Mesospheric temperature trends at mid-latitudes in summer

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[1] The Leibniz-Institute Middle Atmosphere Model LIMA is used to study mesospheric temperature trends in summer during the last 5 decades (1961–2009). In order to account for realistic atmospheric conditions LIMA adapts several observational data sets, namely a) tropospheric and stratospheric temperatures and winds from ECMWF at heights 0–35 km, b) daily Lyman-α fluxes, c) monthly carbon dioxide concentrations since 1961, and d) annual total ozone from ground-based data for 1964–1978 and monthly ozone profiles up to 0.60 hPa from satellites since 1979. This paper presents a comparison of simulated temperature trends with a) ground-based observations of lidar temperatures at 44°N, b) phase height measurements at mid-latitudes (51°N), and c) temperature trends derived from satellite data. In general there is excellent agreement between trends from LIMA and observations. Cooling in the mesosphere is on the order of 2–4 K/decade. The magnitude of the mesospheric temperature trend varies during the last five decades. In particular, the period from 1979–1997 shows large mesospheric cooling of 3–5 K/decade. This large cooling is primarily caused by long-term changes of ozone in the upper stratosphere in combination with a CO₂ increase. For the first time, modeling of mesospheric temperature trends confirm the extraordinary large trends from observations. Citation: Berger, U., and F.-J. Lübken (2011), Mesospheric temperature trends at mid-latitudes in summer, Geophys. Res. Lett., 38, L22804, doi:10.1029/2011GL049528.

1. Introduction

[2] It has been suggested since many years that an increase of greenhouse gases results in a cooling in the middle atmosphere [Roble and Dickinson, 1989]. Since carbon dioxide and ozone are the main radiative cooling gases in this region it is expected that temperatures have decreased in the stratosphere and mesosphere in recent decades. In the lower stratosphere observed cooling trends and simulations with climate models are generally consistent [Austin et al., 2009]. In the upper stratosphere some inconsistencies between observed and modeled temperature trends were reported by Steinbrecht et al. [2009]. Observations show that in the period 1985–2008 upper stratospheric temperatures are almost constant, whereas chemistry climate models show an ongoing temperature decline. In the mesosphere, however, there are even much larger uncertainties and also discrepancies between observations and modeling (see review by Beig et al. [2003]). Global satellite observations of stratospheric temperatures started in the 1970s with the Stratospheric Sounding Units (SSU) which provide the only global decadal data set for trend analysis in the upper stratosphere (see ftp://ftp.cpc.ncep.noaa.gov/wd53rl/ssu/) [Randel et al., 2009]. The uppermost altitude (channel 47X) from SSU provides data for the lower mesosphere (~50 km) with a maximum weight at pressures near 0.60 hPa [Shine et al., 2008]. For the mesosphere, no direct multi-decadal measurements of temperatures by satellites are available. Instead we have to rely on single station ground based observations. Temperature trends detected at a lidar station at mid-latitudes show exceptional large cooling rates in the mesosphere and stratosphere [see recent update by Keckhut et al., 2011]. Another piece of evidence for large trends in the middle atmosphere comes from multi-decadal measurements of the reflection height of radio waves near 82 km which is presumably the longest data record from the mesopause region based on active sounding. This reflection height has decreased by ~1.5 km in the last 50 years which relates to a cooling in the mesosphere of up to 4–5 K/decade [Bremer and Berger, 2002; Bremer and Peters, 2008]. Several model studies have shown that increasing CO₂ and decreasing O₃ indeed cause a cooling in the middle atmosphere [e.g., Bremer and Berger, 2002; Akmaev et al., 2006; Schmidt et al., 2006; García et al., 2007]. However, the magnitude of the effect in models is much smaller compared to observations [Beig et al., 2003].

[3] In this paper we study the effect of CO₂ increase and O₃ changes on trends in the middle atmosphere, in particular in the mesosphere. Tropospheric and stratospheric effects are implicitly taken into account. We concentrate on summer at mid-latitudes because natural variability is small in summer and some long-term observations are available here (see above). We present trend simulations from the LIMA model for the period 1961–2009 and compare our results with observations from lidar, phase heights, and SSU.

2. Model Description

[4] The LIMA model (Leibniz-Institute Middle Atmosphere) is a global circulation model of the middle atmosphere (0–150 km, Δz = 1.1 km) which especially aims at representing the thermal structure around mesopause altitudes in order to simulate the morphology of polar mesospheric ice clouds [Lübken and Berger, 2011]. LIMA takes into account major processes of radiation, chemistry, and transport [Berger, 2008]. The model has recently been upgraded to include additional radiation parameterizations which improve simulations of solar irradiance variations, e.g., during the 11-year solar cycle. In the new version of LIMA daily Lyman-α fluxes from August 1960 until June 2011 are taken as a proxy for solar activity (ftp://haspftp.colorado.edu/pub/SEE-DATA/composite-lya). The absorption of solar Lyman-α radiation at 121.6 nm by photolysis of O₂ is calculated using the

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method described by Chabrilat and Kockarts [1998]. Variable solar activity also alters the strength of solar absorption from the near infrared to the UV-spectrum [Lean et al., 1997]. Infrared cooling by CO$_2$, including effects from non-local thermodynamic equilibrium conditions (non-LTE) above heights of 75 km, is calculated using the parametrization of Fomichev et al. [1998], recently upgraded by A. A. Kutepov et al. [2007]. Finally we added a parametrization of IR cooling by water vapor in the rotational and the 6.3 $\mu$m vibrational bands according to Zhu [1994].

LIMA adapts several observational data sets. In order to account for realistic lower atmosphere conditions LIMA uses tropospheric and lower stratospheric data with complete global coverage from ECMWF (European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom). LIMA loads the 40-yr ECMWF reanalysis data set (ERA-40) for the period from August 1960 to August 2002, and ECMWF operational analysis fields after August 2002. The ECMWF data used by LIMA are extracted with $1^\circ \times 1^\circ$ latitudinal/longitudinal resolution at 21 pressure levels from 1000 to 1 hPa and every 6 hours at 0, 6, 12, and 18 UT. LIMA adapts these data in the following way: at every model time step forcing functions are added to the governing model equations to gradually nudge the model toward observations of temperature, zonal wind, meridional wind, and surface geopotential. The nudging coefficient is constant from the ground to the middle stratosphere (35 km), and decreases linearly to zero from 35–45 km.

Global monthly changes of CO$_2$ are taken from http://www.esrl.noaa.gov/gmd/ccgg/trends. Ozone as the second major greenhouse gas is quantified by monthly, latitudinal, longitudinal, and altitude-dependent profiles available from SBUV (Solar Backscatter in the Ultraviolet) satellite data from 1979 to 2009 (http:// acdb-ext.gsfc.nasa.gov/Data_services/merged). The uppermost level of SBUV ozone data corresponds to a pressure of 0.5 hPa. Above this level LIMA interpolates and fits the SBUV ozone fields within one scale height to the standard ozone climatology used in LIMA. For the period 1964–1978 we adapt annual total ozone data from ground-based measurements for 1964–1978 published in the WMO report 2011 [Douglass and Fioletov, 2011]. The years 1961–1963 have been extrapolated from 1964. Three different simulations have been performed with LIMA to assess the sensitivity of mesospheric temperature trends: 1) taking into account long term changes of CO$_2$ in the entire atmosphere and O$_3$ changes up to approximately 55 km (see above), 2) same, but keeping O$_3$ constant from year to year, and 3) keeping CO$_2$ and O$_3$ constant from year to year. We note that long term changes of CO$_2$ and O$_3$ in the troposphere and stratosphere are implicitly taken into account in all three runs by the nudging procedure described above.

Unless noted otherwise, we show trends from run 1. Lübken [2011] has shown mean temperatures at a latitude section 40°–90°N in the mesopause region for summer conditions (mean from 1997–2007 for July) from run 1. Temperatures in the mesosphere are in good agreement with satellite observations as, e.g., from SABER [Garcia et al., 2007].

3. Temperature Trends at Midlatitudes

In Figure 1a we show summer temperature anomalies in the period 1979–2005 from lidar temperatures at the Observatory of Haute-Provence (OHP) in southern France (44°N, 7°E) [Keckhut et al., 2011]. We also show temperatures from SSU channel 47X at approximately 50 km. Unless noted otherwise we define ‘summer’ as the mean of June to August. LIMA results are taken at the geographical position of OHP at a pressure level of 0.60 hPa. No attempt has been made to remove any solar cycle signal in the curves shown in Figure 1a. There is excellent agreement between LIMA and SSU anomalies, whereas the lidar data show somewhat larger deviations in some years. We have also selected LIMA temperatures with geographic sampling scenarios with LIMA. More precisely, we sampled...
Figure 2. (a) Long-term variation of reflection heights of radio waves for summer from Bremer and Peters [2008] (red), compared to the height variation of the pressure level at 0.00576 hPa from LIMA (blue). LIMA data are taken at the geographical position of radio wave reflection (50°N, 7°E). The dashed lines mark the linear trend of the reflection height for the period 1961–1997. Solar cycle is considered in the trend analysis. (b) Summerly averaged temperature anomalies at 70 km altitude derived from three LIMA runs discussed in section 2 (50°N, 7°E). We also show results from run 1 but at a constant pressure level of 0.0487 hPa (orange). Anomalies are defined relative to the 1961–2009 mean. Linear trends (red lines) are determined for run 1 from multiple regression which considers solar activity. Ozone anomalies (black) are taken from SBUV at 0.70 hPa, 35.5°–62.5°N for the summer period 1979–2009. For the period 1961–1978 ozone is approximated from total ozone data [Douglass and Fioletov, 2011].

a) at a fixed geometric altitude of 50 km, b) at a fixed pressure level of 0.60 hPa, c) applying the SSU weighting function for channel 47X according to Shine et al. [2008], and d) modifying the weighting function considering the instrumental effect mentioned above. All sampling methods result in almost identical temperature anomalies (deviations smaller than 0.5 K) and give very similar trends. The agreement between SSU and LIMA trends is perhaps not surprising since the nudging region within LIMA is only ~10 km below SSU channel 47X. The good agreement is also based on the quality of the SBUV ozone data set. This statement comes from a sensitivity test where we have replaced SBUV ozone (in run 1) by ozone climatology not varying from year to year (in run 2 and 3). This indeed results in somewhat worse agreement between LIMA and SSU temperatures. For example, for run 3 the anomalies are ~2 K lower (~0.5–1 K higher) at the beginning (end) of the period shown in Figure 1a.

Figure 1b vertical profiles of temperature trends for the period 1979–1997 derived from LIMA and from lidar measurements at the geographical position of OHP are shown. Lidar trends are taken from Keckhut et al. [2011, Figure 10a]. LIMA trends are obtained from a multiple regression fit considering solar cycle effects. Above 30 km large cooling trends (~3–5 K/decade) are obtained in LIMA and also in observations which reduce and even turn to warming around the mesopause. Modeled and observed trends are consistent at almost all altitudes. For the first time, modeling of mesospheric temperature trends confirm the extraordinarily large trends observed by lidar. As will be discussed later such large trends are confined to the period 1979–1997.

[10] We also compare LIMA trends with long-term measurements of radio wave reflection heights performed since 1959 at the IAP in Kühlungsborn [Bremer and Peters, 2008]. Radio waves at 162 kHz transmitted from Allouis (France) are reflected in the ionosphere and detected at IAP. The reflection occurs at a pressure level of ~0.006 hPa (corresponding to an altitude of ~82 km) at the mid point position which is at 50.7°N, 6.6°E. More details on the phase height technique and potential effects of long term trends of electron densities are presented by Bremer and Berger [2002]. In Figure 2a long-term changes of these reflection heights are shown for summer (data are taken from Bremer and Peters [2008, Figure 5a]). Solar cycle and geomagnetic influences have been removed from the observations. We also show LIMA results, namely the height variation of the 0.00576 hPa pressure level averaged during summer. Again, the solar cycle influence is removed from the LIMA data, but it is rather small anyway (typically less than 0.05 km). As can be seen from Figure 2a there is excellent agreement between LIMA and observations. Regarding long term variations we concentrate on the period 1961–1997 since trends are much smaller thereafter. Observations show a height decrease of ~338 m/decade in this period. LIMA gives a very similar result (~300 m/decade) considering combined uncertainties.

4. Discussion

[11] We have performed various LIMA runs to elucidate the physics behind the trends, in particular the role of CO2 and O3 trends in the mesosphere, and the impact of the stratosphere. In Figure 2b we present trend calculations from the three model runs introduced in section 2. Run 3 is labeled ‘stratosphere only’ because it still adapts ECMWF data and therefore implicitly includes long-term changes in the troposphere and stratosphere. Temperature anomalies shown in Figure 2b are derived at 70 km altitude for summer conditions at the geographic position of phase height reflection (51°N, 7°E). Temperature anomalies are largest in run 1, decrease by up to 50% if the effect of O3 is ignored (run 2), and are smallest if stratospheric effects only are considered (run 3). The CO2 effect alone (without any interference by O3) can be indirectly inferred from the difference between run 2 and run 3. The temperature difference is about +2 K in 1961 and declines almost linearly to ~2.75 K in 2009 which corresponds to a cooling trend of about 1 K/decade. In all runs there are pronounced year-to-year variations, for example a steep decrease from the mid 1980s to the mid 1990s. For comparison we show ozone anomalies at
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temperatures at a constant pressure level are considered.
expansion. As can be expected, the effect disappears if
1975 and 1976 where ECMWF temperatures are too high
trends. Accidently, this effect is demonstrated in the years
peratures which includes (through assimilation) ozone
effects in LIMA come from adaptation to ECMWF tem-
this effect as shown in run 1. We repeat that stratospheric
shrinking can cause temperature changes in the
stratosphere near 40 km, presumably in response to a strong
negative ozone forcing [WMO, 2011]. Furthermore, the vertical gradient of background
temperatures at stratopause heights is close to zero, hence
small geometric height changes do not induce differences in
trend derivations.

We have already shown [Lübken et al., 2009] that strato-
spheric ozone trends for the entire mesosphere and
stratospheric ozone trends for the near future.

0.70 hPa from SBUV for the period June–August and
averaged in the latitude band 50 ± 20°N. As can be seen from
Figure 2b year-to-year variations of stratospheric ozone and
temperatures in the mesosphere are rather similar for all runs.
We have already shown [Lübken et al., 2009] that strato-
spheric shrinking can cause temperature changes in the
mesosphere. Ozone anomalies in the mesosphere may add to
effect as shown in run 1. We repeat that stratospheric
effects in LIMA come from adaptation to ECMWF tem-
peratures which includes (through assimilation) ozone
trends. Accidentally, this effect is demonstrated in the years
1975 and 1976 where ECMWF temperatures are too high
due to an erroneous bias in satellite data. As can be seen in
Figure 2b this offset copies into the mesosphere through
expansion. As can be expected, the effect disappears if
temperatures at a constant pressure level are considered.

Stimulated by the evolution of stratospheric ozone as
presented by World Meteorological Organization (WMO)
[2011] we grouped our trend studies into three time peri-
Temperature trends from LIMA show a corresponding
change of trends in these periods. We determined trends for
run 1 from a multiple regression fit which includes solar
cycle variations. For the period 1961–1979 (ignoring 1975
and 1976) a rather weak cooling trend of ~0.5 K/decade is
observed. For the period 1979–1997 we find large cooling
trends of ~4–5 K/decade, and for the period 1997–2009 a
warming of ~1 K/decade. A similar warming is observed
from phase height (see Figure 2a), lidar and SSU observa-
tions (see Figure 1a). We summarize that mesospheric
temperature trends change with time and are significantly
influenced by stratospheric ozone. They are therefore ana-
logue to stratospheric temperature trends [Randel et al.,
2009; Steinbrecht et al., 2009].

In Figure 2b we also compare (for run 1) trends at a
fixed geometric altitude (70 km) and at a fixed pressure
level (0.0487 hPa) which on average is located near 70 km.
While year-to-year variations are rather similar, long term
trends in the mesosphere are significantly larger at geo-
metric altitudes (compared to pressure altitudes) since it
includes atmospheric shrinking [Lübken et al., 2009]. The
latter effect depends on the background temperature gradi-
ent: in the mesosphere (negative gradient) cooling trends at
geometric altitudes are enhanced (relative to constant pres-
sure level), whereas in the thermosphere (positive gradient)
the effect is vice versa. This also explains why the difference
between trends at geometric versus pressure altitudes is
small at 50 km since here the pressure trend at a constant
geometric height is only ~50 m/decade [Lübken and Berger,
2011]. Furthermore, the vertical gradient of background
temperatures at stratopause heights is close to zero, hence
small geometric height changes do not induce differences in
trend derivations.

We put our trend analysis into a broader perspective
by analyzing mesospheric temperature trends on global
scales. Motivated by the results shown in previous sections
we show in Figure 3 temperature trends from LIMA for
summer conditions for two periods, namely 1979–1997 and
1997–2009. Note, that we have obtained the trends in LIMA
from a multiple regression fit considering solar cycle effects.
For the first period strong cooling of up to ~3–4 K/decade
occurs in the middle mesosphere. Additional cooling peaks
of similar magnitude occur in the equatorial and northern
stratosphere near 40 km, presumably in response to a strong
negative ozone forcing [WMO, 2011]. In the southern winter
hemisphere, enhanced cooling is observed in the meso-
sphere at mid and high latitudes, whereas stratospheric
cooling is substantially smaller.

Temperature trends are generally small in magnitude
in the mesopause region in winter and summer which is
consistent with observations and other model results [Beig
et al., 2003; Akmaev et al., 2006; Schmidt et al., 2006; Garcia
et al., 2007]. At polar latitudes in summer, heating is
observed around the mesopause which is caused by radiative
effects and atmospheric shrinking. Trends are entirely dif-
ferent for the second period 1997–2009. In many regions,
for example in the summer mesosphere and at the equatorial
stratopause, positive temperature trends dominate. Our
analysis suggests that this is due to stratospheric ozone
recovery which over-compensates the enhanced cooling
caused by increasing carbon dioxide. As mentioned in the
previous section, Figure 3 emphasizes the importance of
stratospheric ozone trends for the entire mesosphere and
even the lower thermosphere. It also shows that the trend
reversal is not restricted to mid-latitudes but occurs on
global scales. It will be interesting to validate this result with
long-term records of mesospheric temperatures available in
the near future.

5. Summary and Conclusions

Our LIMA model reproduces large temperature
trends deduced from satellites measurements, radio wave
reflection height detections, and lidar observations. To the
best of our knowledge this is first time that models can reproduce such large trends in the mesosphere. We show that mesospheric cooling in summer is not uniform in time but is strong in the period 1979–1997 and small (or even heating) before and after that period. At mid latitudes and in the period 1979–1997 the lower stratosphere cooled by ∼0.5–1 K/decade, whereas further up (∼35–75 km) much larger cooling of up to ∼3–5 K/decade occurs. Mesospheric temperature trends are in general about a factor of 10 larger (and of opposite sign) compared to trends at Earth’s surface (global mean of ∼ + 0.2 K/decade). In the period 1961–1978 both the stratosphere and mesosphere cooled significantly less. After 1997 cooling becomes negligible and even changes to heating. The altitude profile of cooling/heating is rather complex. In general terms, trends at geometric heights are larger compared to trends at constant pressure levels, which is explained by atmospheric shrinking. Temperature trends in the mesosphere are mainly forced by long-term changes of CO₂ and O₃. We find that stratospheric ozone evolution in the past 50 years has a major impact on mesospheric temperature trends. Our model results suggest that the differences of mesospheric temperature trends in the periods 1961–1979, 1979–1997, and 1997–2009 originate from long term ozone changes in the upper stratosphere. Any cooling in the stratosphere leads to a shrinking and a corresponding trend in the meso- and thermosphere. Our results emphasize the importance of considering the entire atmosphere and to specify conditions (geometric/pressure altitude, time period, season, etc.) when presenting observational or model results regarding temperature trends in the mesosphere.

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