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# OVERVIEW OF THE TEMPERATURE RESPONSE IN THE MESOSPHERE AND LOWER THERMOSPHERE TO SOLAR ACTIVITY

G. Beig,<sup>1</sup> J. Scheer,<sup>2</sup> M. G. Mlynczak,<sup>3</sup> and P. Keckhut<sup>4</sup>

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[1] 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 cases revealed 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 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

[2] The study of the 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 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.

[3] Variations arising on decadal and even longer timescales 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 ultraviolet (UV) wavelengths on different timescales [Donnelly, 1991]. Incoming solar radiation pro-

vides 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-d and 11-year solar cycles exhibits the largest changes, up to a factor of 2 over a solar cycle for the solar Lyman alpha flux. Studies on the changes in solar UV spectral irradiance on timescales of the 27-d and 11-year solar cycles have been attempted by many workers in the past [e.g., Donnelly, 1991; Woods and Rottman, 1997]. 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].

[4] 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 (1 or 2 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 to 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 include solar and geomagnetic activity, local time, season, latitude, and maybe some other parameters. The solar and geomagnetic activity may have a crucial impact on the trend determination when data series

<sup>1</sup>Indian Institute of Tropical Meteorology, Pune, India.

<sup>2</sup>Instituto de Astronomía y Física del Espacio, Buenos Aires, Argentina.

<sup>3</sup>Climate Science Branch, NASA Langley Research Center, Hampton, Virginia, USA.

<sup>4</sup>Service d'Aéronomie, Institut Pierre Simon Laplace, Université de Versailles-Saint-Quentin-en-Yvelines, Verrières-Le-Buisson, France.

are relatively short or when we study trends in 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 UV radiation derived from data of insufficient quality and/or length. This situation only changed with the Solar Mesosphere Explorer (SME) and Upper Atmosphere Research Satellite (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 kelvins 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 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 temperatures have been reported. It was thought earlier that it would be hard to identify a trend in the mesosphere and lower thermosphere (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 in temperature of the MLT region have been reported [*She and Krueger*, 2004, and references therein].

[5] 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 temperature trends for the MLT region [*Beig*, 2002] and will have strong implications in the quantification of global change signals. In recent times, the search for the effects of the 11-year 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 amplitude) and at the stratopause (1–2 K amplitude) [e.g., *Brasseur*, 1993; *Matthes 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 increases 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] and also according to several observations; see section 5), 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.

[6] 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 trend in thermal structure for this region be prepared.

[7] Before ground-based instrumentation with sensitive photoelectric registration and rocket-borne in situ measurements became available, the search for solar cycle effects was conducted with visual airglow photometry in the 1920s and with photographic spectrography. These techniques, which were still dominant in the 1960s, are 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 becoming 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 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 work by *Hernandez* [1976]. Other useful references focusing on green line intensity variations can be found in work by *Deutsch and Hernandez* [2003].

[8] This article reviews the present status of observational and modeling evidence of 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 important uncertainty factors are outlined. We also discuss the lower thermosphere briefly. For convenience, the whole region from 50 to 100 km is referred to as the MLT region. The region from 50 to 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

**TABLE 1. Solar Heating, Chemical Heating, and Radiative Cooling Terms and Associated Airglow Losses for the Mesosphere and Lower Thermosphere**

Summary	
Solar heating	O <sub>2</sub> Schumann-Runge continuum, O <sub>2</sub> Schumann-Runge bands, O <sub>2</sub> Lyman alpha, O <sub>2</sub> atmospheric bands, O <sub>3</sub> Hartley band, all radiation $\lambda < 120$ nm
Chemical heating	H + O <sub>3</sub> → OH + O <sub>2</sub> , H + O <sub>2</sub> + M → HO <sub>2</sub> + M, O + OH → H + O <sub>2</sub> , O + HO <sub>2</sub> → OH + O <sub>2</sub> , O + O + M → O <sub>2</sub> + M, O + O <sub>2</sub> + M → O <sub>3</sub> + M, O + O <sub>3</sub> + M → O <sub>2</sub> + O <sub>2</sub>
Radiative cooling	CO <sub>2</sub> ( $\nu_2$ ), 15 $\mu\text{m}$ ; O <sub>3</sub> ( $\nu_3$ ), 9.6 $\mu\text{m}$ ; NO( $\nu$ ), 5.3 $\mu\text{m}$ ; H <sub>2</sub> O rotational, 25–50 $\mu\text{m}$ ; O( <sup>3</sup> P), 63 $\mu\text{m}$
Associated airglow losses	O <sub>2</sub> ( <sup>1</sup> $\Delta$ ), 1.27 $\mu\text{m}$ ; O <sub>2</sub> ( <sup>1</sup> $\Sigma$ ), 762 nm; CO <sub>2</sub> ( $\nu_3$ ), 4.3 $\mu\text{m}$ ; OH( $\nu = 1-9$ ); O <sub>2</sub> ( <sup>1</sup> $\Delta$ ), 1.27 $\mu\text{m}$ ; O <sub>3</sub> ( $\nu_3$ ), 9.6 $\mu\text{m}$

and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument data.

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

[9] 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. 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]. We will provide a brief overview of the energy budget of the MLT region in this section, following the corresponding presentation by Beig et al. [2003], where more details are given.

[10] The critical elements of the MLT energy budget are heating due to the absorption of solar radiation by O<sub>2</sub>, O<sub>3</sub>, and CO<sub>2</sub>; cooling due to infrared emission from NO, CO<sub>2</sub>, O<sub>3</sub>, H<sub>2</sub>O, and atomic oxygen (O); heating due to exothermic chemical reactions involving odd oxygen and odd hydrogen species; energy loss due to airglow emission by O<sub>2</sub>(<sup>1</sup> $\Delta$ ), O<sub>2</sub>(<sup>1</sup> $\Sigma$ ), CO<sub>2</sub>(4.3  $\mu\text{m}$ ), and OH( $\nu$ ). 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 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 when associ-

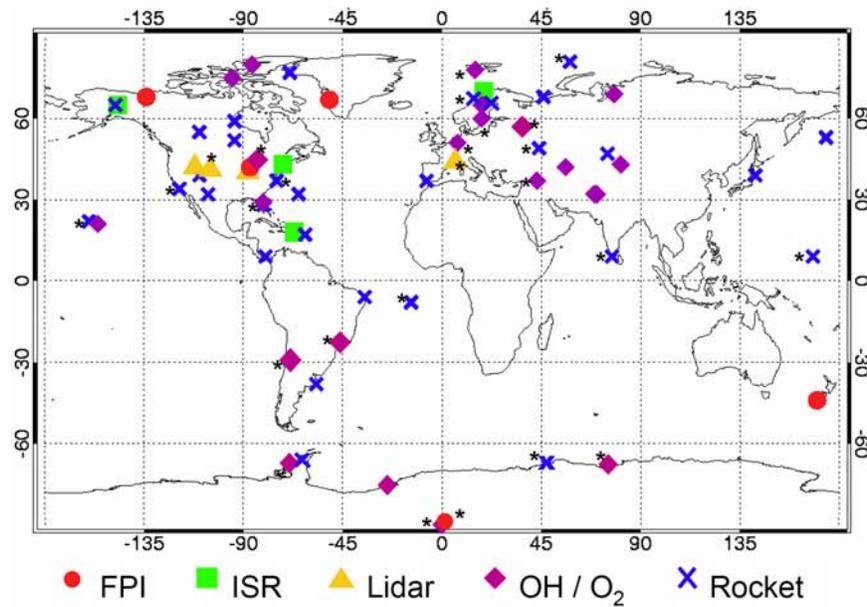
ated with solar flare or coronal mass ejection (CME) events. A summary of key heating (solar and chemical) and infrared cooling terms is given in Table 1.

[11] 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 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 because of these processes, as low as 65%. The details of the solar and chemical heating and the associated efficiencies are reviewed by Mlynczak and Solomon [1993].

[12] 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 consideration of the exchange of energy (thermal, radiative, and 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 CO<sub>2</sub> and O<sub>3</sub> [Curtis and Goody, 1956], H<sub>2</sub>O [e.g., Mlynczak et al., 1999], NO [Kockarts, 1980], and O [Bates, 1951]. Of these, the CO<sub>2</sub>, O<sub>3</sub>, 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  $\mu\text{m}$ ) that are more readily thermalized by collisions and thus are maintained in LTE.

[13] 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-d 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.

[14] 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



**Figure 1.** Ground-based mesospheric and lower thermospheric data stations for the measurements of temperature. 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 asterisks.

ozone abundance and thereby modifying 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.

### 3. TECHNIQUES AND OBJECTIVE EVALUATION OF TEMPERATURE DATA SETS

[15] In addition to the satellite data sets, 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.

[16] In addition to ground-based observations which are capable of supplying long data sets at fixed geographic locations, in situ data from rocketsondes and global observations from satellites can also 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 by *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 by *Beig et al.* [2003], even for standard instrumentation used for a 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-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 for studying solar cycle variations.

[17] 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 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 the work by *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, 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  $1.9 \pm 1.4$  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. The observed variability does not invalidate ground-based measurements of hydroxyl rotational 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 can be considered as part of the phenomenon. The same holds for the O<sub>2</sub> atmospheric band, with a nominal emission peak height of 95 km.

[18] From OH or O<sub>2</sub> airglow observations, temperature precisions of a few kelvins 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 an influence on trend or solar activity results only if they vary with time. They are not a problem if long-term stability can be assured, and one way to ensure stability is with good instrument calibration. The discussion about this point by *Beig et al.* [2003] is mostly important in the context of the possibility of detecting small long-term trends. For detecting effects of the 11-year solar cycle, which has a risetime of only about 4 years, and where responses of several kelvins have been reported, the instrument stability requirements are less stringent. The relative calibration of the instrument response at two or more wavelengths necessary for determining rotational temperature is not difficult.

[19] The rotational temperatures in the mesopause region vary on timescales from a few minutes for short-period gravity waves to the solar cycle and beyond. Nocturnal mean temperatures 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 canceled out. This “geophysical noise” can be expected to be quite variable and so to create only small uncertainties on longer timescales. There is, however, also a day-to-day variability from planetary waves and unknown sources which could not be avoided even if 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.

[20] Apart from O<sub>2</sub> rotational temperatures, some data sets extend the information available above the altitude of OH by using atomic line intensities from sodium or atomic oxygen as a proxy for temperature on the basis of 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, whether by the measurement of O<sub>2</sub> rotational temperature, by the measurement of Doppler width with Fabry-Perot instruments, or by laser spectroscopy with sodium lidars.

[21] 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, seasonal) or is itself strongly variable. The data sets from different measurement techniques vary widely in the number of years

covered and even more widely 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, 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 less than 100 to several hundred profiles may be available from a given site, but a considerable altitude range is covered. 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 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 and refers to only slowly varying local time, and the available long-term coverage is still small. The Scanning Imaging Absorption Spectrometer for Atmospheric Cartography instrument on Envisat is capable of measuring OH rotational temperature by limb sounding [*von Savigny et al.*, 2004]. It was launched only in 2004 but can be expected to contribute data on solar activity response in the near future.

#### 4. OBSERVATIONS OF THE SOLAR RESPONSE IN THE MESOSPHERE

[22] 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, instrument drifts, and the strong longitudinal variability that makes zonal means appear quite noisy [see *Chanin*, 2007]. On this timescale the quasi-coincidence of the recent major volcanic eruptions with solar maximum conditions [*Kerzenmacher et al.*, 2006] 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 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 fewer resources for continuous operations have replaced the rocket techniques. From space, the Halogen Occultation Experiment (HALOE) aboard the UARS is the only experiment that measures mesospheric temperature over more than a decade with a single instrument. However, while global, the number of solar occultations does not provide as large a sampling as is desirable.

[23] The solar activity is also modulated by the solar rotation, and UV series exhibit strong responses with periods of 27 d and harmonics. On this scale more temper-

ature series are available. From the ground, rockets and lidars can be used. However, lidars are more adequate for performing 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 present smaller amplitudes than the solar cycle and are highly nonstationary. In the case of the Sun, the physical processes governing the evolution of active regions and the resulting variations in the solar output are, at best, only quasi-stationary over a limited time period.

[24] On the time range of solar cycle the radio flux at 10.7 cm is used as a proxy of solar activity 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.* [2008] for a recent investigation of this topic). In the middle atmosphere, ozone and temperature are highly connected because of thermal ozone absorption and thermal sensitivity of the ozone dissociation, so the simultaneous investigations of ozone and temperature allow for a better understanding of the middle atmosphere response to solar activity changes. Ozone measurements on SME and on Nimbus 7 were analyzed. At high latitudes, direct ozone response to solar activity variations (and hence temperature) 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 the work by *Scheer and Reisin* [2007]).

[25] In photochemical models, the ozone sensitivity on the 27-d and 11-year scales is 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.

#### 4.1. Changes due to 27-Day UV Solar Forcing

[26] 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 Stratospheric and Mesospheric Sounder (SAMS) instrument on the Solar Mesosphere Explorer (SME) satellite. In the  $\pm 20^\circ$  latitude band at 2 hPa a temperature variation of 1.5 K for 10% ozone change is reported, which grows to 2.5 K 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 d in the mesosphere, and the altitude of maximum temperature sensitivity is close to the altitudes of maximum ozone depletion. Therefore, in addition to the  $\text{HO}_x$  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 midlatitudes, 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 d. On the other hand, planetary waves may be directly involved in the solar forcing (see below).

[27] *Ebel et al.* [1986] have suggested that the generation of vertical wind oscillations in the 27-d 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] because of the compensating effect of adiabatic heating.

[28] Radiance measurements were made with the pressure modulated radiometer (PMR) on board Nimbus 6 [*Crane*, 1979]. Maximum values obtained for the 27-d 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  $50^\circ$  and  $70^\circ$  [*Ebel et al.*, 1986]. Since indirect perturbations seem to exceed the direct ones in amplitude, nonlinear 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.

#### 4.2. Changes on the 11-Year Solar Scale

[29] 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 shows a positive correlation between the temperature and the solar activity with an effect of 1–2 K 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 simulation, a positive effect is expected in the mesosphere. Because the winter response results in a dynamic feedback, the signature is expected to be nonzonal 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

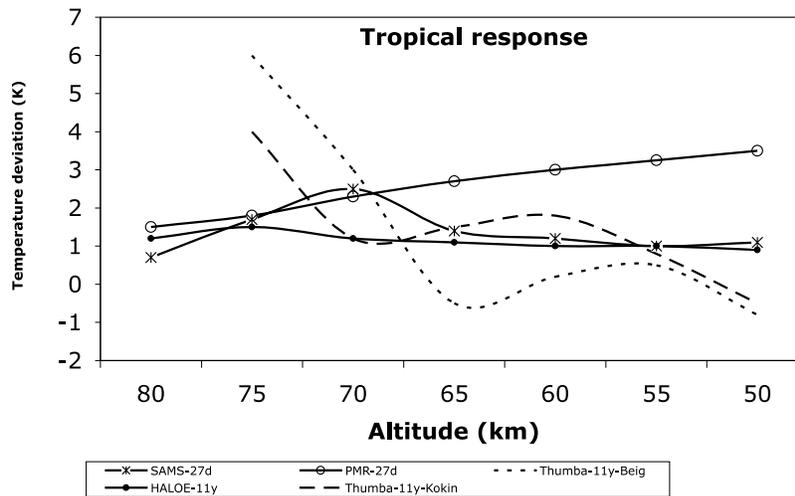
TABLE 2. Solar Response in Temperature in the Mesosphere (50–79 km) Region

Reference	Technique	Years of Analysis	Location	Height, km	11-Year Solar Cycle Response, K	Remarks
<i>Keating et al.</i> [1987]	SAMS	1980s	tropics	70	2.5	27 d
				60	1.2	
<i>Ebel et al.</i> [1986]	PMR	1975–1978	tropics	50	1.1	27 d
				60	3	
				70	2.3	
<i>Remsberg</i> [2007]	HALOE	1991–2005	tropics	50	0.9	
				60	1	
				70	1.2	
<i>Remsberg</i> [2007]	HALOE	1991–2005	midlatitude	50	0.95	
				60	1.5	
				70	2.05	
Beig and Fadnavis (unpublished manuscript, 2003)	Indian rocketsonde	1971–1993	8.5°N, 77°E	50	–0.8	
				60	0.2	
<i>Kokin et al.</i> [1990]	Indian rocketsonde	1971–1993	8.5°N, 77°E	70	3	
				50	–0.5	
				60	1.8	
<i>Keckhut et al.</i> [2005]	U.S. rocketsonde	1969–1995	22°N–34°N	70	1.2	
				50	1.8	
				60	2.4	
<i>Keckhut et al.</i> [2005]	lidar	1979–1997	44°N, 6°E	70	0.4	
				50	0.75	
				60	2.2	
<i>Golitsyn et al.</i> [2006] and <i>Kokin et al.</i> [1990]	Volgograd rocketsonde	1971–1993	48.7°N, 44°E	70	1.7	
				50	–1.8	
				60	4	
	Heiss Island rocketsonde	1971–1993	80.6°N, 58°E	70	3	
				50	–3	
				60	3	
Molodezhnaya rocketsonde	1971–1993	68°S, 46°E	70	5		
			50	1		
			60	0.5		
<i>Lübken</i> [2000, 2001]	rocket grenades, falling spheres	1960s and 1970+, 1987–2000	69°N, 10°E	50–80	no response (summer)	most observations during solar minimum 1960s, 1980s, and 1990s
					5	

at midlatitudes and high latitudes [*Matsuno*, 1971]. In the tropical mesosphere, a response can also be expected, as 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.

[30] The search for a solar trend in the mesosphere had started in the late 1970s when a few authors 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 midlatitudes. *Labitzke and Chanin* [1988], using rocketsonde data at Heiss Island, located at 81°N, reported solar cycle temperature variations on the order of 25 K at 80 km. *Kubicki et al.* [2008] have reanalyzed the same set of data and deduced a negative solar response of several 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 times, results are found to be quite different. The reanalysis of the Thumba (8°N) tropical data extending to more than two solar cycles (G. Beig and S. Fadnavis, Implication of solar signal in the correct detection of temperature trend over the equatorial middle atmosphere, unpublished manuscript, 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]. U.S. rockets have shown a clear solar response in the upper stratosphere [*Dunkerton et al.*, 1998]. In the mesosphere only two subtropical sites allow retrieval of the solar response. 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



**Figure 2.** Atmospheric temperature response to the 27-d and 11-year solar cycles as a function of altitude from different studies with focus on tropical regions. SAMS [Keating *et al.*, 1987] and PMR [Ebel *et al.*, 1986] analyses are performed on the solar rotation timescale. HALOE analyses above the  $\pm 20^\circ$  latitude band [Remsberg, 2007] concern the 11-year timescale. Two different analyses [Kokin *et al.*, 1990; Beig and Fadnavis, unpublished manuscript, 2003] have been used to analyze the Russian rocket station of Thumba.

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 HALOE on UARS. The HALOE temperature data are being obtained using atmospheric transmission measurements from its  $\text{CO}_2$  channel centered at  $2.8 \mu\text{m}$  [Russell *et al.*, 1993; Remsberg *et al.*, 2002]. While the length of the data set is still short, Remsberg *et al.* 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. At midlatitude, responses are larger, and in the tropical latitude band, only 0.4–1.1 K is reported. The long-term series of lidar data obtained at Haute Provence ( $44^\circ\text{N}$ ) has revealed a positive (in-phase) solar response of 2 K/100 solar flux units (sfu) in the mesosphere up to 70 km. The response was found to fall off with height above 65 km, with a tendency toward a negative response above 80 km [Keckhut *et al.*, 1995].

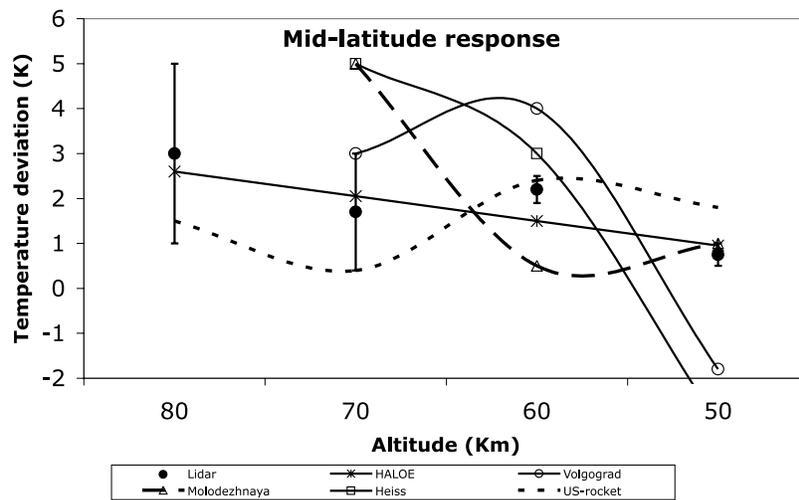
[31] Atmospheric temperature response to the 27-d and 11-year solar cycles as a function of altitude from different studies that focus on tropical regions is shown in Figure 2. SAMS [Keating *et al.*, 1987] and PMR [Ebel *et al.*, 1986] analyses are performed on the solar rotation timescale. HALOE analyses above the  $\pm 20^\circ$  latitude band [Remsberg, 2007] concern the 11-year timescale. Two different analyses [Kokin *et al.*, 1990; Beig and Fadnavis, unpublished manuscript, 2003] have been used to analyze the data of the rocket station Thumba ( $8.5^\circ\text{N}$ ,  $77^\circ\text{E}$ ).

[32] Atmospheric temperature response to the 11-year solar cycle as a function of altitude from different studies covering midlatitudes is shown in Figure 3. Error bars associated with the Observatoire de Haute Provence

(OHP) lidar correspond to the range of seasonal changes [Keckhut *et al.*, 2005]. US-rocket corresponds to an average of three subtropical rocket stations [Keckhut *et al.*, 1999]. The Russian rocket site (Heiss, Volgograd, and Molodezhnaya) data have been 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

[33] Mohanakumar [1995] shows that the summer response varied in the same way with latitude between the Arctic and Antarctic but was about half the wintertime values. The Thumba results also indicate a stronger positive solar component in winter as compared to summer for the mesosphere, which is in agreement with midlatitude lidar results [Keckhut *et al.*, 1995]. Hauchecorne *et al.* [1991] had already reported earlier that solar response changes sign from winter to summer depending on height, using lidar data (1978–1989) at heights from 33 up to 75 km. They found about 5 K/100 sfu during winter for 60–70 km altitude (where the maximum response is observed), and about 3 K/100 sfu for summer. 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 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 temperature data on the solar activity variations for the altitudes 30–100 km. They obtained the minimal solar response at



**Figure 3.** Atmospheric temperature response to the 11-year solar cycle as a function of altitude from different studies covering midlatitudes. Error bars associated with the OHP lidar correspond to the range of seasonal changes [Keckhut *et al.*, 2005]. US-rocket corresponds to an average of three subtropical rocket stations [Keckhut *et al.*, 1999]. The Russian rocket sites (Volgograd, Molodezhnaya, and Heiss) have been analyzed by Kokin *et al.* [1990] and Golitsyn *et al.* [2006].

heights  $\sim 55\text{--}70$  km with a value of  $+2 \pm 0.4$  K/100 sfu for winter and a value of  $-1 \pm 0.4$  K/100 sfu for summer.

#### 4.4. Atmospheric Response due to Solar Flares

[34] 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 20–40% 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  $\text{NO}_x$  rapidly downward and may enhance the effect of ozone destruction [Hauchecorne *et al.*, 2007]. As expected from numerical models [Reagan *et al.*, 1981; Reid *et al.*, 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 National Centers for Environmental Prediction temperature analyses [Jackman and McPeters, 1985] report no detectable temperature decrease associated with the event of July 1982.

[35] A recent search for a response of the mesopause region to solar flares and geomagnetic storms by Scheer and Reisin [2007] in the airglow database from El Leoncito ( $32^\circ\text{S}$ ,  $69^\circ\text{W}$ ) 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.

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

### 5.1. Annual Mean Response

[36] The majority of the results discussed in this section are obtained from measurements of OH airglow which correspond to nominal altitudes of 87 km. Beig *et al.* [2003, section 4] provide information on some earlier solar activity studies since the 1970s, with an emphasis on OH rotational temperature, only part of which will again be discussed here.

[37] Sahai *et al.* [1996] reported a solar activity effect of 32 K/100 sfu from OH airglow temperature measurements at Calgary ( $51^\circ\text{N}$ ,  $114^\circ\text{W}$ ) on the basis of the comparison of 2 low-activity years (1987 and 1988) to a high-activity year (1990). The solar signal found by Gavril'yeva and Ammosov [2002] from their OH data obtained at Maimaga ( $63^\circ\text{N}$ ,  $130^\circ\text{E}$ ) between 1997 and early 2000 was only one third as great as the result from Calgary but is still a high-end result ( $11 \pm 3$  K/100 sfu) 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 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 (approximately  $-30$  K/100 sfu) found by Hernandez [1976] at midlatitudes and

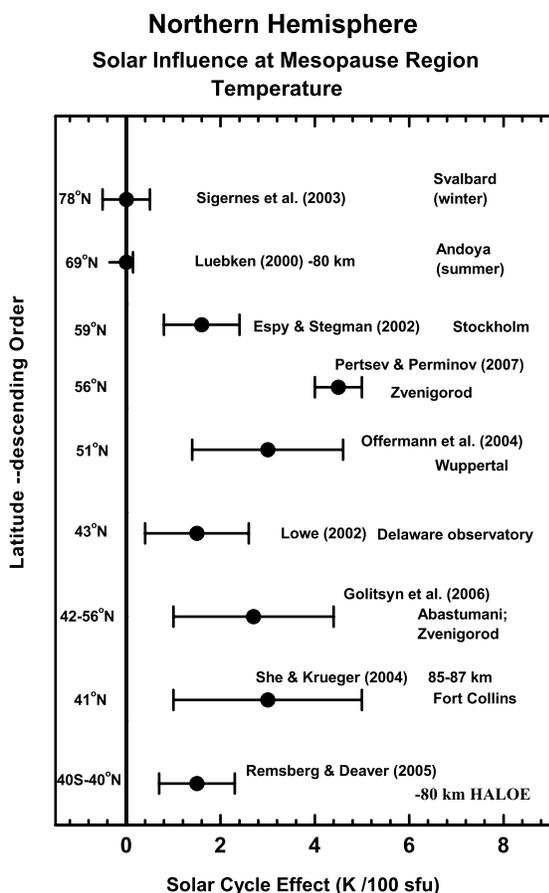


Figure 4. Solar cycle response in the Northern Hemisphere for the mesopause region.

low latitudes and by *Nikolashkin et al.* [2001] at Maimaga (approximately  $-15$  K/100 sfu), although *Nikolashkin et al.*'s result for OH temperature ( $+5$  K/100 sfu for eastward quasi-biennial oscillation phase and  $-30$  K/100 sfu for westward) is somewhat at odds with the more recent data by *Gavriilyeva and Ammosov* [2002] from the same site.

[38] Figures 4 and 5 show the solar response in temperature (K/100 sfu) as reported by different authors using various experimental data in recent times for the Northern and Southern hemispheres, respectively. For easier reference, the pertinent details corresponding to each result are also listed in Tables 3a and 3b.

[39] *Sigernes et al.* [2003] found no solar signal in the time series of OH airglow data from the auroral station Adventsdalen ( $78^{\circ}\text{N}$ ,  $15^{\circ}\text{E}$ ) that span 22 years. On the other hand, in the midlatitude 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 ( $59^{\circ}\text{N}$ ,  $18^{\circ}\text{E}$ ), but after a new analysis that includes more recent data, these authors find evidence for a positive effect of about 2 K/100 sfu ( $1.6 \pm 0.8$  K/100 sfu in winter) (P. J. Espy, personal communication, 2007). New results from Zvenigorod ( $56^{\circ}\text{N}$ ,  $37^{\circ}\text{E}$ ), for the years 2000–2006, reported by *Pertsev and Perminov*

[2008] indicate an annual mean response of  $4.5 \pm 0.5$  K/100 sfu, which is somewhat stronger than previous results partly derived from the same site [*Golitsyn et al.*, 2006] (see below).

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

[41] *Bittner et al.* [2000] analyzed the Wuppertal ( $51^{\circ}\text{N}$ ,  $7^{\circ}\text{E}$ ) data for the period 1981–1995 with respect to temperature variability with periods of several days but not with respect to absolute temperature (as in most other studies). They found positive solar correlation response for temperature oscillations with periods greater than  $\sim 30$  d and negative correlation for periods less than  $\sim 10$  d. 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 d had disappeared, but there was, surprisingly, evidence for a correlation with the 22-year heliomagnetic cycle. The authors investigated

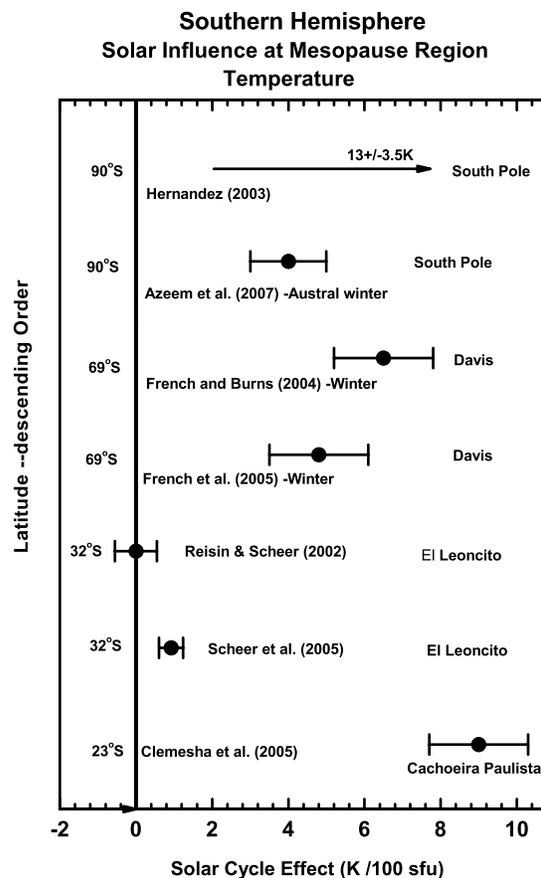


Figure 5. Solar cycle response in the Southern Hemisphere for the mesopause region.

TABLE 3a. Solar Response in Temperature of the Lower Mesopause Region<sup>a</sup>

Reference	Technique	Years of Analysis	Location	Height, km	Temperature Solar Response, K/100 sfu	Remarks
<i>Sigernes et al.</i> [2003]	hydroxyl rotational temperature, band 8-3, band 6-2	1980–1983, 1983–2002	<i>Northern Hemisphere</i> 78°N, 15°E	OH emission layer	+0.0 ( $\pm 0.5$ ) (winter)	
<i>Lübken</i> [2000, 2001]	rocket grenades, falling spheres	1960s and 1970+, 1987–2000	69°N, 10°E	80	no response (summer)	most observations during solar minimum 1960s, 1980s, and 1990s
<i>Espy and Siegmán</i> [2002]	hydroxyl rotational temperature, bands 3-1 and 4-2	1991–1998	59.5°N, 18°E	OH emission layer	1.6 ( $\pm 0.8$ ) (winter)	consistent with +2 K/100 sfu (P. J. Espy, personal communication, 2007)
<i>Pertsev and Perminov</i> [2008]	hydroxyl rotational temperature, band 6-2	2000–2006	55.7°N, 37°E	OH emission layer	7.5 ( $\pm 0.5$ ) (winter) 2 ( $\pm 2.0$ ) (summer) 4.5 ( $\pm 0.5$ ) (annual) +3.0 ( $\pm 1.6$ )	also intensity response for OH and O <sub>2</sub> bands
<i>Offermann et al.</i> [2004]	hydroxyl rotational temperature, band 3-1	1980–1984, 1987–2002	51.3°N, 7°E	OH emission layer	+1.5 ( $\pm 1.1$ )	
<i>Lowe</i> [2002]	hydroxyl rotational temperature, bands 3-1 and 4-2	1989–2001	42.5°N, 81°W	OH emission layer	–5 ( $\pm 1.7$ ) (winter) +8 ( $\pm 1.7$ ) (summer) +2.7 ( $\pm 1.7$ ) (annual) 0.0 ( $\pm 1.0$ ) 3 ( $\pm 1$ )	
<i>Gótsyn et al.</i> [2006]	combined (major: hydroxyl rotational temperature, band: several)	1976–1991	41.8°N, 43°E and	80–95		
<i>She and Krueger</i> [2004]	Na-Lidar	1990–2001	55.7°N, 37°E 41°N, 105°W	83 87		updated by C.-Y. She, personal communication (2007)
<i>Remsberg and Deaver</i> [2005]	UARS-HALOE: sunrise, sunset (satellite)	1991–2004	40°S – 40°N	80	0.5–1.7 amplitudes ( $\pm 0.6$ )-> 1.5 ( $\pm 0.8$ ) K/100 sfu	range of solar response estimated from published amplitude
<i>Azeem et al.</i> [2007]	hydroxyl rotational temperature, band 3-1	1994–2004	<i>Southern Hemisphere</i> 90°S	OH emission layer	4.0 ( $\pm 1.0$ ) (winter)	
<i>Hernandez</i> [2003]	Doppler temperature, OH (6-2)	1991–2002	Antarctica 90°S	OH emission layer	13.2 ( $\pm 3.5$ ) (winter)	Doppler (kinetic) temperature
<i>French et al.</i> [2005]	hydroxyl rotational temperature, band 6-2	1990, 1995–2003	69°S, 78°E	OH emission layer	4.8 ( $\pm 1.3$ ) (winter)	
<i>French and Burns</i> [2004]	hydroxyl rotational temperature, band 6-2	1995–2001	69°S, 78°E	OH emission layer	6–7 (midwinter)	published range
<i>Reisin and Scheer</i> [2002]	hydroxyl rotational temperature, band 6-2	1986, 1987, 1992, 1997–2001	32°S, 69°W	OH emission layer	no response	
<i>Scheer et al.</i> [2005]	hydroxyl rotational temperature, band 6-2	1998–2002	32°S, 69°W	OH emission layer	0.92 ( $\pm 0.32$ )	
<i>Clemesha et al.</i> [2005]	hydroxyl rotational temperature, band 9-4, band 6-2	1987–1994, 1994–2000	23°S, 45°W	OH emission layer	8–10	range of solar response estimated from published amplitude

<sup>a</sup>Lower mesopause region is at 80–90 km.

TABLE 3b. Solar Response in Temperature of the Upper Mesopause Region and the Lower Thermosphere<sup>a</sup>

Reference	Technique	Years of Analysis	Location	Height, km	Temperature Solar Response, K/100 sfu	Remarks
<i>Golitsyn et al.</i> [2006]	estimated from sodium emission intensity	1976–1991	41.8°N, 43°E and 55.7°N, 37°E	92	2.8 (±1.2)	
<i>Golitsyn et al.</i> [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)	
<i>She and Krueger</i> [2004]	Na-Lidar	1990–2001	41°N, 105°W	92–98 103	4.0 (±1.8) 0.0 (±1.4)	
<i>Reisin and Scheer</i> [2002]	O <sub>2</sub> (0-1) rotational temperature	1986, 1987, 1992, 1997–2001	32°S, 69°W	O <sub>2</sub> emission height (95 km)	1.6–5.6	range of upper limit estimates
<i>Scheer et al.</i> [2005]	O <sub>2</sub> (0-1) rotational temperature	1998–2002	32°S, 69°W	O <sub>2</sub> emission height (95 km)	3.3 (±0.3) no trend 1.32 (±0.3) with temporal trend	mean response; see text for details

<sup>a</sup>Upper mesopause region and the lower thermosphere are at 90–110 km.

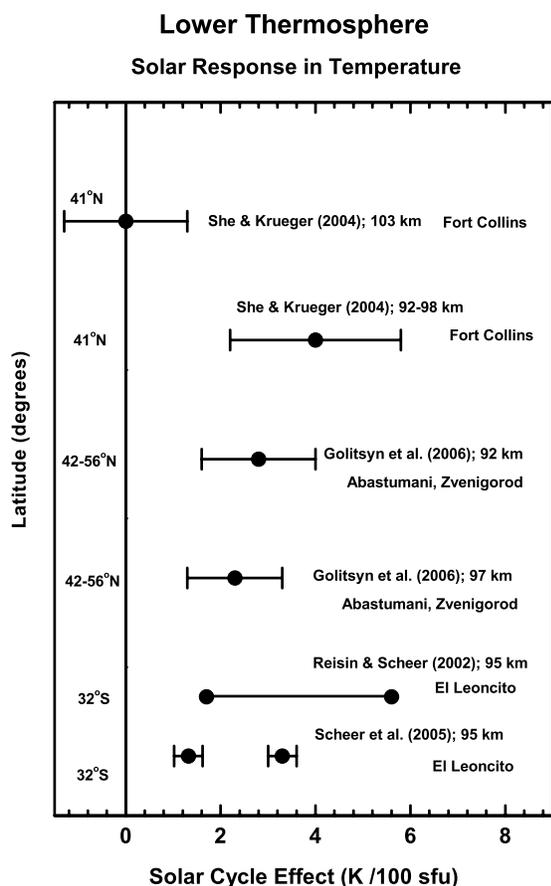
the possibility of a magnetic coupling between the solar and terrestrial magnetic fields and indeed found a weak modulation in the Earth's rotation period with a shape similar to the observed variation of the standard deviation of OH temperature. *Lowe* [2002] has made OH layer measurements for one full solar cycle at the Delaware Observatory (43°N, 81°W) in Canada and found a positive solar response of  $1.5 \pm 1.1$  K/100 sfu.

[42] *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 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  $2.7 \pm 1.7$  K/100 sfu, with a tendency to grow with altitude.

[43] An alternating negative and positive temperature response is consistently found in Northern Hemisphere midlatitude results obtained by incoherent scatter radar, Rayleigh lidar [*Chanin et al.*, 1989], and sodium lidar [*She and Krueger*, 2004] for altitudes between 30 km 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 found a positive effect of  $3 \pm 2$  K/100 sfu at 87 km (updated numbers according to C.-Y. She (personal communication, 2007)). The HALOE results by *Remsberg and Deaver* [2005] mentioned in section 4.2 also refer to the lower limit of the mesopause region. For different latitude zones, 11-year solar cycle terms with amplitudes of 0.5 to 1.7 K were found for the middle to upper mesosphere (80 km).

[44] 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  $6.0 \pm 1.3$  K with maxima in 1990 (and therefore also in 2001), well in phase with solar activity. The linear trend of  $10.8 \pm 1.5$  K per 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%/a, which, in view of the combined error bounds, is not considerably above the intensity trend observed by *Reisin and Scheer* (about +1%/a). 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/100 sfu 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 1.4 K. 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 to be contradictory.

[45] Results about OH temperatures from Davis (69°S, 78°E) will be discussed in section 5.2. *Hernandez* [2003] measured the polar mesospheric temperature above the South Pole (90°S) from 1991 to 2002 using the Doppler width of the OH line at 840 nm by means of a high-resolution Fabry-Perot interferometer and deduced a solar signal as high as 13 K/100 sfu. 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



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

approximate equivalence of the temperatures obtained by both techniques, the solar cycle effect of  $4.0 \pm 1.0$  K/100 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.

[46] 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 on the extrapolation of OH temperature response to greater heights. Their composite profile indicates an annual mean solar response of 2.8 and 2.3 K/100 sfu for the altitudes of 92 and 97 km, respectively. *She and Krueger* [2004] have found a solar signal of 4 K/100 sfu 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 O<sub>2</sub> rotational 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  $3.3 \pm 0.3$  K/100 sfu is reported (which would reduce to  $1.32 \pm 0.3$  K/100 sfu if a temporal trend is simultaneously fitted). The authors conclude, however, that the mean values are only the net effect of successive short-term spells of anticorrelation, the absence of correlation, each lasting many months, and a 32-month regime of strong

correlation. Therefore, there is obviously no seasonal regularity in the solar signal at this site. All these recent results for northern and southern midlatitudes that refer to heights around 95 km compare quite well with each other although they are obtained by quite different techniques.

## 5.2. Seasonal Differences

[47] As mentioned in section 5.1, 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. Response is most variable in autumn, winter, and spring, and a strong but stable response prevails in summer. *Golitsyn et al.* [2006] deduced a solar response of  $-5 \pm 1.7$  K/100 sfu for winter and  $8 \pm 1.7$  K/100 sfu for summer in this altitude range.

[48] The absence of a solar response in the OH data from Adventsdalen (78°N) for winter was mentioned in section 5.1 [*Sigernes et al.*, 2003; *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 positive solar response of 6–7 K/100 sfu in midwinter but smaller values (possibly even zero) outside this season. With the inclusion of data from 2002 and 2003, thus extending the Davis database from 7 to 9 years, the winter effect changed to  $4.8 \pm 1.3$  K/100 sfu [*French et al.*, 2005].

[49] *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  $3.0 \pm 1.6$  K/100 sfu. This is in agreement with the analysis based on annual means that gave 3.4 K/100 sfu. The authors concluded that long-term trend effects as measured at Wuppertal and solar cycle influences are almost statistically independent, which means that there is little interference between both types of results.

## 6. MODEL SIMULATIONS OF SOLAR RESPONSE

[50] In principle, those models which are able to account properly for the vertical coupling processes in different altitudes of the atmosphere are suitable for studying solar variability effects. There are only a few model studies for assessing the effect of solar variability on temperature or other parameters in the MLT region, in comparison to stratospheric regions where many models have been used [*Rozanov et al.*, 2004, and references therein]. Some studies addressed the effect of the 27-d rotational variation with 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 the 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. The 11-year solar cycle variability was studied with different versions of the Simulation of Chemistry, Radiation, and Transport of Environmentally Important Species (SOCRATES) 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 10 K, whereas *Khosravi et al.* [2002] derived a value of 5 K. *Garcia et al.* [1984] have reported a solar response of 6 K between solar minimum and maximum activity using their 2-D model.

[51] Most of the initially developed general circulation models (GCMs) extend generally from the surface to the midstratosphere. 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; *Sonnenmann et al.*, 1998] in which the complex processes of the troposphere are replaced by boundary conditions applied in the vicinity of the tropopause. However, 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 [*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.

[52] The newly developed HAMMONIA 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 2–3 km, depending on temperature. *Schmidt et al.* [2006] have performed model simulations on both the doubled CO<sub>2</sub> case and the role of

the 11-year solar cycle in trend studies. They find a temperature response to the solar cycle as 2–10 K in the mesopause region, with the largest value occurring slightly above the summer mesopause (~100 km). Up to the mesopause, the temperature response may be either positive or negative depending upon longitude, particularly for middle and high latitudes 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 altitude than at constant pressure altitude. *Marsh et al.* [2007] have recently used the WACCM (version 3). The response of the MLT region in WACCM3 is broadly similar to that of HAMMONIA shown by *Schmidt et al.* [2006]. *Marsh et al.* [2007] reported that the global mean change in temperature is between 0.3 and 1.5 K/100 sfu for 50–80 km, from 1.5 to 2.5 K/100 sfu for 80–90 km, and 2.5 to about 5 K/100 sfu for 90–110 km. There is a local minimum around 66 km above which the solar temperature response increases with increasing height.

## 7. CONCLUSIONS

[53] As is 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.

[54] 1. The results show recognition of positive signal in the annual mean solar response of the MLT regions with an amplitude of a few degrees per 100 sfu. This agrees with numerical simulations of coupled models.

[55] 2. Most Northern Hemispheric results indicate a solar response of the order of 1–3 K/100 sfu near the OH airglow emission height at midlatitude which becomes negligible near the North Pole.

[56] 3. In the Southern Hemisphere, the few results reported so far indicate the existence of a stronger solar response near the South Pole and a weaker response at lower latitudes.

[57] 4. There is increasing evidence for a solar component of the order of 2–4 K/100 sfu in the lower thermosphere (92–100 km) which becomes negligible around 103 km.

[58] 5. In the mesosphere, the midlatitude solar response of 1–3 K/100 sfu is consistent with satellite, lidar, and U.S. rocketsonde data, whereas Russian results indicate a more variable behavior.

[59] 6. There exists a solar response of 1–3 K/100 sfu for the mesospheric region in the tropics.

[60] Most recent GCM results indicate a higher upper limit of solar temperature response as compared to observations (2–10 K per solar cycle in the mesopause region), with the largest value occurring slightly above the summer

mesopause ( $\sim 100$  km). Up to the mesopause, the temperature response may be either positive or negative depending upon longitude, particularly for middle and high latitudes in winter.

[61] 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 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 problem to be explored more rigorously in the future.

[62] However, the major challenge is in the interpretation of the various reported results which are diverse and even indicate latitudinal variability and a considerable amount of longitudinal variability in solar response. The high degree of similarity in the response of the mesosphere to increasing 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  $\text{CO}_2$ , 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 contributions to the thermal and chemical change in the mesosphere. The cyclic nature of the variability in solar UV flux over decadal timescales 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

[63] Looking forward, there are many compelling scientific questions and analyses still waiting to be addressed and undertaken. Among those relating to the long-term response in the MLT region to solar variations are the following.

[64] 1. The detailed analysis of the trends of parameters like winds and minor constituent concentration (water vapor and ozone) in the mesopause region is required in order to properly understand the MLT temperature trends and solar response.

[65] 2. The monthly-to-seasonal long-term temperature trend and solar cycle response in the mesosphere, including the mesopause region, is required.

[66] 3. Modeling studies of solar trends as derived from existing general circulation models (GCMs) are required to be done in detail. The consistency between observed and

modeled temperature, radiation, and chemistry must be evaluated. These studies are expected to yield future measurement recommendations.

[67] 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 *Mlynczak 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/N<sub>2</sub> ratio, etc.), and solar irradiance will enable a unique data set from which the effects of the 11-year solar cycle can be confidently determined. Efforts are now under way to secure operation of the TIMED mission through the next solar maximum in approximately 4–5 years.

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- G. Beig, Indian Institute of Tropical Meteorology, Pashan, Pune- 411008, India. (beig@tropmet.res.in)
- P. Keckhut, Service d'Aéronomie, Institut Pierre Simon Laplace, Université de Versailles-Saint-Quentin-en-Yvelines, F-91371, Verrières-Le-Buisson, France.
- M. G. Mlynchak, Climate Science Branch, NASA Langley Research Center, Hampton, VA 23681, USA.
- J. Scheer, Instituto de Astronomía y Física del Espacio, Ciudad Universitaria, Buenos Aires, 1428, Argentina.