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The temperature structure of the winter atmosphere at South Pole

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[1] Fe/Rayleigh lidar measurements and balloon observations made recently at the geographic South Pole are used to characterize the monthly mean winter temperature profiles from the surface to about 110 km. The measured temperatures during mid-winter in both the stratopause and mesopause regions are 20–30 K colder than current model predictions. These differences are caused by weaker than expected compressional heating associated with subsidence over the polar cap. The measured mesopause temperature responds much more rapidly to changes in sunlight than model predictions, which suggests that IR heating by CO_2 absorption may also be important to the thermal balance in the mesopause region. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3319 Meteorology and Atmospheric Dynamics: General circulation; 1610 Global Change: Atmosphere (0315, 0325)

1. Introduction

[2] Global atmospheric change resulting from variations in greenhouse gas concentrations is now known to extend throughout the Earth's atmosphere [e.g., *Roble and Dickinson*, 1989; *Aikin et al.*, 1991]. In the stratosphere and mesosphere, rising CO_2 concentrations increase the effects of radiative cooling. Modeling studies have predicted that the stratopause will cool by 10–12 K and the mesopause by 6–12 K in response to a doubling of CO_2 [*Portmann et al.*, 1995]. The polar regions are more sensitive to these effects than lower latitudes so that observations there may provide some of the first conclusive evidence of global change in the middle and upper atmospheres. Measurements of temperature, wind, and constituent profiles at the poles also provide a convenient means of validating and calibrating global circulation models. Unfortunately, such observations are challenging and until recently, measurements of key parameters, such as temperature, have only been conducted in the troposphere and lower stratosphere at the poles with balloonsondes to altitudes less than 30 km.

[3] During winter at the poles, the balance between radiative cooling and adiabatic heating associated with subsidence over the polar cap, determines the temperature structure of the stratosphere and mesosphere. This latter process, called the downward control principle [*Haynes et al.*, 1991], is especially important in the Southern Hemisphere. It results in relatively warm winter polar temperatures and explains the existence of a stratopause in a region where solar heating is absent. It is difficult to accurately model this process because it involves the modulation of the meridional circulation system by the sporadic generation of planetary and gravity waves in the lower atmosphere and their dissipation in the middle atmosphere [*Garcia and Boville*, 1994]. While extensive temperature observations of the stratosphere and mesosphere have been conducted at several high latitude sites in the Arctic, little data are available from the Antarctic and until now, only a few airglow measurements have been made at the South Pole. *Hernandez et al.* [1992] and *Greet et al.* [1994] reported a few observations of OH airglow temperatures near 85 km, respectively at South Pole and Mawson (67.6°S). *Lübken et al.* [1999] reported rocket measurements of temperature profiles during summer in the mesosphere at Rothera (68°S), while *Kawahara et al.* [2002] used a Na lidar to determine the mesopause region temperature profiles during winter at Syowa (69°S).

[4] From Dec 1999 until Oct 2001, the University of Illinois lidar group operated an Fe/Rayleigh temperature lidar at the Amundsen-Scott South Pole Station [*Gardner et al.*, 2001]. In this paper we report the monthly mean winter temperature profiles for Apr through Aug derived from more than 150 h of measurements made with this instrument during the winters of 2000 and 2001. By combining the lidar data with ballonsonde measurements of the troposphere and lower stratosphere, we characterize the winter temperature structure above South Pole from the surface to about 110 km altitude. The measurements exhibit significantly colder temperatures in the stratopause and mesopause regions than predicted by the MSIS-00 empirical model and the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics Global Circulation Model (TIME-GCM) [*Roble and Ridley*, 1994]. Our results suggest that adiabatic warming is not as strong as these models have assumed.

2. Observations

[5] Radiosonde balloons are launched daily during winter at the Amundsen-Scott South Pole Station. The monthly mean temperature profiles up to 30 km for Apr through Aug were derived from the South Pole balloon data [*Pfenninger et al.*, 1999] and are plotted in Figure 1 along with the MSIS-00 model. In Nov 1999 the University of Illinois Fe lidar was installed in the Atmospheric Research Laboratory, which is located 488 m north of the geographic South Pole. The system was operated for two years collecting measurements of Fe densities, temperatures, and polar mesospheric clouds [*Gardner et al.*, 2001]. It can measure temperatures

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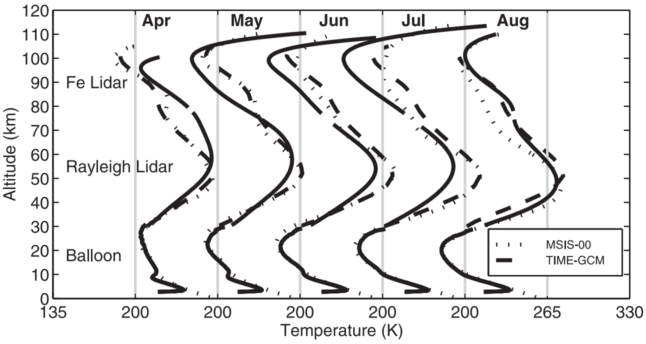

Figure 1. South Pole monthly mean temperature profiles for Apr through Aug (separated by 65 K for successive months). Lidar/balloon measurements are in solid lines, MSIS-00 model in dotted lines, and TIME-GCM model in dashed lines.

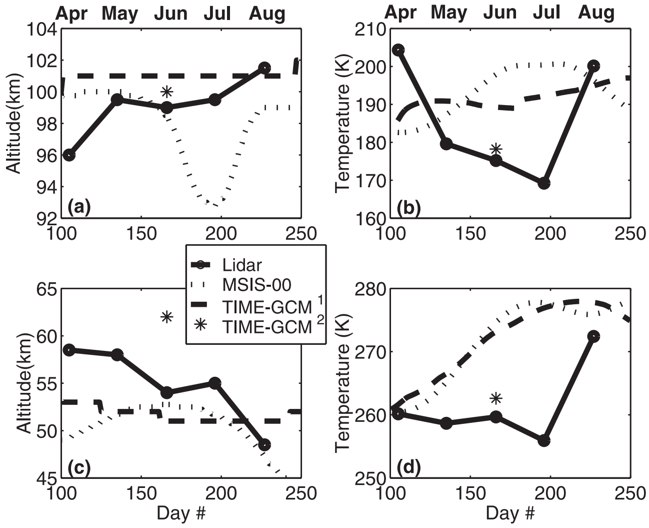

Figure 2. The (a) mesopause altitudes, (b) mesopause temperatures, (c) stratopause altitudes, and (d) stratopause temperatures at the South Pole from Apr through Aug. Lidar measurements are in solid lines and circles, MSIS-00 model in dotted lines, the original TIME-GCM[1] predictions in dashed lines, and the TIME-GCM[2] predictions with weaker gravity wave forcing under Jun solstice conditions marked as stars.

in the stratosphere and lower mesosphere using the Rayleigh technique, and in the mesopause region and lower thermosphere using the Fe Boltzmann technique [*Gelbwachs*, 1994]. *Chu et al.* [2002] provide a detailed description of the instrument design and its temperature measurement capabilities. The monthly average Rayleigh and Fe temperature profiles are also plotted in Figure 1 along with the TIME-GCM predictions for altitudes above 30 km. The accuracies of the lidar temperature profiles vary with altitude and observation time for the month, and are summarized in Table 1.

[6] The monthly mean mesopause altitudes and temperatures measured by the lidar are plotted versus time of year in Figures 2a and 2b, respectively, along with the daily values predicted by the MSIS-00 and TIME-GCM models. Similar data for the stratopause are plotted in Figures 2c and 2d. In May, Jun, and Jul, both the stratopause and mesopause temperatures are significantly colder than predicted by MSIS-00 and TIMEGCM.

3. Discussion

[7] The base altitude of the South Pole Station is 2.835 km. There is a persistent inversion layer near 3.5 km throughout the winter. Although the tropopause typically lies near 8 km, in winter the temperature continues to decrease with increasing altitude above the tropopause reaching a minimum near 20 km in the lower stratosphere. Solar heating is absent during the long polar night and the stable polar vortex in mid-winter prevents the transport of warmer air from lower latitudes to the pole. This leads to extreme cooling of the lower stratosphere and the formation of polar stratospheric clouds [*Collins et al.*, 1993]. Except for the inversion layer, the balloon profiles are in excellent agreement with MSIS-00. This is not surprising since MSIS-00 is an empirical model, which was developed in part, using the balloon data gathered at several sites in Antarctica including South Pole. In May, Jun, and Jul, the stratopause region is considerably colder than MSIS-00 and TIME-GCM predictions. The greatest difference occurs in Jul when the measured stratopause temperature is 256 K compared to about 277 K predicted by MSIS-00 and TIME-GCM. However by Aug, the stratopause has warmed to 272 K, comparable to that predicted by the models.

Table 1. Temperature Uncertainty and Observation Time for Apr Through Aug (80 km and above for Fe lidar, 70 km and below for Rayleigh lidar)

	Temperature Uncertainty (K)				
Altitude (km)	Apr	May	Jun	Jul	Aug
110	n/a	11.6	5.9	6.9	7.4
100	12.7	3.1	2.9	2.2	4.1
90	8.1	2.8	2.9	2.6	3.5
80	6.0	4.3	5.4	3.5	4.8
70	2.2	1.2	1.9	2.5	2.9
60	0.7	0.5	0.8	1.0	1.1
50	0.2	0.2	0.4	0.4	0.5
40	0.05	0.08	0.12	0.14	0.17
30	0.01	0.02	0.03	0.03	0.05
	Observation Time				
Fe Lidar	6.3 h	7.5 h	3.5 h	5.5 h	9.0 h
Rayleigh Lidar	51 h	31 h	25 h	23 h	22 h

[8] After the autumnal equinox in March, radiative processes begin cooling the polar atmosphere. This is accompanied by strong down welling over the south polar cap and weak upwelling elsewhere. The down welling heats the atmosphere through adiabatic compression and partially offsets the effects of radiative cooling [*Schoeberl and Hartmann*, 1991]. In the lower stratosphere, adiabatic warming is weak compared to the strong cooling associated with the emission of thermal radiation in the 15-μm band of CO_2. This region between about 10 and 30 km cools to much lower temperatures than the mid-latitude stratosphere. A latitudinal pressure gradient then develops between the south polar cap and mid-latitudes, which in combination with the Earth's rotation, establishes the circumpolar belt of westerly winds known as the polar vortex. The vortex inhibits the transport of warmer air from lower latitudes

into the polar cap. However, horizontal transport within the vortex is possible.

[9] Apparently the effects of radiative cooling are also quite substantial at stratopause heights (~50 km) when the polar cap is in darkness. The atmosphere below 50 km and south of 80°S is in complete darkness from 9 May to 5 Aug. At 50 km above South Pole, darkness extends from 10 Apr to 3 Sep. In Apr the observed stratopause temperature (260 K) is comparable to the MSIS-00 and TIME-GCM values. The region above 55 km, which is still illuminated by the Sun for much of the month, is warmer than the models, while the region in shadow below 55 km is colder. This shadowing effect in the Earth's lower atmosphere during Apr distorts the temperature profile and results in a higher stratopause than that predicted by the models. In May, Jun, and Jul when the polar cap stratopause region is in complete darkness, the observed temperature remains relatively constant at values between 256 and 260 K. In contrast, the predicted MSIS-00 and TIME-GCM temperatures increase in response to the expected adiabatic heating caused by down welling associated with the meridional circulation system. However, the observed temperatures suggest that the compressional heating of the stratopause region is just sufficient to balance the radiative cooling during this period. In Aug, when the polar cap is again illuminated by the Sun, the stratopause region is rapidly warmed by the ozone absorption of UV radiation so that the measured and predicted stratopause temperatures are comparable.

[10] The mesopause temperatures exhibit similar differences with MSIS-00 and TIME-GCM. The atmosphere below 100 km and south of 80°S is in complete darkness from 21 May to 24 Jul. At 100 km above South Pole, the atmosphere is in complete darkness from 18 Apr to 26 Aug. In Apr when the mesopause region over the polar cap is still illuminated by the Sun, the mesopause temperature is 204 K, which is ~20 K warmer than MSIS-00 and TIME-GCM. In May when much of the region is in darkness, the mesopause temperature falls to 180 K and is ~10 K colder than the models. Radiative cooling probably causes this rapid temperature decrease from Apr to May. In Jun and Jul, when the entire polar cap mesopause region is in complete darkness, mesopause temperatures average about 170 K and are 20–30 K colder than the models. *Kawahara et al.* [2002] have also observed similar cold mesopause temperatures during this period at Syowa Station (69°S). In Aug, when the region is again sunlit, UV absorption by O and O_3 quickly warms the mesopause to about 200 K and the temperature is comparable to those predicted by MSIS-00 and TIME-GCM. From Apr to Aug both models exhibit a gradual warming of the mesopause by about 10 K while the actual temperature decreases abruptly when the polar night begins and then increases quickly when sunlight returns. In fact the whole region from about 75 to 105 km is substantially colder than the models during May, Jun, and Jul. Apparently compressional heating associated with down welling in the mesopause region is not sufficient to balance radiative cooling until mid-winter when the mesopause temperature stabilizes around 170 K.

[11] The TIME-GCM results used for comparison with the South Pole data were from a year long run of the model that was discussed by *Roble* [2000]. The solar flux and auroral inputs to the model were held constant for solar cycle medium and geomagnetic quiet conditions and the only variation was caused by the seasonal variation of solar heating and photodissociation, gravity wave forcing at the lower boundary and a zonal average 10 mb geopotential height and temperature variation over the year as prescribed by an empirical model.

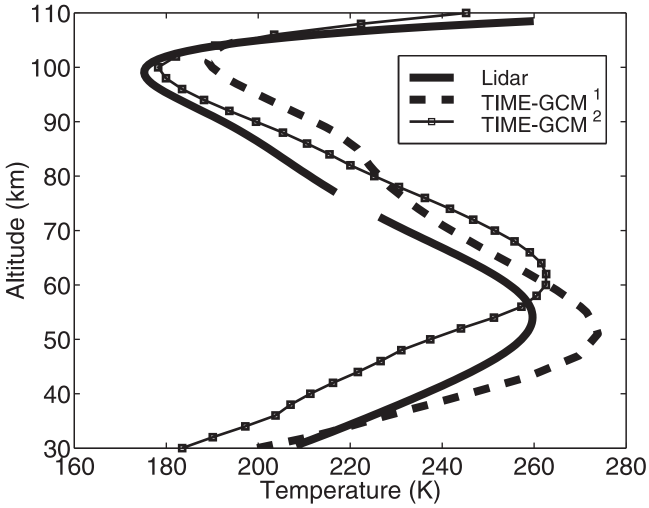

Figure 3. Comparison of the observed South Pole monthly mean temperature in Jun (solid line) with the original TIME-GCM[1] predictions, and the TIME-GCM[2] predictions with weaker gravity wave forcing under Jun solstice conditions.

[12] The TIME-GCM warmer stratopause and mesopause temperatures suggest that the model employed a stronger meridional circulation with subsequent stronger adiabatic warming than what is inferred from the measurements. To test this hypothesis, TIME-GCM was run for Jun solstice conditions but with weaker gravity wave forcing compared to the year long run. As shown in Figure 3, the mesopause temperature decreased from 189 to 178 K in better agreement with the measurements for mid-winter conditions (also in Figures 2a and 2b). In the stratopause region, the temperature decreased from 274 to 262 K and the stratopause altitude increased from 51 to 62 km also in better agreement with the measurements (also in Figures 2c and 2d). However, more work clearly needs to be done to bring the predicted temperature profile into better agreement with the observations.

[13] The observations also suggest that the mesospause temperature may be responding much more rapidly to sunlight over the pole in Apr and Aug than the model prediction. The TIME-GCM at present does not include the heating caused by CO_2 IR absorption of solar radiation primarily in the 2.0, 2.7 and 4.3-μm regions as discussed by *Fomichev and Shved* [1988]. The model calculates the global CO_2 and O distribution self-consistently [*Lopez-Puertas et al.*, 2000] and uses the CO_2 non-LTE cooling parameterization of *Fomichev et al.* [1998] with an O-CO_2 vibrational rate coefficient of 4×10^{-12} cm^{-6}/s for calculating radiative cooling in the mesosphere and lower thermosphere. The differences between model calculations and observations may indicate the importance of IR heating in the MLT region. Because our data have only been averaged over two winter

seasons, short-term variations in the mean meridional circulation may also be influencing the fast temperature transitions we have observed in the fall and spring of 2000 and 2001.

[14] CO_2 sensitivity calculations made with the TIME-GCM indicate that the winter polar region in both the stratosphere and mesosphere will cool by about 10 K for a CO_2 doubling from present day conditions. This cooling is also associated with a weaker meridional circulation and a weaker adiabatic heating in the winter polar region. The colder South Pole temperature profile derived from the present day model calculations may be further enhanced by stronger radiative cooling as CO_2 concentrations increase beyond current values.

4. Conclusions

[15] Temperatures during mid-winter in the stratopause and mesopause regions at the South Pole are 20–30 K colder than current model predictions. These differences are caused by weaker than expected compressional heating associated with subsidence over the polar cap. When less gravity wave forcing is incorporated in TIME-GCM, the weakened meridional circulation and down welling over the polar cap produce colder stratopause and mesopause temperatures as observed. The measured mesopause temperature responds much more rapidly to changes in sunlight than the model predicts. This suggests that IR heating by CO_2 absorption may also be important to the thermal balance in the mesopause region.

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