100sfu is reported (which would reduce to 1.32 ± 0.3 K/100sfu, if a temporal trend is simultaneously fitted). The authors conclude however that the mean values are however only the net effect of successive short-term spells of anti-correlation, the absence of
650 correlation, each lasting many months, and a 32-months regime of strong correlation. So, there is obviously no seasonal regularity in the solar signal at this site. All these recent results for northern and southern mid-latitudes that refer to heights around 95 km compare quite well with each other, although they are obtained by quite different techniques.

655 5.2 Seasonal Differences

As mentioned above, the results reported by *Golitsyn et al.* [2006] are seasonally resolved, and solar response changes with season (even in sign) and assumes the most extreme values (both positive, and negative) in the mesopause region, at heights of about 80-95 km.

660 Response is most variable in autumn, winter and spring, and a strong, but stable response prevails in summer. These authors deduced a solar response of -5 ± 1.7 K/100sfu for winter, and 8 ± 1.7 K/100sfu for summer, in this altitude range.

The absence of a solar response in the OH data from Adventsdalen (78°N) for winter was
665 already mentioned [Sigernes *et al.*, 2003, and also Nielsen *et al.*, 2002]. Lübken [2000] arrived at a similar conclusion about 80 km at Andoya (69° N), from the comparison of rocket soundings, but those were made mostly during summer. Since most of the soundings correspond to low solar activity, this evidence is however not very strong. For high latitudes in the Southern Hemisphere (Davis, 69°S, 78°W), French and Burns [2004] have reported a
670 positive solar response of 6 to 7K/100sfu in mid-winter, but smaller values (even possibly zero), outside this season. With the inclusion of data from 2002 and 2003, thus extending the Davis data base from 7 to 9 years, the winter effect changed to 4.8 ± 1.3 K/100sfu [French *et al.*, 2005].

675 Offermann *et al.* [2004] have also reported different solar influence during different months of the year. The monthly responses suggest considerable variations even though the estimated error bars are large, because of the strong dynamical variability. The mean of the data is 3.0 ± 1.6 K/100sfu. This is in agreement with the analysis based on annual means that gave 3.4 K/100sfu. The authors concluded that long-term trend effects as measured at Wuppertal and
680 solar cycle influences are almost statistically independent, which means that there is little interference between both types of results as noted by them.

6. MODEL SIMULATIONS OF SOLAR RESPONSE

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In principle, those models which are able to account properly for the vertical coupling processes in different altitudes of the atmosphere are suitable to study solar variability effects. There are only few model studies to assess the effect of solar variability on temperature or other parameters in the MLT region, in comparison to stratospheric regions where many
690 models have been used [Rozanov *et al.*, 2004 and references therein]. Some studies addressed the effect of the 27-day rotational variation with one-dimensional (1-D) [Brasseur *et al.*, 1987; Summers *et al.*, 1990; Chen *et al.*, 1997] or 2-D [Zhu *et al.*, 2003] chemical dynamical

models. Current models of the effect of 11-year solar cycle on the middle atmosphere temperatures are inconclusive. Studies by *Brasseur* [1993] and *Matthes et al.* [2004] suggest variations of upper mesospheric temperatures of about 2 K in response to changes in the solar UV flux. (red added extra in rev-1). The 11-yr solar cycle variability was studied with different versions of the SOCRATES (Simulation of Chemistry, Radiation, and Transport of Environmentally Important Species) interactive 2-D model by *Huang and Brasseur* [1993] and *Khosravi et al.* [2002]. *Huang and Brasseur* [1993] arrived at a peak-to-peak temperature response to solar activity in the mesopause region of about 10K, whereas *Khosravi et al.* [2002] derived a value of 5K. *Garcia et al.* [1984] have reported a solar response of 6K between solar minimum and maximum activity using their 2-D model .

Most of the initially developed general circulation models (GCMs) extend generally from the surface to the mid-stratosphere. Later, some of these GCMs have been extended to approximately 75–100 km altitude [e.g., *Fels et al.*, 1980; *Boville*, 1995; *Hamilton et al.*, 1995; *Manzini et al.*, 1997; *Beagley et al.*, 1997] or even up to the thermosphere [*Miyahara et al.*, 1993; *Fomichev et al.*, 2002; *Sassi et al.*, 2002]. Chemical transport models that treat chemical processes up to the mesosphere “offline” from the dynamics have also been developed [e.g., *Chipperfield et al.*, 1993; *Brasseur et al.*, 1997]. Coupled dynamical–chemical models covering this altitude range used mostly a mechanistic approach [e.g., *Rose and Brasseur*, 1989; *Lefèvre et al.*, 1994; *Sonnemann et al.*, 1998] in which the complex processes of the troposphere are replaced by boundary conditions applied in the vicinity of the tropopause. However, all these three-dimensional upper atmospheric numerical models for the mesosphere and lower thermosphere usually do not include the troposphere. However, it is well known that mesospheric dynamics are largely determined by upward propagating waves of different kinds that have their origin, in general, in the troposphere. Only very recently, models have been developed which include a detailed dynamical description of the atmosphere including the troposphere, have their upper lid in the thermosphere, and can be coupled to comprehensive chemistry modules (GCMs with interactive chemistry are referred to as chemistry climate models, CCMs). Models of this type are the *Extended Canadian Middle Atmosphere Model* [EXCMAM, *Fomichev et al.*, 2002], the *Whole Atmosphere Community Climate Model* [WACCM, e.g. *Beres et al.*, 2005; *Garcia et al.*, 2007], and the *Hamburg Model of the Neutral and Ionized Atmosphere* [HAMMONIA, *Schmidt and Brasseur*, 2006; *Schmidt et al.*, 2006]. Only these recent models can be expected to realistically describe the atmospheric response to the variability of solar irradiance.

The newly developed HAMMONIA model combines the 3-D dynamics from the ECHAM5 model with the MOZART-3 chemistry scheme and extends from Earth's surface up to about 250 km. In the mesosphere and lower thermosphere the distance between the levels is constant in log-pressure and corresponds to about 2 to 3 km, depending on temperature. *Schmidt et al.* [2006] have performed model simulations on both the doubled CO₂ case and the role of the 11-year solar cycle in trend studies. They find a temperature response to the solar cycle as 2 to 10 K in the mesopause region, with the largest value occurring slightly above the summer mesopause (ca. 100 km). Up to the mesopause, the temperature response may either be positive or negative depending upon longitude, particularly for middle and high latitude in winter. This study (like several other modeling reports) also points out the importance of distinguishing the presentation of results according to the choice of the vertical coordinate system, since the effects of subsidence look quite different at constant geometric than at constant pressure altitude. *Marsh et al.* [2007] have recently used the WACCM (version 3) model. The response of the MLT region in WACCM3 is broadly similar to that of the HAMMONIA model shown in *Schmidt et al.* [2006]. *Marsh et al.* [2007] reported that the global-mean change in temperature for 50-80 km is between 0.3 and 1.5 K/100sfu, for 80-90 km it ranges from 1.5 to 2.5 K/100sfu, and for 90-110 km it is 2.5 to about 5 K/100sfu. There is a local minimum around 66 km above which the solar temperature response increases with increasing height.

7. CONCLUSIONS

As evident from the paper, the comparison of the results obtained by different observations separated by several decades is complicated. Nevertheless, there are a number of occasions where most of the temperature responses to solar variability indicate consistency and some of the differences are even understandable. The present status of MLT region solar response based on the available measurements can be broadly described as follows:

755

- (1) Recognition of positive signal in the annual mean solar response of the MLT regions with an amplitude of a few degrees per 100sfu. This agrees with numerical simulations of coupled models.

- 760 (2) Most Northern Hemispheric results indicate a solar response of the order of 1-3K/100sfu near the OH airglow emission height at mid-latitude which becomes negligible near the Pole.
- (3) In the Southern Hemisphere, the few results reported so far indicate the existence of a stronger solar response near the pole and a weaker response at lower latitudes.
- 765 (4) There is increasing evidence for a solar component of the order of 2-4K/100sfu in the lower thermosphere (92-100 km) which becomes negligible around 103 km.
- (5) In the mesosphere, the mid-latitude solar response of 1-3K/100sfu is consistent with satellite, lidar and US-rocksonde data whereas Russian results indicate a more variable behavior.
- 770 (6) Existence of a solar response of 1-3K/100sfu for the mesospheric region in the tropics.

Most recent GCM model results indicate a higher upper limit of solar temperature response as compared to observations (2 to 10 K per solar cycle in the mesopause region), with the largest value occurs slightly above the summer mesopause (ca. 100 km). Up to the mesopause, the temperature response may either be positive or negative depending upon
775 longitude, particularly for middle and high latitude in winter.

It is becoming increasingly evident that the solar response in the MLT region is highly seasonally dependent. This might explain the dispersion of the values in annually averaged solar response reported in this paper as it might have been caused by the seasonal distribution
780 of observation. The differences in temperature response to solar activity in the mesopause region are mainly caused by changes in the vertical distribution of chemically active gases and by changes in UV irradiation. The intervention of dynamics (e.g., the mediation by planetary waves) further compounds the picture, which is only likely to become clearer, after more results on the long term solar response become available. Hence this topic remains a
785 problem to explore more rigorously in the future.

However, the major challenge is in the interpretation of the various reported results which are diverse and even indicate latitudinal and a considerable amount of longitudinal variability in solar response. The high degree of similarity in the response of the mesosphere to increasing
790 surface concentration of greenhouse gases and to 11-year solar flux variability suggests that climate change in the mesosphere may not be associated with anthropogenic perturbations, alone. If long-term increase in the well-mixed greenhouse gases, in particular CO₂, alters the

thermal structure and chemical composition of the mesosphere significantly and if these anthropogenic effects are of the same magnitude as the effects associated with the 11-year solar cycle then the problem is more difficult to analyze. It is therefore necessary to discriminate between the two effects, and to identify their respective contribution to the thermal and chemical change in the mesosphere. The cyclic nature of the variability in solar UV flux over decadal time scales may provide the periodic signature in the observed response that could be used to identify variations in solar activity and other perturbations causing the changes, but this requires longer series of observations.

8. OUTLOOK

Looking forward, there are many compelling scientific questions and analyses still waiting to be addressed and undertaken. Amongst those relating to the long term response in the MLT region to solar variations are:

- The detailed analysis of the trends of parameters like winds and minor constituent concentration (water vapor and ozone) in the mesopause region in order to properly understand the MLT temperature trends and solar response.
- The monthly-to-seasonal long-term temperature trend and solar cycle response in the mesosphere, including the mesopause region.
- Modeling studies of solar trends as derived from existing General Circulation Models (GCMs). The consistency between observed and modeled temperature, radiation, and chemistry must be evaluated. These studies are expected to yield future measurement recommendations.

Finally, we expect that great progress in understanding the MLT response to solar variations will be provided by the NASA TIMED mission that has just completed 6 years in orbit. Strong evidence for solar cycle influence on the infrared cooling of the thermosphere has already been shown by *Mlynchak et al.*, [2007]. They noted a factor of 3 decrease in the power radiated by NO in the thermosphere from the start of the mission (near solar maximum) through calendar year 2006, which corresponds nearly to solar minimum. The TIMED data set with its measurements of temperatures, constituents (ozone, water vapor, carbon dioxide, O/N₂ ratio, etc.) and solar irradiance will enable a unique dataset from which the effects of the 11-year solar cycle can be confidently determined. Efforts are now

underway to secure operation of the TIMED mission through the next solar maximum in approximately 4-5 years.

9. REFERENCES

830

Azeem, S. M. I., G. G. Sivjee, Y.-I. Won, and C. Mutiso (2007), Solar cycle signature and secular long-term trend in OH airglow temperature observations at South Pole, Antarctica, *J. Geophys. Res.*, 112, A01305, doi:10.1029/2005JA011475.

835

Baker, D.J., and A.T. Stair (1988), Rocket measurements of the altitude distribution of the hydroxyl airglow, *Phys. Scr.*, 37, 611-622.

Bates, D. R. (1951), The temperature of the upper atmosphere, *Proc. Phys. Soc.*, B64, 805-821.

840

Beagley, S. R., J. de Grandpré, J. N. Koshyk, N. A. McFarlane, and T. G. Shepherd (1997), Radiative-dynamical climatology of the first-generation Canadian middle atmosphere model, *Atmos.–Ocean*, 35, 293–331.

Beig, G. (2000), The relative importance of solar activity and anthropogenic influences on the ion composition, temperature and associated neutrals of the middle atmosphere, *J. Geophys. Res.*, 105, 19841-19856.

845

Beig, G. (2002), Overview of the mesospheric temperature trend and factors of uncertainty, *Phys. Chem. Earth*, 27/6-8, 509-519.

Beig, G. and Fadnavis, S. (2003), Implication of Solar Signal in the Correct Detection of Temperature Trend over the Equatorial Middle Atmosphere, *Private communication*.

850

Beig, G., P. Keckhut, R.P.Lowe, R.G.Roble, M.G. Mlynczak, J. Scheer, V.I. Fomichev, D. Offermann, W.J.R. French, M.G. Shepherd, A.I. Semenov, E.E. Remsberg, C.Y. She, , F.J. Lübken, J. Bremer, B.R. Clemesha, J. Stegman, F. Sigernes, and S. Fadnavis (2003), Review of mesospheric temperature trends, *Rev. Geophys.* 41(4), 1015, doi:10.1029/2002RG000121.

855

Beres, J. H., R. R. Garcia, B. A. Boville, and F. Sassi (2005), ‘Implementation of a gravity wave source spectrum parameterization dependent on the properties of convection in the Whole Atmosphere Community Climate model (WACCM)’. *J. Geophys. Res.*, 110, doi:10.1029/2004JD005504.

Bittner, M., D. Offermann, and H.H. Graef (2000), Mesopause temperature variability above a midlatitude station in Europe, *J. Geophys. Res.*, 105(D2), 2045-2085.

- 860 Bittner, M., D. Offermann, H.-H. Graef, M. Donner, and K. Hamilton (2002), An 18-year
time series of OH rotational temperatures and middle atmosphere decadal variations, *J.*
Atmos. Sol. Terr. Phys., *64*(8-11), 1147-1166.
- Boville, B. A. (1995), Middle atmosphere version of the CCM2 (MACCM2): Annual cycle
and interannual variability, *J. Geophys. Res.*, *100*, 9017–9039.
- Brasseur, G. (1993), The response of the middle atmosphere to long-term and short-term
865 solar variability : A two dimensional model, *J. Geophys. Res.*, *98*, 23079-23090.
- Brasseur, G. and S. Solomon (1986), Book "Aeronomy of the Middle Atmosphere" (2nd ed.),
D. Reidel, Norwell, Mass.
- Brasseur, G.P., A. de Rudder, G. M. Keating, and M.C. Pitts (1987), Response of middle
atmosphere to short-term solar ultraviolet variations: II. Theory. *J. Geophys. Res.*,
870 *92*(1), 903–914.
- Brasseur, G.P., X. Tie, P. J. Rasch, and F. Lefvre (1997), A three-dimensional model
simulation of the antarctic ozone hole: Impact of anthropogenic chlorine on the lower
stratosphere and upper troposphere, *J. Geophys. Res.*, *102*, 8909–8930.
- Callis, L.B., M. Nataragan, and J.D. Lambeth (2002), Observed and calculated mesospheric
875 NO_x 1992-1997, *Geophys. Res. Lett.*, *29*, 1030, doi:10.1029/2001GL013995.
- Chanin, M.-L. (2006), Signature of the 11-year solar cycle in the upper atmosphere, *Space*
Sci. Rev., *125*, 261-272.
- Chanin, M.L., P. Keckhut, A. Hauchecorne, and K. Labitzke (1989), The solar activity -
QBO effect in the lower thermosphere, *Ann. Geophys.*, *7*, 463-470.
- 880 Chen, L., J. London, and G. Brasseur (1997), Middle atmospheric ozone and temperature
responses to solar irradiance variations over 27-day periods. *J. Geophys. Res.*, *102*,
29,957– 29,979.
- Chipperfield, M. P., D. Cariolle, P. Simon, R. Ramaroson, and D. J. Lary (1993), A 3-
dimensional modeling study of trace species in the arctic lower stratosphere during
885 winter 1989– 1990, *J. Geophys. Res.*, *98*, 7199–7218.
- Clemesha, B., H. Takahashi, D. Simonich, D. Gobbi, P. Batista (2005), Experimental
evidence for solar cycle and long term changes in the low-latitude MLT region, *J.*
Atmos. Sol. Terr. Phys., *67*, 191-196.
- Crane, A.J. (1979), Annual and semiannual wave in the temperature of the mesosphere as
890 deduced from the NIMBUS 6 PMR measurements, *Q. J. Roy. Meteorol. Soc.*, *105*,
509-520.

- Crutzen, P.J. (1975), Solar proton events: Stratospheric sources of nitric oxide, *Science*, *189*, 457-458.
- 895 Curtis, A. R., and R. M. Goody (1956), Thermal radiation in the upper atmosphere, *Proc. Roy. Soc. London Ser. A*, *236*, 193.
- Deutsch, K.A., and G. Hernandez (2003), Long-term behavior of the OI 558 nm emission in the night sky and its aeronomical implications, *J. Geophys.Res.*, *108*, 1430, doi:10.1029/2002JA009611.
- 900 Donnelly, R. F. (1991), Solar UV spectral irradiance variations, *J. Geomagn. Geoelectr.*, *43*, 835–842.
- Dudok de Wit, T., M. Kretzschmar, J. Aboudarham, P.O. Amblard, F. Auchère, and J. Liliensten (2007), Which solar EUV indices are best for reconstructing the solar EUV irradiance?, *Adv. Space Res.*, doi: 10.1016/j.asr.2007.04.019, in press.
- 905 Dunkerton, T. J., D. P. Delisi, and M. P. Baldwin (1998), Middle atmosphere cooling trend in historical rocketsonde data, *Geophys. Res. Lett.*, *25*, 3371–3374.
- Ebel, A., M. Dameris, H. Hass, A.M. Manson, C.E. Meek, and K. Petzoldt (1986), Vertical change of the response to solar activity oscillations with periods around 13 and 27 days in the middle atmosphere, *Ann. Geophys.*, *4*, 271-280.
- 910 Espy, P. J., and J. Stegman (2002), Trends and variability of mesospheric temperature at high-latitudes, *Phys. Chem. Earth*, *27*, 543–553.
- Fels, S. B., J. D. Mahlman, M. D. Schwarzkopf, and R. W. Sinclair (1980), Stratospheric sensitivity to perturbations in ozone and carbon dioxide: Radiative and dynamical response, *J. Atmos. Sci.*, *37*, 2265–2297.
- 915 Fomichev, V.I., W. E. Ward, S. R. Beagley, C. McLandress, J. C. McConnell, N. A. McFarlane, and T. G. Shepherd (2002), Extended Canadian Middle Atmosphere Model: Zonal mean climatology and physical parameterizations, *J. Geophys. Res.*, *107*, 4087, doi:10.1029/2001JD000479.
- French, W.J.R., and G.B. Burns (2004), The influence of large-scale oscillations on long-term trend assessment in hydroxyl temperatures over Davis, Antarctica, *J. Atmos. Sol. Terr. Phys.*, *66(6-9)*, 493-506.
- 920 French, J.R., G.B. Burns, and P.J. Espy (2005), Anomalous winter hydroxyl temperatures at 69°S during 2002 in a multiyear context, *Geophys. Res. Lett.*, *32(12)*, L12818, doi:10.1029/2004GL022287.
- 925 Garcia, R.R., S. Solomon, R.C. Roble, and D.W. Rusch (1984), A numerical response of the middle atmosphere to the 11-year solar cycle, *Planet. Space Sci.*, *32*, 411.

- Garcia R. R., D. R. Marsh, D. E. Kinnison, B. A. Boville, and F. Sassi (2007), Simulation of secular trends in the middle atmosphere, 1950–2003, *J. Geophys. Res.*, *112*, D09301, doi:10.1029/2006JD007485.
- 930 Golitsyn, G. S., A. I. Semenov, N. N. Shefov, L. M. Fishkova, E. V. Lysenko, and S. P. Perov (1996), Long-term temperature trends in the middle and upper atmosphere, *Geophys. Res. Lett.*, *23*, 1741–1744.
- Golitsyn, G. S., A. I. Semenov, N. N. Shefov, and Khomich, V.Yu. (2006), The response of middle-latitude atmospheric temperature on the solar activity during various seasons, *Phys. Chem. Earth*, *31(1-3)*, 10-15.
- 935 Hamilton, K., R. J. Wilson, J. D. Mahlman, and L. J. Umscheid (1995), Climatology of the SKYHI troposphere–stratosphere–mesosphere general circulation model, *J. Atmos. Sci.*, *52*, 5–43.
- Hampson, J., P. Keckhut, A. Hauchecorne, and M.L. Chanin (2005), The effect of the 11-year solar-cycle on the temperature in the upper-stratosphere and mesosphere: Part II numerical simulation and role of planetary waves, *J. Atmos. Sol. Terr. Phys.*, *67(11)*, 948-958, doi:10.1016/j.jastp.2005.03.005.
- 940 Hampson, J., P. Keckhut, A. Hauchecorne, and M.L. Chanin (2006), The effect of the 11-year solar-cycle on the temperature in the upper-stratosphere and mesosphere - Part III. Investigations of zonal asymmetry, *J. Atmos. Terr. Sol. Phys.*, *68 (14)* 1591–1599, doi:10.1016/j.jastp.2006.05.006.
- 945 Hauchecorne, A., M.-L. Chanin, and P. Keckhut (1991), Climatology and trends of the middle atmospheric temperature (33–87 km) as seen by Rayleigh lidar over the south of France, *J. Geophys. Res.*, *96*, 15,297–15,309.
- Hauchecorne, A., J.-L. Bertaux, and R. Lallement (2005), Impact of solar activity on stratospheric ozone and NO₂ observed by Gomos/Envisat, *Space Science Reviews*, *125(1-4)*, doi:10.1007/s11214-006-9072-3.
- 950 Heath, D.F., A.J. Krueger, and P.J. Crutzen (1977), Solar proton event: Influence on stratospheric ozone, *Science*, *197*, 886-889.
- Hernandez, G. (1976), Lower-thermosphere temperatures determined from the line profiles of the O I 17,924-K (5577 Å) emission in the night sky. 1. Long-term behavior, *J. Geophys. Res.*, *81(28)*, 5165-5172.
- 955 Hernandez, G. (2003), Climatology of the upper mesosphere temperature above South Pole (90°S): Mesospheric cooling during 2002, *Geophys. Res. Lett.*, *30*, 1535, doi: 10.1029/2003GL016887.

- 960 Hood, L (2004), 'Effects of solar UV variability on the stratosphere'. In: J. M. Pap and P. Fox (eds.): *Solar variability and its effects on climate*, No. 141 in Geophys. Monogr. Ser. Washington, DC: AGU, pp. 283–304.
- Höppner, K., and Bittner, M. (2007), Evidence for solar signals in the mesopause temperature variability?, *J. Atmos. Sol. Terr. Phys.*, *69*(4-5), 431-448.
- 965 Huang, T. Y. W., and G. P. Brasseur (1993), Effect of long-term solar variability in a two-dimensional interactive model of the middle atmosphere, *J. Geophys. Res.*, *98*, 20,412–20,427.
- Jackman, C.H., and R.D. McPeters (1985), The response of ozone to solar proton events during solar cycle 21: A theoretical interpretation, *J. Geophys. Res.*, *90*, 7955-7966.
- 970 Keating G., G. Brasseur, J.Y. Nicholson III and A. De Rudder (1985), Detection of the response of ozone in the middle atmosphere to short-term solar ultraviolet variations, *Geophys. Res. Lett.*, *12*, 449-452.
- Keating, G.M., J.Y. Nicholson III, D.F. Yong, G. Brasseur, and A. De Rudder (1987), Response of middle atmosphere to short-term solar ultraviolet variations: 1.
- 975 Observations, *J. Geophys. Res.*, *92*, 889-902.
- Keckhut P., and M.L. Chanin (1992), Middle atmosphere response to the 27-day solar rotation as observed by lidar, *Geophys. Res. Lett.*, *19*, 809-812.
- Keckhut, P., A. Hauchecorne, and M.L. Chanin (1995), Mid-latitude long-term variability of the middle atmosphere trends, and cyclic and episodic changes, *J. Geophys. Res.*, *100*,
- 980 18,887-18,897.
- Keckhut, P., M.E. Gelman, J.D. Wild, F. Tissot, A.J. Miller, A. Hauchecorne, M.L. Chanin, E.F. Fishbein, J. Gille, J.M. Russell III, and F.W. Taylor (1996), Semi-diurnal and diurnal temperature tides (30-55 km): Climatology and effect on UARS-lidar data comparisons, *J. Geophys. Res.*, *101*, 10,299-10,310.
- 985 Keckhut P., F.J. Schmidlin, A. Hauchecorne, and M.L. Chanin (1999), Stratospheric and mesospheric cooling trend estimates from U.S. rocketsondes at low latitude stations (8°S-34°N), taking into account instrumental changes and natural variability, *J. Atmos. Sol. Terr. Phys.*, *61*, 447-459.
- Keckhut P., C. Cagnazzo, M-L. Chanin, C. Claud, and A. Hauchecorne (2005), The 11-year solar-cycle effects on the temperature in the upper-stratosphere and mesosphere: Part I
- 990 - Assessment of observations, *J. Atmos. Sol. Terr. Phys.*, *67*(11), 940-947, doi:10.1016/j.jastp.2005.01.008.

- 995 Kerzenmacher T.E., P. Keckhut, A. Hauchecorne, and M.L. Chanin (2006), Methodological uncertainties in multi-regression analyses of middle-atmospheric data series, *J. Environ. Monit.*, 8, 682-690, doi:10.1039/b603750j.
- Khosravi, R., G. Brasseur, A. Smith, D. Rusch, S. Walters, S. Chabrillat, and G. Kockarts (2002), Response of the mesosphere to human-induced perturbations and solar variability calculated by a 2-d model, *J. Geophys. Res.*, 107, 4358, doi:10.1029/2001JD001235.
- 1000 Kockarts, G. (1980), Nitric oxide cooling in the terrestrial thermosphere, *Geophys. Res. Lett.*, 7(2), 137-140.
- Kokin, G. A., E. V. Lysenko, and S. K. Rosenfeld (1990), Temperature change in the stratosphere and mesosphere during 1964–1988 based on rocket sounding data (in Russian), *Izv. Akad. Nauk. Phys. Atmos. Okeana*, 26, 702–710.
- 1005 Kubicki, A., P. Keckhut, M-L. Chanin, A. Hauchecorne, and G.S. Golitsyn (2007), Temperature trends in the middle atmosphere as seen by historical Russian rocket launches: Part 2, Heiss Island (80.6°N, 58°E), *J. Atmos. Sol. Terr. Phys.*, in press.
- Labitzke, K., and M. L. Chanin (1988), Changes in the middle atmosphere in winter related to the 11-year solar cycle, *Ann. Geophys.*, 6, 643–644.
- 1010 Lefèvre, F. (1994), Chemistry of the 1991/1992 stratospheric winter: Three dimensional model simulations, *J. Geophys. Res.*, 99, 8183–8195.
- Liu, G., and G.G. Shepherd (2006), An empirical model for the altitude of the OH nightglow emission, *Geophys. Res. Lett.*, 33(9), L09805, doi:10.1029/2005GL025297.
- Lopez-Puertas, M., and F. Taylor (2002), Non-LTE Radiative Transfer in the Atmosphere, 1015 World Scientific Publishing Company, pp 450.
- Lowe, R. P. (2002), Long-term trends in the temperature of the mesopause region at mid-latitude as measured by the hydroxyl airglow, paper presented at the 276 WE-Heraeus-Seminar on Trends in the Upper Atmosphere, Wilhelm und Else Heraeus-Stift., Kühlungsborn, Germany.
- 1020 Lübken, F. J. (2000), Nearly zero temperature trend in the polar summer mesosphere, *Geophys. Res. Lett.*, 27, 3603-3606.
- Lübken, F. J. (2001), No long term change of the thermal structure in the mesosphere at high latitudes during summer, *Adv. Space. Res.*, 28(28), 947-953.
- 1025 Manzini, E., N. A. McFarlane, and C. McLandress (1997), Impact of the Doppler spread parameterization on the simulation of the middle atmosphere circulation using the MA/ECHAM4 general circulation model, *J. Geophys. Res.*, 102, 25,751–25,762.

- Marsh, D. R., R. R. Garcia, D. E. Kinnison, B. A. Boville, F. Sassi, S. C. Solomon, and K. Matthes (2007), Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, *J. Geophys. Res.*, *112*, doi:10.1029/2006JD008306.
- 1030 Matsuno, T. (1971), A dynamical model of the stratospheric sudden warming, *J. Atmos. Sci.*, *28*, 1479-1494.
- Matthes, K., U. Langematz, L.J. Gray, K. Kodera, and K. Labitzke (2004), Improved 11-year solar signal in the Freie Universität Berlin Climate Middle Atmosphere Model (FUB-CMAM), *J. Geophys. Res.*, *109*, D06101, doi:10.1029/2003JD004012.
- 1035 McPeters, R.D., C.H. Jackman, and E.G. Stassinopoulos (1981), Observation of ozone depletion associated with solar proton events, *J. Geophys. Res.*, *86*, 12071-12081.
- McPeters, R.D., and C.H. Jackman (1985), The response of ozone to solar proton events during solar cycle 21 – The observations, *J. Geophys. Res.*, *90*, 7945-7954.
- Miyahara, S., Y. Yoshida, and Y. Miyoshi (1993), Dynamic coupling between the lower and upper atmosphere by tides and gravity waves, *J. Atmos. Terr. Phys.*, *55*, 1039–1053.
- 1040 Mohanakumar, K. (1985), An investigation of the influence of the solar cycle on mesospheric temperature, *Planet. Space Sci.*, *33*, 745-805.
- Mohanakumar, K. (1995), Solar activity forcing of the middle atmosphere, *Ann. Geophys.*, *13*, 879–885.
- 1045 Mlynczak, M.G. (1997), Energetics of the mesosphere and lower thermosphere and the SABER experiment, *Adv. Space Res.*, *20*, 1177-1183.
- Mlynczak, M. G., and S. Solomon (1993), A detailed evaluation of the heating efficiency in the middle atmosphere, *J. Geophys. Res.*, *98*, 10, 517-10,542.
- Mlynczak, M. G., C. J. Mertens, R. R. Garcia, and R. W. Portmann (1999), A detailed evaluation of the stratospheric heat budget. II. Global radiation balance and diabatic circulations, *J. Geophys. Res.*, *104*, 6039-6066.
- 1050 Mlynczak M. G., F. J. Martin-Torres, B. T. Marshall, R. E. Thompson, J. Williams, T. Turpin, D. P. Kratz, J. M. Russell III, T. Woods, L. L. Gordley (2007), Evidence for a solar cycle influence on the infrared energy budget and radiative cooling of the thermosphere, *J. Geophys. Res.*, *112*, A12302, doi:10.1029/2006JA012194.
- 1055 Nielsen, K. P., F. Sigernes, E. Raustein, and C. S. Deehr (2002), The 20-year change of the Svalbard OH-temperatures, *Phys. Chem. Earth*, *27*, 555–561.
- Nikoukar, R., G.R. Swenson, A.Z. Liu, and F. Kamalabadi (2007), On the variability of mesospheric OH emission profiles, *J. Geophys. Res.*, *112(D19)*, D19109, doi:10.1029/2007JD008601.
- 1060

- Offermann, D., M. Donner, P. Knieling, and B. Naujokat (2004), Middle atmosphere temperature changes and the duration of summer, *J. Atmos. Solar-Terr. Phys.*, *66*, 437-450.
- 1065 Reagan, J.B, R.E. Meyerott, R.W. Nightingale, R.C. Gunton, R.G. Johnson, J.E. Evans, W.L. Imhof, D.F. Heath, and A.J. Krueger (1981), Effect of the August 1972 solar particle events on stratospheric ozone, *J. Geophys. Res.*, *86*, 1473-1494.
- Reid, G.C., and S. Solomon (1991), Response of the middle atmosphere to the solar proton events of August-December 1989, *Geophys. Res. Lett.*, *18*, 1019-1022.
- 1070 Reisin, E.R., and J. Scheer (2002), Searching for trends in mesopause region airglow intensities and temperatures at El Leoncito, *Phys. Chem. Earth*, *27*(6-8), 563-569.
- Remsberg E. (2007), A reanalysis for seasonal and longer period cycles and the trends in middle-atmosphere temperature from the Halogen Occultation Experiment, *J. Geophys. Res.*, *112*, D099118, doi:10.1029/2006JD007489.
- 1075 Remsberg, E.E., and L.E. Deaver (2005), Interannual, solar cycle, and trend terms in middle atmospheric temperature time series from HALOE, *J. Geophys. Res.*, *110*, D06106, doi: 10.1029/2004JD004905.
- Remsberg, E., L. Deaver, J. Wells, G. Lingenfelser, P. Bhatt, L. Gordley, R. Thompson, M. McHugh, J. M. Russell III, P. Keckhut, and F. Schmidlin (2002), An assessment of the quality of Halogen Occultation Experiment temperature profiles in the mesosphere based on comparisons with Rayleigh backscatter lidar and inflatable falling sphere measurements, *J. Geophys. Res.*, *107*(D20), 4447, doi:10.1029/2001JD001521.
- 1080 Rind, D., R. Suozzo, N.K. Balachandra, and M.J. Prather (1992), Climate change and the middle atmosphere. Part II: The impact of volcanic aerosols, *J. Clim.*, *5*, 189-207.
- 1085 Roble, R.G. (1995), Major greenhouse cooling (yes, cooling): The upper atmosphere response to increased CO₂, *Rev. Geophys.*, *33*, 539-546.
- Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere, *Geophys. Res. Lett.*, *16*, 1441-1444.
- 1090 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*(A9), A09S39, doi:10.1029/2004JA010984.
- Rose, K. and G. Brasseur (1989), A three-dimensional model of chemically active trace

- species in the middle atmosphere during disturbed winter conditions, *J. Geophys. Res.*,
1095 94, 16387-16403.
- Rozanov, E. V., M. E. Schlesinger, T. A. Egorova, B. Li, N. Andronova, and V. A. Zubov
(2004), Atmospheric response to the observed increase of solar UV radiation from
solar minimum to solar maximum simulated by the University of Illinois at Urbana-
Champaign climate-chemistry model, *J. Geophys. Res.*, 109, D01110,
1100 doi:10.1029/2003JD003796.
- Russell, J.M., III, L.L. Gordley, J.H. Park, S.R. Drayson, D.H. Hesketh, R.J. Cicerone, A.F.
Tuck, J.F. Frederick, J.E. Harries, and P.J. Crutzen (1993), The Halogen Occultation
Experiment, *J. Geophys. Res.*, 98, 10,777-10,797.
- Sahai, Y., D. H. Giers, L. L. Cogger, P. R. Fagundes, and G. Garbe (1996), Solar flux and
1105 seasonal variations of the mesopause temperatures at 51°N, *J. Atmos. Terr. Phys.*, 58,
1927– 1934.
- Sassi, F., R.R. Garcia, B.A. Boville, and H. Liu (2002), On temperature inversions and the
mesospheric surf zone, *J. Geophys. Res.*, 107, 4380, doi:10.1029/2001JD001525.
- Scaife, A., J. Austin, N. Butchart, S. Pawson, M. Keil, J. Nash, and I. N. James (2000),
1110 Seasonal and interannual variability of the stratosphere diagnosed from UKMO TOVS
analyses, *Quart.J. Roy. Meteor. Soc.*, 126, 2585–2604.
- Scheer, J., and Reisin, E.R. (2007), Is there an influence of short-term solar activity variations
on mesopause region airglow?, *Adv. Space Res.*, 39(8), 1248-1255,
doi:10.1016/j.asr.2007.01.002.
- 1115 Scheer, J., E.R. Reisin, and C.H. Mandrini (2005), Solar activity signatures in mesopause
region temperatures and atomic oxygen related airglow brightness at El Leoncito,
Argentina, *J. Atmos. Sol. Terr. Phys.*, 67, 145-154, doi:10.1016/j.jastp.2004.07.023.
- Schmidt, H., and G.P. Brasseur (2006), The response of the middle atmosphere to solar cycle
forcing in the Hamburg model of the neutral and ionized atmosphere, *Space Sci. Rev.*,
1120 125(1-4), 345-356.
- Schmidt, H., G. P. Brasseur, M. Charron, E. Manzini, M. A. Giorgetta, 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 CO2
doubling. *J. Climate.*, 19, 3903-3931.
- 1125 Seppälä A., P. T. Verronen, E. Kyrölä, S. Hassinen, L. Backman, A. Hauchecorne, J. L.
Bertaux, D. Fussen (2004), Solar proton events of October–November 2003: Ozone

- depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat, *Geophys. Res. Lett.*, 31, L19107, doi:10.1029/2004GL021042.
- 1130 She, C.Y., and D.A. Krueger (2004), Impact of natural variability in the 11-year mesopause region temperature observation over Fort Collins, CO (41°N, 105°W), *Adv. Space Res.*, 34(2), 330-336.
- Shefov, N.N. (1969), Hydroxyl emission of the upper atmosphere - I. The behaviour during a solar cycle, seasons and geomagnetic disturbances, *Planet. Space Sci.*, 17, 797-813.
- 1135 Shepherd M.G., D.L. Wu, I.N. Fedulina, S. Gurubaran, J.M. Russell, M.G. Mlynczak, and G.G. Shepherd (2007), Stratospheric warming effects in the tropical mesospheric temperature field, *J. Atmos. Sol. Terr. Phys.*, 69(17-18), 2309-2337.
- Sigernes, F., N. Shumilov, , C.S. Deehr, , K.P. Nielsen,, T. Svenøe, , and O. Havnes (2003), , Hydroxyl rotational temperature record from the auroral station in Adventdalen, Svalbard (78°N, 15°E), *J. Geophys. Res.*, 108(A9), 1342,doi:10.1029/2001JA009023.
- 1140 Sivakumar, V., B. Morel, H. Bencherif, J.L. Baray, S. Baldy, A. Hauchecorne, and P.B. Rao (2004), Rayleigh lidar observation of a warm stratopause over a tropical site, Gadanki (13,5°N, 79,2°E), *Atmos. Chem. Phys.*, 4, 1989-1996.
- Summers, M. E., D. F. Strobel, R. M. Bevilacqua, X. Zhu, M. T. DeLand, M. Allen, and G. M. Keating (1990), A model study of the response of mesospheric ozone to short-term solar ultraviolet flux variations, *J. Geophys. Res.*, 95, 22,523– 22,538.
- 1145 Thomas, R.J., C.A. Barth, G.J. Rottman, D.W. Rusch, G.H. Mount, G.M. Lawrence, R.W. Sanders, G.E. Thomas, and L.E. Clemens (1983), Mesospheric ozone depletion during the solar proton event of July 13, 1982 measurements, *Geophys. Res. Lett.*, 10, 253-255.
- 1150 von Savigny, C., K.-U. Eichmann, E.J. Llewellyn, H. Bovensmann, J.P. Burrows, M. Bittner, K. Hoepfner, D. Offermann, M.J. Taylor, Y. Zhao, W. Steinbrecht, and P. Winkler (2004), First near-global retrievals of OH rotational temperatures from satellite-based Meinel band emission measurements, *Geophys. Res. Lett.*, 31, L15111, doi:10.1029/2004GL020410.
- 1155 Week, L.H., R.S. Cuikay, and J.R. Corbin (1972), Ozone measurements in the mesosphere during the solar proton event of 2 Novembre 1969, *J. Atmos. Sci.*, 29, 1138-1142.
- Woods, T. N., and G. J. Rottman (1997), Solar Lyman-alpha irradiance measurements during two solar cycles, *J. Geophys. Res.*, 102, 8769–8779.
- 1160 Zadorozhny, A.M., V.N. Kikhtenko, G.A. Kokin, G.A. Tuchkov, A.A. Tyutin, A.F. Chizhov, and O.V. Shtirkov (1994), Middle atmosphere response to the proton events of October

1989 using the results of rocket measurements, *J. Geophys. Res.*, *99(D10)*, 21059-21070.

Zhu, X., J.-H. Yee, and E. R. Talaat (2003), Effect of short-term solar ultraviolet flux variability in a coupled model of photochemistry and dynamics, *J. Atmos. Sci.*, *60*, 491–509.

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FIGURE CAPTIONS:

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Figure 1: Ground based mesospheric and lower thermospheric data stations for the measurements of temperature. The FPI represents Fabry-Perot Interferometer and ISR represents Incoherent Scatter Radar. Those stations whose results have been used in the present paper are marked with *sign.

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Figure 2: Atmospheric temperature response to the 27-days and 11-years solar cycle as a function of altitude from different studies focus on tropical regions. SAMS [Keating *et al.*, 1987] and PMR [Ebel *et al.*, 1986] analyses are performed on the solar rotation time scale. HALOE analyses above the $\pm 20^\circ$ latitude band [Remsberg, 2007] concern the 11-years time scale. Two different analyses [Beig and Fadvanis, 2003, Kokin *et al.*, 1990] have been used to analyze the soviet rocket station of Thumba.

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Figure 3: Atmospheric temperature response to the 11-years solar cycle as a function of altitude from different studies covering mid-latitudes. Error bars associated with the OHP lidar correspond to the range of seasonal changes [Keckhut *et al.*, 2005]. The hatched area corresponds to the HALOE observations in different latitude bands [Remsberg, 2007]. ‘US Rocket’ correspond to an average of 3 subtropical rocket stations [Keckhut *et al.*, 1999]. The Soviet rocket sites (Volgograd, Molodezhnaya, Heiss) have been analysed by Kokin *et al.* [1990] and Golitsyn *et al.* (2006).

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Figure 4: Solar cycle response in the Northern Hemisphere for the mesopause region.

Figure 5: Solar cycle response in the Southern Hemisphere for the mesopause region.

Figure 6: Solar cycle response in the lower thermospheric region.

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Table 1. Solar heating, chemical heating, and radiative cooling terms, and associated airglow losses, for the mesosphere and lower thermosphere.

Table 2. Solar response in Temperature in the Mesosphere (50-79 km) Region

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Table 3. Solar response in temperature of the mesopause region

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Table 1. Solar heating, chemical heating, and radiative cooling terms, and associated airglow losses, for the mesosphere and lower thermosphere

	<u>Solar Heating</u>	<u>Chemical Heating</u>	<u>Radiative Cooling</u>
1210	O ₂ Schumann-Runge Continuum	H + O ₃ → OH + O ₂	CO ₂ (ν ₂) - 15 μm
	O ₂ Schumann-Runge Bands	H + O ₂ + M → HO ₂ + M	O ₃ (ν ₃) - 9.6 μm
	O ₂ Lyman-alpha	O + OH → H + O ₂	NO(ν) - 5.3 μm
	O ₂ Atmospheric Bands	O + HO ₂ → OH + O ₂	H ₂ O rotational - 25-50 μm
1215	O ₃ Hartley Band	O + O + M → O ₂ + M	O(³ P) - 63 μm
	All radiation λ < 120 nm	O + O ₂ + M → O ₃ + M	
		O + O ₃ + M → O ₂ + O ₂	
	<u>Associated airglow losses</u>		
1220	O ₂ (¹ Δ) - 1.27 μm	OH(ν = 1 to 9)	
	O ₂ (¹ Σ) - 762 nm	O ₂ (¹ Δ) - 1.27 μm	
	CO ₂ (ν ₃) - 4.3 μm	O ₃ (ν ₃) - 9.6 μm	

Table 2. Solar response in temperature in the mesosphere (50-79 km) Region

Reference	Technique	Years of Analysis	Location	Height (km)	11 year Solar cycle response (K)	Remarks
Keating et al. (1987)	SAMS	1980's	tropics	70 60 50	2.5 1.2 1.1	27 days
Ebel et al., (1986)	PMR	1975-1978	tropics	50 60 70	3.5 3 2.3	27 days
Remsberg, (2007)	HALOE	1991-2005	tropics	50 60 70	0.9 1 1.2	
Remsberg, (2007)	HALOE	1991-2005	mid-latitude	50 60 70	0.95 1.5 2.05	
Beig and Fadnavis (2002)	Indian-rocketsonde	1971-1993	8.5°N, 77°E	50 60 70	-0.8 0.2 3	
Kokin et al., (1990)	Indian-rocketsonde	1971-1993	8.5°N, 77°E	50 60 70	-0.5 1.8 1.2	
Keckhut et al., (2005)	US-rocketsonde	1969-1995	22°N-34°N	50 60 70	1.8 2.4 0.4	
Keckhut et al., (2005)	Lidar	1979-1997	44°N, 6°E	50 60 70	0.75 2.2 1.7	
Golitsyn et al. (2006) and Kokin et al. (1990)	Volgograd rocketsonde	1971-1993	48.7°N, 44°E	50 60 70	-1.8 4 3	
Golitsyn et al. (2006) and Kokin et al. (1990)	Heiss Island rocketsonde	1971-1993	80.6°N, 58°E	50 60 70	-3 3 5	

Golitsyn et al. (2006) and Kokin et al.(1990)	Molodezhnaya rocketsonde	1971-1993	68°S, 46°E	50 60 70	1 0.5 5	
Lübken (2000a, b)	Rocket grenades Falling spheres	1960s, 1970+ 1987-2000	69°N, 10°E	50-80	no response (summer)	most observations during solar minimum 1960s, 80s, 90s

Table 3. Solar response in temperature of the mesopause region

(a) Lower mesopause region (80-90 km)						
Reference	Technique	Years of Analysis	Location	Height (km)	Temperature solar response (K /100sfu)	Remarks
NORTHERN HEMISPHERE						
Sigernes et al. (2003)	Hydroxyl rotational temperature Bands: 6-2 Bands: 8-3	1983-2002 1980-1983	78°N, 15°E	OH emission layer	+0.0 (±0.5) (winter)	
Lübken (2000, 2001)	Rocket grenades Falling spheres	1960s, 1970+ 1987-2000	69°N, 10°E	80	no response (summer)	most observations during solar minimum 1960s, 80s, 90s
Espy and Stegman (2002)	Hydroxyl rotational temperature Band: 3-1 also 4-2	1991-1998	59.5°N, 18°E	OH emission layer	1.6 (±0.8) (winter)	consistent with +2 K/100sfu [Espy, personal communication 2007]
Pertsev and Perminov (2007)	Hydroxyl rotational temperature Band: 6-2	2000-2006	55.7°N, 37°E	OH emission layer	7.5 (±0.5) (winter) 2 (±2.0) (summer) 4.5 (±0.5) (annual)	Also intensity response for OH and O ₂ bands
Offermann et al. (2004)	Hydroxyl rotational temperature Band: 3-1	1980-1984 1987-2002	51.3°N, 7°E	”	+3.0 (±1.6)	
Lowe (2002)	Hydroxyl rotational temperature Band: 3-1, 4-2	1989-2001	42.5°N, 81°W	”	+1.5 (± 1.1)	
Golitsyn et al. (2006)	Combined (Major: Hydroxyl rotational temperature Bands: several)	1976-1991	41.8°N, 43°E and 55.7°N, 37°E	80-95	-5 (±1.7) (winter) +8 (±1.7) (summer) +2.7 (±1.7) (annual)	
She and Krueger	Na-Lidar	1990-2001	41°N, 105°W	83	0.0 (±1.0)	update C.-Y.She, personal

(2004)				87	3 (± 1)	communication [2007]
Remsberg, and Deaver (2005)	UARS –HALOE - sunrise, sunset (satellite)	1991-2004	40°S - 40°N	80	0.5-1.7 amplitudes (± 0.6)-> 1.5 (± 0.8) K/100sfu	range of solar response estimated from published amplitude
SOUTHERN HEMISPHERE						
Azeem et al. (2007)	Hydroxyl rotational temperature Bands: 3-1	1994–2004	90°S Antarctica	OH-emission layer height (87)	4.0 (± 1.0) (winters)	
Hernandez et al. (2003)	Hydroxyl rotational temperature Bands:6-2	1991-2002	90°S	”	13.2 (± 3.5) (winter)	Doppler (kinetic) temperature
French et al.(2005)	Hydroxyl rotational temperature, Band: 6-2	1990, 1995-2003	69°S, 78°E	”	4.8 (± 1.3) (winter)	
French and Burns (2004)	Hydroxyl rotational temperature, Band: 6-2	1995-2001	69°S, 78°E	”	6-7 (mid-winter)	published range
Reisin and Scheer (2002)	Hydroxyl rotational temperature Band: 6-2	1986, 1987, 1992, 1997-2001	32°S, 69°W	”	no response	
Scheer et al. (2005)	Hydroxyl rotational temperature Band: 6-2	1998-2002	32°S, 69°W	”	0.92 (± 0.32)	
Clemesha et al. (2005)	Hydroxyl rotational temperature Band: 9-4 Bands: 6-2	1987-1994 1994-2000	23°S, 45°W	”	8-10	range of solar response estimated from published amplitude
(b) upper mesopause region and lower thermosphere (90-110 km)						
Reference	Technique	Years of Analysis	Location	Height (km)	Temperature solar response (K /100sfu)	Remarks
Golitsyn et al.	estimated from	1976-1991	41.8°N, 43°E	92	2.8 (± 1.2)	

(2006)	Sodium emission intensity		and 55.7°N, 37°E			
Golitsyn et al. (2006)	estimated from Atomic oxygen emission intensity	1976-1991	41.8°N, 43°E and 55.7°N, 37°E	97	2.3 (±1.1)	
She and Krueger (2004)	Na-Lidar	1990-2001	41°N, 105°W	92-98 103	4.0 (±1.8) 0.0 (±1.4)	
Reisin and Scheer (2002)	O ₂ (0-1) rotational temperature	1986, 1987, 1992, 1997- 2001	32°S, 69°W	O ₂ emission height (95 km)	1.6-5.6	range of upper limit estimates
Scheer et al. (2005)	O ₂ (0-1) rotational temperature	1998-2002	32°S, 69°W	O ₂ emission height (95km)	3.3 (± 0.3) no trend 1.32 (± 0.3) with temporal trend	mean response. See text for details

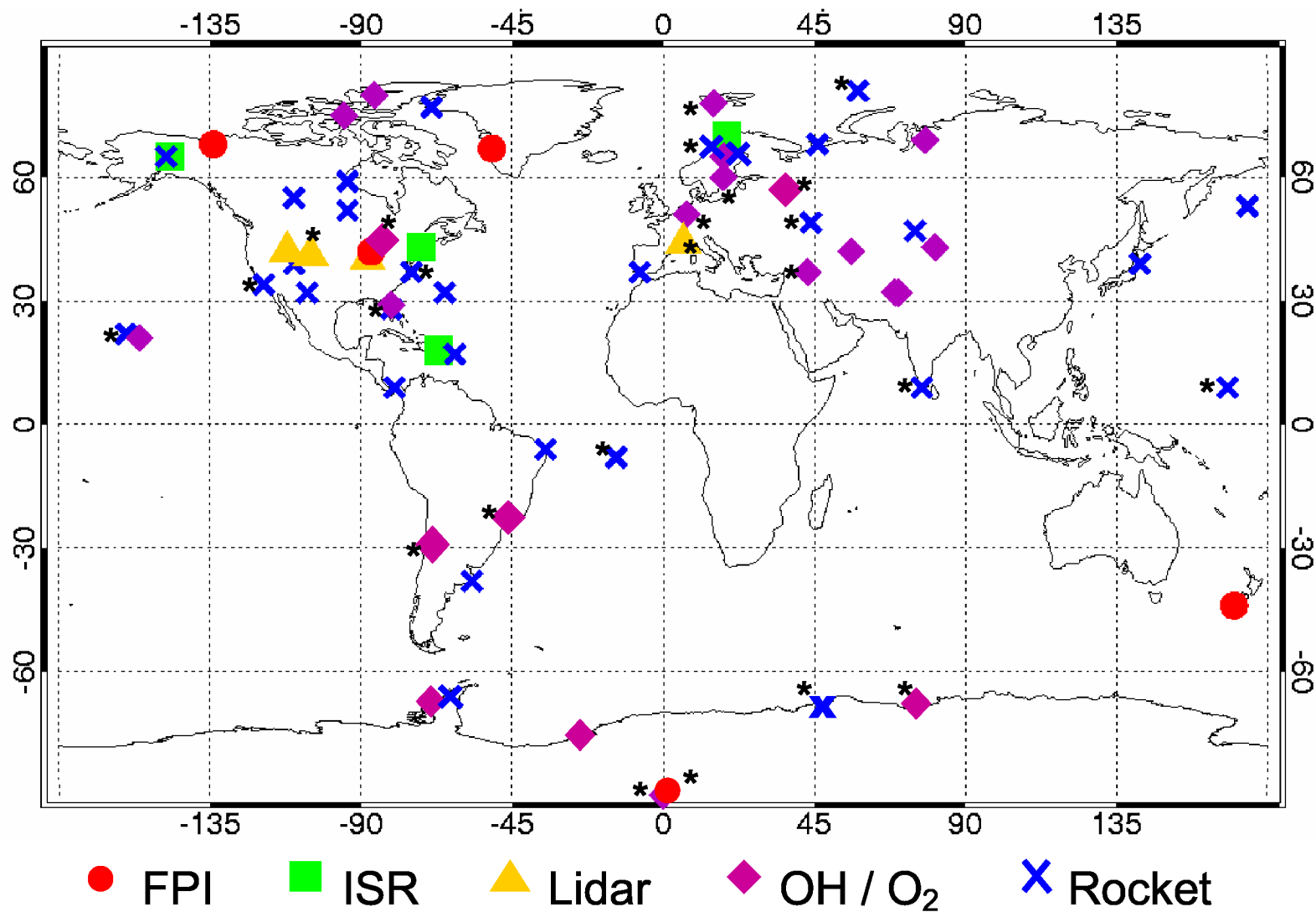
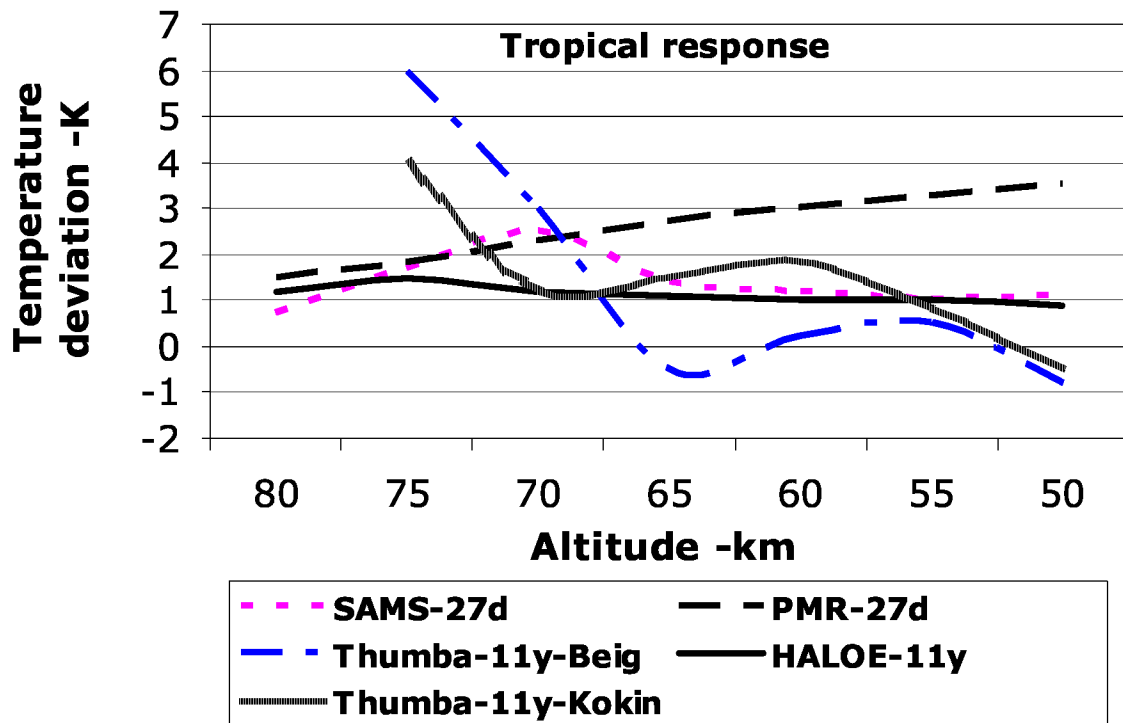


Figure 1: Ground based mesospheric and lower thermospheric data stations for the measurements of temperature. The FPI represents Fabry-Perot Interferometer and ISR represents Incoherent Scatter Radar. Those stations whose results have been used in the present paper are marked with *sign.



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Figure 2: Atmospheric temperature response to the 27-days and 11-years solar cycle as a function of altitude from different studies focus on tropical regions. SAMS [Keating *et al.*, 1987] and PMR [Ebel *et al.*, 1986] analyses are performed on the solar rotation time scale. HALOE analyses above the $\pm 20^\circ$ latitude band [Remsberg, 2007] concern the 11-years time scale. Two different analyses [Beig and Fadvanis, 2003, Kokin *et al.*, 1990] have been used to analyze the soviet rocket station of Thumba.

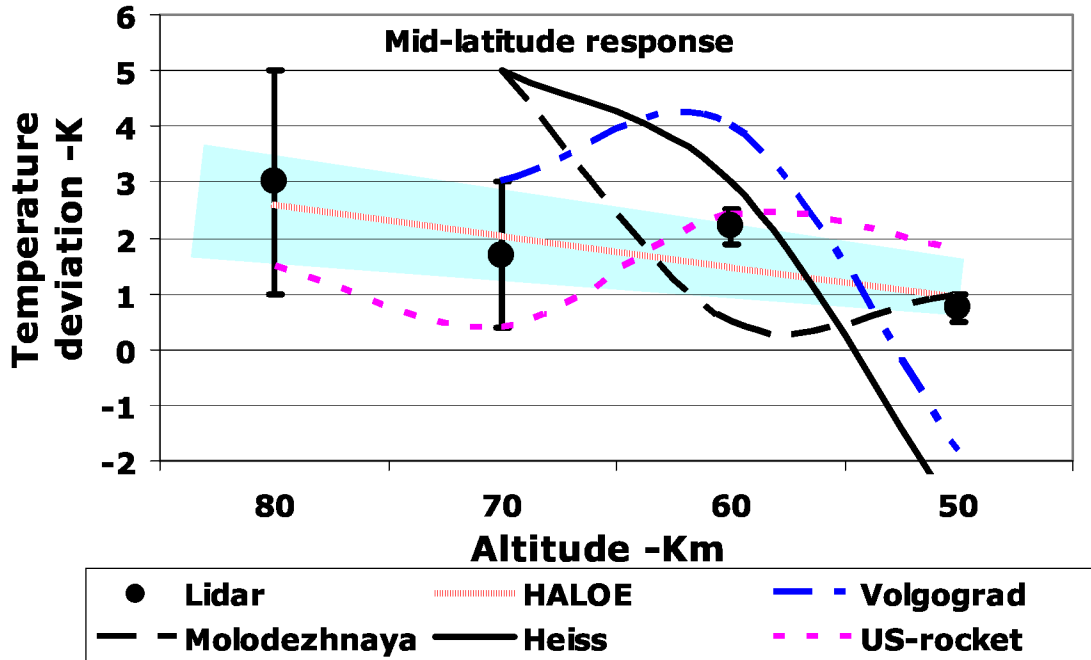


Figure 3: Atmospheric temperature response to the 11-years solar cycle as a function of altitude from different studies covering mid-latitudes. Error bars associated with the OHP lidar correspond to the range of seasonal changes [Keckhut *et al.*, 2005]. The hatched area corresponds to the HALOE observations in different latitude bands [Remsberg, 2007]. ‘US Rocket’ correspond to an average of 3 subtropical rocket stations [Keckhut *et al.*, 1999]. The Soviet rocket sites (Volgograd, Molodezhnaya, Heiss) have been analysed by Kokin *et al.* [1990] and Golitsyn *et al.* (2006).

Northern Hemisphere
Solar Influence at Mesopause Region
Temperature [87 (+/-) km]

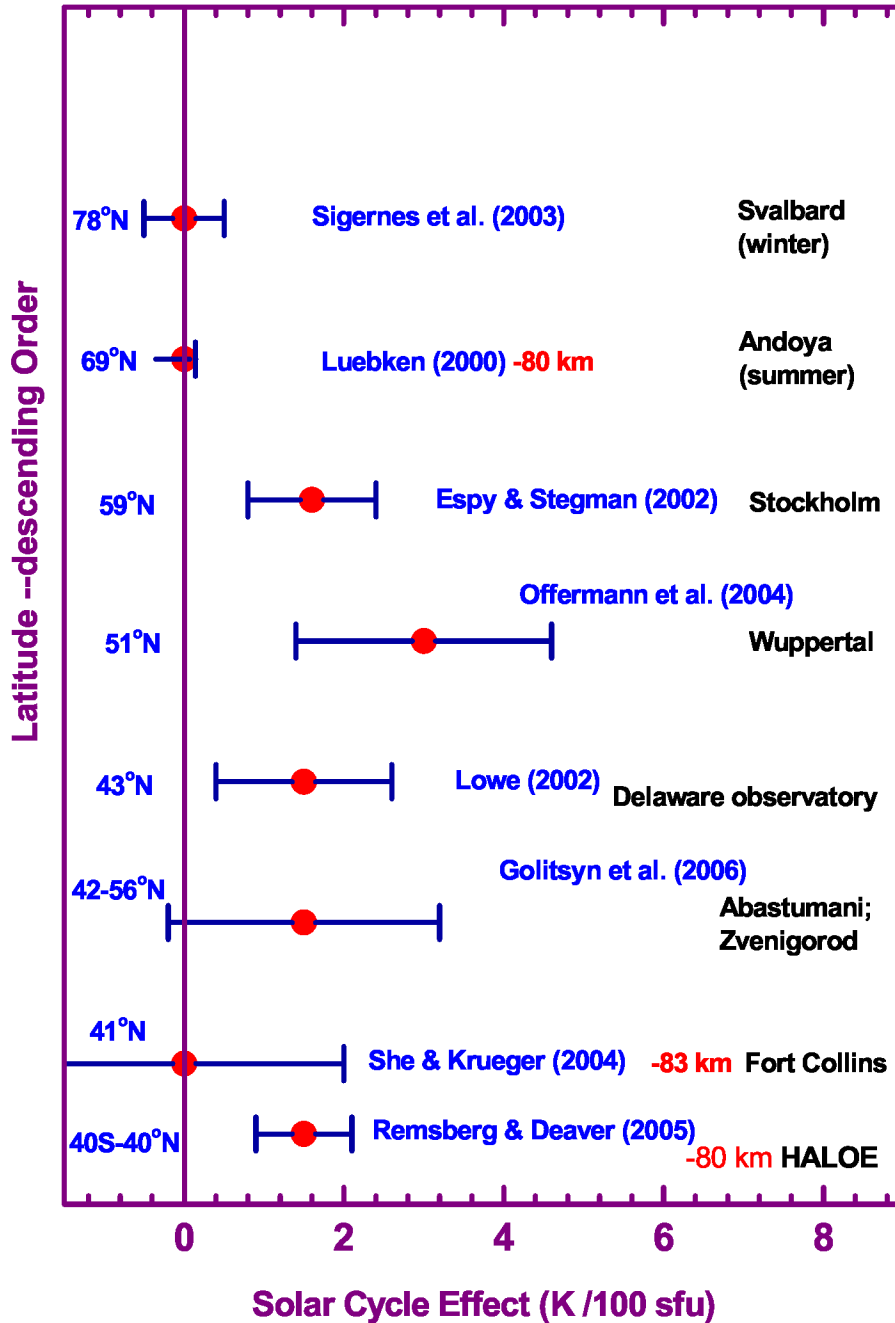


Figure 4: Solar cycle response in the Northern Hemisphere for the mesopause region.

Southern Hemisphere
Solar Influence at Mesopause Region
Temperature [87 (+/-) km]

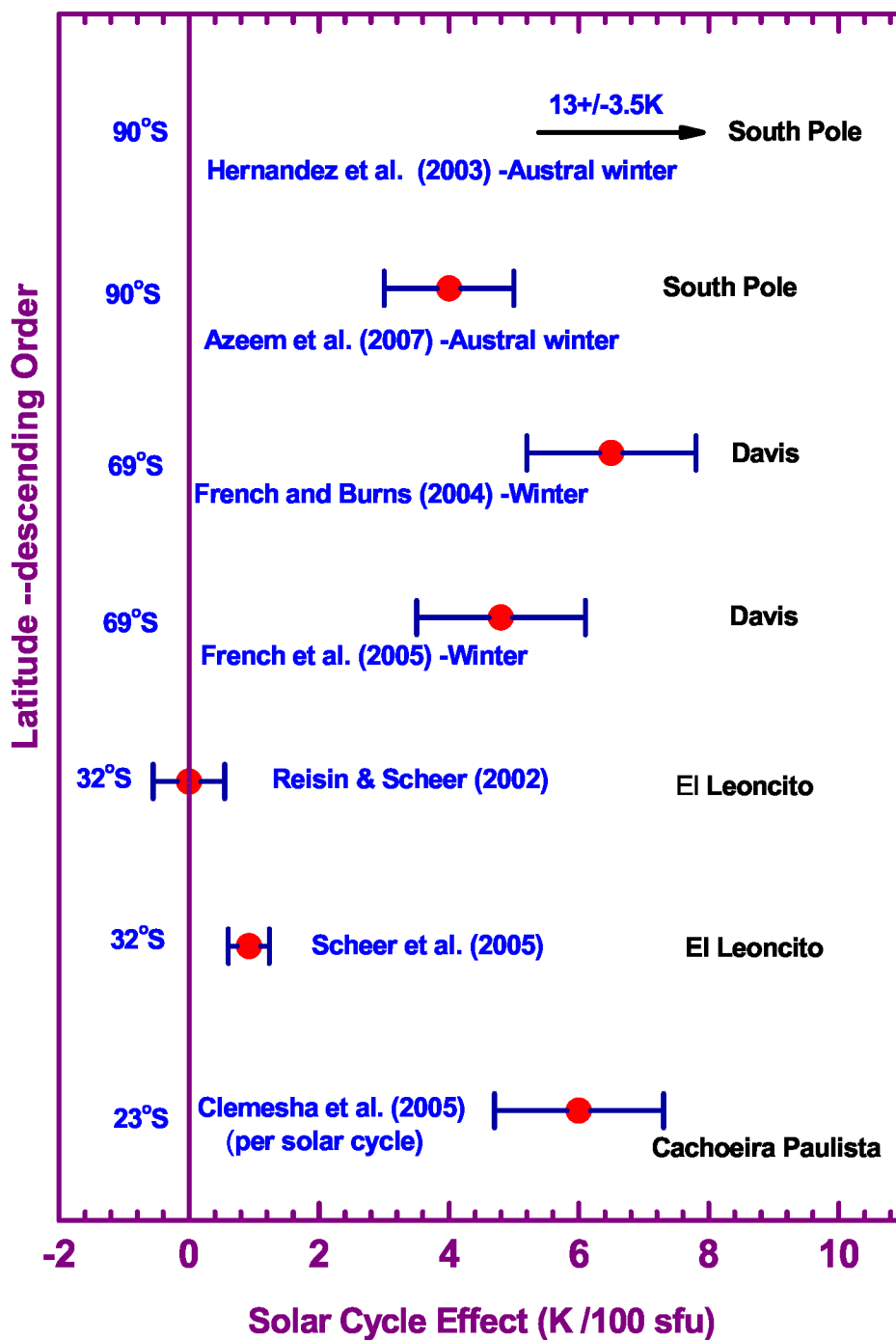


Figure 5: Solar cycle response in the Southern Hemisphere for the mesopause region.

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Lower Thermosphere Solar Response in Temperature

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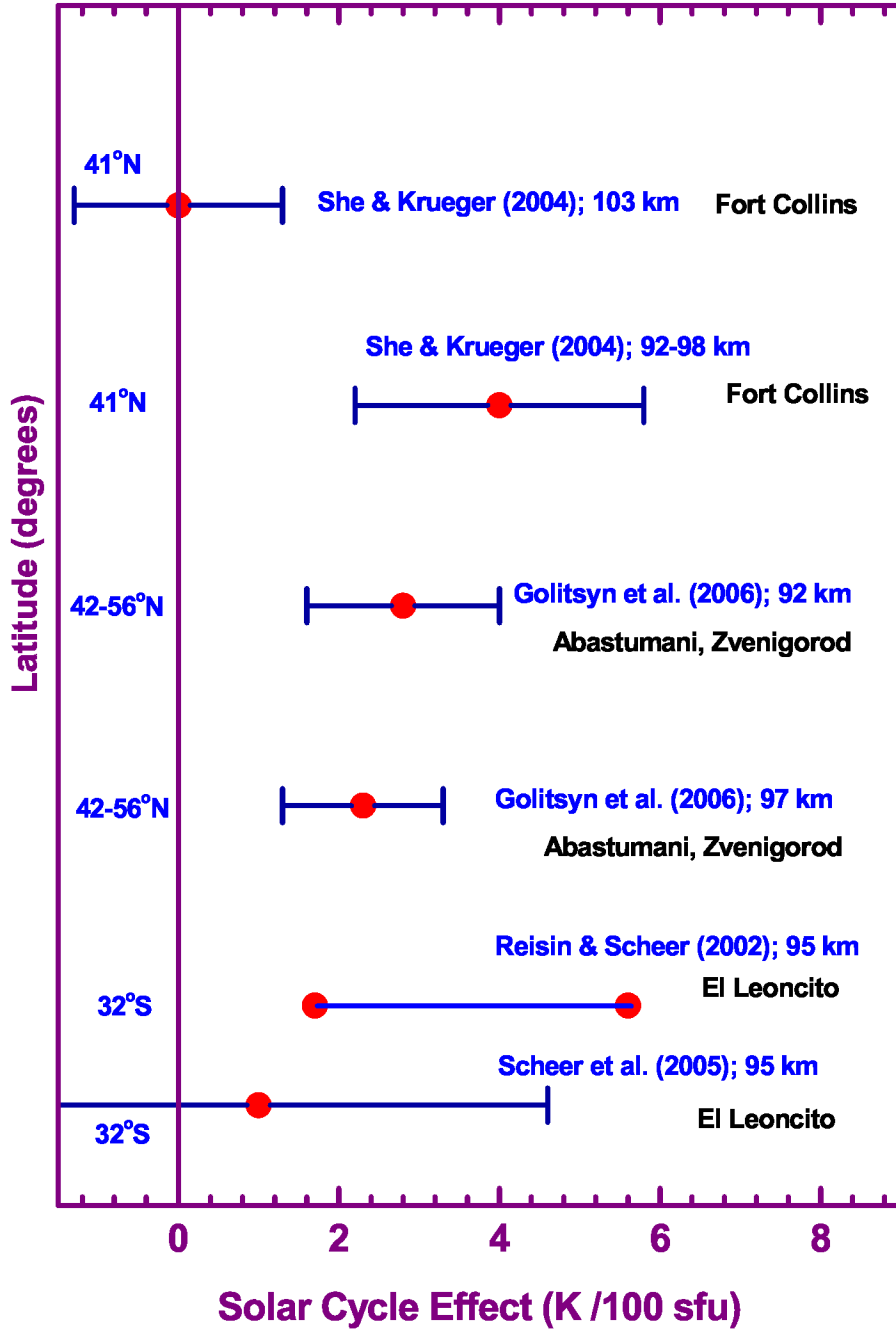


Figure 6: Solar cycle response in the lower thermospheric region.