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First Lidar Observations of Middle Atmosphere Temperatures, Fe Densities, and Polar Mesospheric Clouds Over the North and South Poles

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Abstract. An Fe Boltzmann temperature lidar was used to obtain the first measurements of middle atmosphere temperatures, Fe densities, and polar mesospheric clouds (PMCs) over the North and South Poles during the 1999-2000 summer seasons. The measured temperature structure of the mesopause and lower thermosphere regions in mid-summer at both Poles is consistent with the MSIS90 model. The density profiles of the normal Fe layer between 80-100 km at summer solstice are similar at both the North and South Poles with maximum densities of about 2000 cm^{-3}. Sporadic Fe (Fe_s) layers were observed at both Poles with peak densities at 106 km altitude. The maximum densities of the Fe_s layers were 232×10^3 cm^{-3} at North Pole and 6.52×10^3 cm^{-3} at South Pole. PMCs were detected above both Poles. The altitudes of PMCs over the South Pole were consistently 2-3 km higher than those observed over the North Pole.

Introduction

Modelling studies and observations have shown that global change resulting from trace gas variations is not confined to the lower atmosphere but extends into the middle and upper atmospheres as well [e.g., *Roble and Dickinson*, 1989; *Aiken et al.*, 1991]. Doubling CO_2 concentrations is predicted to cool the stratopause (~50 km) by 10-12 K and the mesopause region (~80-100 km) by 6-12 K [*Portmann et al.*, 1995]. The Polar Regions are more sensitive to global change effects than elsewhere and profiles of atmospheric parameters and constituents at the Poles can provide a convenient means of validating and calibrating global circulation models. However, measurements of key parameters such as temperature profiles, have only been conducted in the troposphere and lower stratosphere at the Poles with balloon borne sensors to altitudes less than 30 km. While it is clear that polar middle atmosphere data are vital for testing the atmospheric circulation models that underlie our understanding of global change, collecting data from this remote and inaccessible region with sophisticated remote sensing instruments is challenging.

To help address this crucial measurement need, our group, in collaboration with The Aerospace Corporation and the NCAR Research Aviation Facility, has developed a robust new lidar system for measuring temperature profiles from the middle stratosphere to the lower thermosphere that can be deployed on research aircraft or operated at remote sites. This Fe Boltzmann temperature lidar was initially deployed to the North Pole in Jun/Jul 99 aboard the NSF/NCAR Electra aircraft and to the South Pole in Nov 99. During these campaigns the instrument made the first measurements of middle atmosphere temperatures, Fe densities, and polar mesospheric clouds (PMCs) over both Poles during mid-summer. To illustrate the measurement capabilities of this new lidar technique, we summarize those initial measurements and discuss key differences between the North and South Pole observations.

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Experimental Configuration

The University of Illinois Fe Boltzmann temperature lidar system is designed to measure temperatures from 30-80 km using the Rayleigh technique and from about 85 to 105 km in the mesopause region using the Fe Boltzmann technique [*Gelbwachs*, 1994]. The system includes two 0.4 m diameter telescopes and two injection-seeded pulsed Alexandrite lasers that are frequency doubled to probe the Fe resonance lines at 372 and 374 nm. The nominal average output power of each laser is about 3 W in the UV. The lidar can operate during both day and night. It was first deployed on the NSF/NCAR Electra aircraft to make observations of Fe meteor trails over Okinawa during the 1998 Leonid meteor shower [*Chu et al.*, 2000]. Additional information on the system characteristics and capabilities can be found in *Chu et al.* [2001a,b].

In Jun/Jul 99, the lidar system was again deployed on the NSF/NCAR Electra to make temperature and Fe density observations over the north polar cap during the Arctic Mesopause Temperature Study (AMTS). AMTS began on 16 Jun with a ferry flight from Broomfield, CO (40°N, 105°W) to Resolute Bay, Canada (75°N, 95°W) where the campaign was based. One roundtrip flight was made to Sondrestromfjord, Greenland (67°N, 50°W) on 19 Jun and four flights were made to the geographic North Pole on 21 Jun, 1 Jul, 2 Jul, and 4 Jul. On the last three flights to the geographic Pole, the return flight path passed directly over the magnetic North Pole (79°N, 105°W). On 5 Jul the system was flown to Anchorage, AK (61°N, 150°W) and one additional flight was made on 8 Jul to probe NLCs (noctilucent clouds) over the Gulf of Alaska. A total of 52 hrs of airborne lidar observations were made during AMTS. In Nov 99, the Fe lidar system was installed in the Atmospheric Research Observatory 488 m north of the geographic South Pole. Observations began on 2 Dec 99 and continued through the austral summer and winter. A total of 470 hrs of measurements have been made through Sep 00. In this paper we focus primarily on data collected during the few weeks near summer solstice at both the North and South Poles.

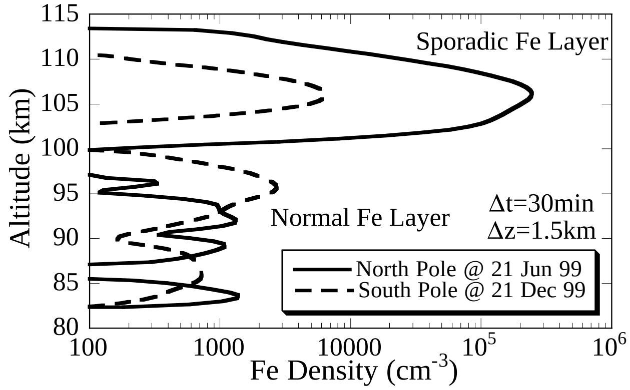

Figure 1. Fe density profiles obtained on the 1999 summer solstices at the geographic North (21 Jun 99) and South Poles (21 Dec 99).

Fe Densities

The mesospheric Fe layer typically extends from about 80 to 100 km altitude with sporadic Fe (Fe_s) layers sometimes observed at altitudes as high as 115 km. The layer is created by meteoric ablation and depleted at its lower boundary by chemical processes. Fe chemistry is temperature dependent. The primary sink reaction $FeO + O_2 \rightarrow FeO_3$ on the layer bottom side proceeds most rapidly at low temperatures [*Rollason and Plane*, 2000]. This reaction drives the seasonal variations in the Fe column abundance [*Kane and Gardner*, 1993; *Helmer et al.*, 1998]. Lidar observations at Urbana, IL (40°N) have revealed that the Fe abundance varies from a summertime low of $\sim 5\times 10^9$ cm^{-2} to a wintertime high of $\sim 15\times 10^9$ cm^{-2} with an annual mean of $\sim 11\times 10^9$ cm^{-2} [*Kane and Gardner*, 1993].

Because mesopause temperatures are extremely low over the polar caps at mid-summer, the Fe densities are also expected to be quite low. Existing models predict peak densities of about 10^3 cm^{-3} compared to several times that value at mid-latitudes [*John Plane*, private communication, 1999]. Plotted in Figure 1 are the Fe density profiles observed over the geographic North Pole on 21 Jun 99 and the geographic South Pole on 21 Dec 99. The normal Fe layers between 80 and 100 km at both sites exhibit very low densities of approximately 2000 cm^{-3}. The abundance of the normal Fe layer is 0.90×10^9 cm^{-2} at North Pole and 1.55×10^9 cm^{-2} at South Pole. These abundances are about a factor of 5 less than those observed during summer at mid-latitudes [*Kane and Gardner*, 1993]. Both profiles also exhibit sporadic Fe layers with peak densities near 106 km altitude. At the North Pole the peak density and abundance of the Fe_s layer are 232×10^3 cm^{-3} and 122×10^9 cm^{-2}, respectively. The corresponding values at South Pole are 6.52×10^3 cm^{-3} and 2.18×10^9 cm^{-2}.

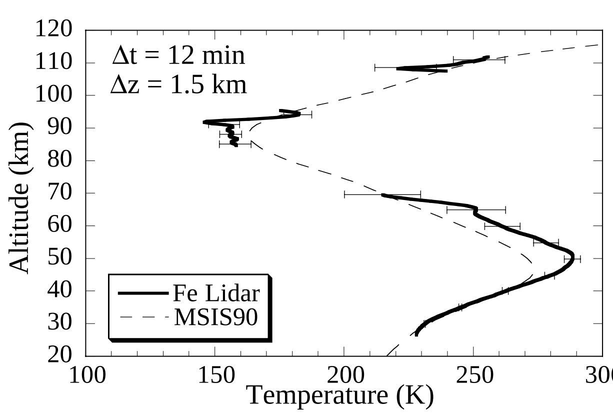

Figure 2. Middle atmosphere temperature profile obtained from the NSF/NCAR Electra aircraft at night near Rapid City, SD (44°N, 103°W) at 0415 UT on 16 Jun 99.

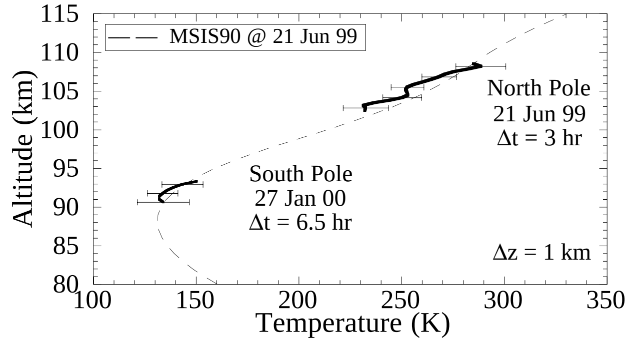

Figure 3. Temperature profiles obtained over the geographic North and South Poles on 21 Jun 99 and 27 Jan 00.

The sporadic layers dominate these Fe profiles at both sites but the 21 Jun 99 North Pole Fe_s is quite unusual because of the extremely high peak density and abundance. This prominent feature was observed on the subsequent three flights to the North Pole, however the peak densities and abundances of the Fe_s on these later flights were much smaller and comparable to the 21 Dec 99 South Pole observations. Although more than 300 h of Fe lidar observations were made at South Pole during the 1999-2000 austral summer, the Fe_s layer was only observed on summer solstice 21 Dec 99. Additional observations conducted in Nov and Dec 00 at South Pole exhibit numerous Fe_s. Sporadic metal layers are linked to sporadic E (E_s). Fe_s appears to result from the release of Fe from Fe^+, $FeO_2{}^+$, and FeO^+ in the presence of the enhanced electron and Fe^+ densities in sporadic E layers [*Kane and Gardner*, 1993]. E_s is commonly observed at high latitudes in the Northern Hemisphere, and ionosonde observations at Resolute Bay and Eureka (80°N, 85°W) during the period of our North Pole flights did reveal the presence of E_s [*John MacDougall*, private communications, 1999].

Middle Atmosphere Temperatures

Temperatures are derived using the Rayleigh technique by summing the 372 and 374 nm molecular scatter profiles and using the Boltzmann technique by ratioing the 372 and 374 nm Fe density profiles [*Gelbwachs*, 1994]. Plotted in Figure 2 is the temperature profile obtained at night near Rapid City, SD (44°N, 103°W) at 0415 UT on 16 Jun 99. The MSIS90 model profile for this latitude and date is plotted for comparison. The lower mesosphere is about 20 K warmer than MSIS90, while the mesopause about 10 K colder. The observed thermospheric temperatures near 110 km are comparable to model predictions. The mesopause temperatures near 92 km are very cold (145-150 K) and in the range conducive to the formation of NLCs. Just six days after these

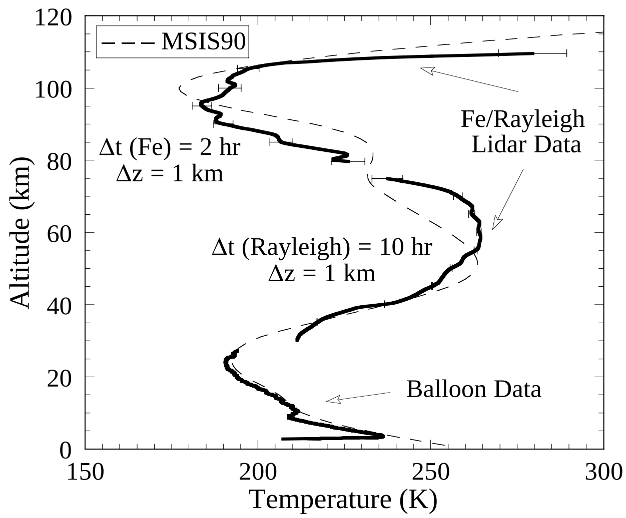

Figure 4. Composite temperature profile measured over the geographic South Pole on 8 May 00 using balloon and Fe/Rayleigh lidar data.

measurements were made, noctilucent clouds were observed near Salt Lake City, UT (42°N, 112°W), the first time the phenomenon has been observed that far south [*Mike Taylor*, private communications, 2000]. This figure illustrates the impressive capability of the airborne Fe Boltzmann lidar to make temperature measurements in the upper stratosphere, mesosphere, and lower thermosphere.

Because of the extremely low Fe densities over the North and South Poles in summer and the high background noise from the daytime sky, it was not possible to measure temperature profiles over as large a height range or with as high a resolution as the nighttime observations at Rapid City. The temperature profiles obtained in the thermosphere over the North Pole on 21 Jun 99 and in the mesopause region over the South Pole on 27 Jan 00, are plotted in Figure 3 along with the MSIS90 model profile for 21 Jun 99 at 90°N. Both observations are compatible with the MSIS90 model. Several groups have reported data that suggest the summer mesopause region in the Southern Hemisphere is a few degrees warmer than in the Northern Hemisphere. Recent rocket measurements of summertime temperatures at Rothera, Antarctica (68°N, 68°W) revealed that mesopause temperatures are 2-6 K warmer than at Andoya, Norway (69°N, 16°E) [*Lübken et al.*, 1999]. Polar mesospheric summer echoes (PMSEs), a phenomenon related to polar mesospheric clouds (PMCs), are weaker and more sporadic in the Southern Hemisphere [*Huaman and Balsley*, 1999], which may also be related to warmer temperatures. Our limited summertime temperature observations do not reveal any obvious differences from the MSIS90 model.

Significant departures from the MSIS90 temperature model were observed in the fall over the South Pole. Plotted in Figure 4 is a composite temperature profile obtained on 8 May 00 using balloon and Fe/Rayleigh lidar data. On this night it was possible to derive Fe temperatures in the lower thermosphere up to 110 km because of the presence of a high altitude Fe_s layer. The lower mesosphere is about 20 K warmer and the upper mesosphere is about 20 K colder than predicted by the MSIS90 model.

Polar Mesospheric Clouds

Polar mesospheric clouds and their visual counterparts, noctilucent clouds, form between 82 and 86 km at high latitudes during the three months around summer solstice when mesopause region temperatures fall below 150 K [*Thomas*, 1991]. The PMC and NLC volume backscatter coefficient profiles obtained near the geographic North Pole (> 85°N) on 4 Jul 99, over the Gulf of Alaska (58°N) on 8 Jul 99, and over the geographic South Pole on 18 Jan 00 are plotted for comparison in Figure 5. More extensive data on the seasonal and diurnal variations of the South Pole PMCs can be found in the papers by *Chu et al.* [2001a, b]. The most striking difference among these profiles is the altitudes of the scattering layers. The centroid altitude of the South Pole PMC, 85.6 km, is close to the seasonal mean of 85.5 km reported by *Chu et al.* [2001a]. The centroid altitude of the North Pole PMC, 83.3 km, is only slightly higher than the values typically reported for Northern Hemisphere observations [e.g., *von Zahn et al.*, 1998], but is 2.3 km lower than at South Pole. The centroid altitude of the NLC observed at night over the Gulf of Alaska, 81.8 km, is 1.5 km lower than the PMC observed 4 days earlier at the North Pole.

Chu et al. [2001b] and *von Zahn et al.* [1998] have shown that the altitude of the PMC layers are strongly influenced by the cm/s vertical winds oscillations associated with tides and waves. *Chu et al.* [2001a] also showed that the seasonal variations in the PMC altitudes at South Pole appear to be influenced by the cm/s upwelling over the polar cap associated with the diabatic circulation system [*Garcia and Solomon*, 1985]. The upwelling is strongest over the poles and becomes progressively weaker at lower latitudes. Thus, the altitude difference between the PMC observed near North Pole on 4 Jul and the NLC observed over the Gulf of Alaska (58°N) on 8 Jul is probably a consequence of the weaker upwelling at 58°N. The significant altitude difference between the North and South Pole PMCs is surprising. Perhaps it is associated with differences in the temperature structure. If the South Pole mesopause temperatures were several K warmer than the North Pole temperatures, then the South Pole PMCs would be expected to form several km higher nearer the mesopause where the temperatures are colder. Alternatively, the higher South Pole PMCs may

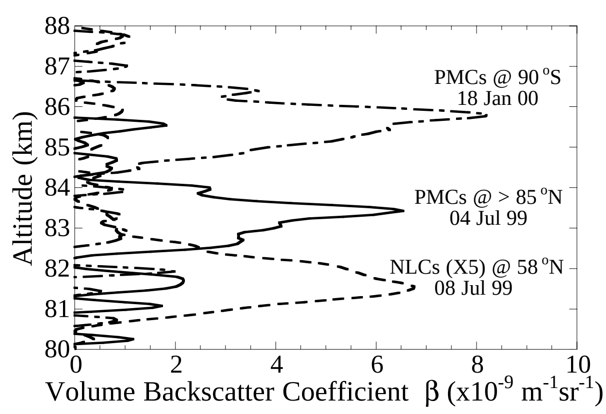

Figure 5. PMC and NLC volume backscatter coefficient profiles obtained near the North Pole (> 85°N) on 4 Jul 99, over the Gulf of Alaska (58°N) on 8 Jul 99, and over the South Pole on 18 Jan 00.

be an indication of stronger upwelling in the summer mesosphere over Antarctica compared to the North polar cap. Stronger upwelling would increase adiabatic cooling and result in a cooler, not warmer, mesopause region.

Conclusions

These initial observations demonstrate the impressive measurement capabilities of the Fe Boltzmann temperature lidar. The North Pole airborne observations, conducted near summer solstice when the Fe densities are minimum and background noise from the daytime sky is maximum, provided the toughest environmental tests of the instrument. In spite of these challenges, scientifically useful Fe density, temperature, and PMC profiles were obtained over both the North and South Poles in mid-summer. These initial measurements revealed interesting and surprising differences in Fe_s layer characteristics and altitudes of PMCs. The lidar will remain at South Pole for two more years where it will be used to characterize the seasonal variations of the temperature structure from 30-100 km, the Fe and Fe_s layer structure in the mesopause and lower thermosphere regions, and PMCs near 85 km.

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References

Aiken, A. C., *et al.*, Temperature trends in the lower mesosphere, *Geophys. Res. Lett., 18,* 416-419, 1991.

Chu, X., *et al.*, Characteristics of Fe ablation trails observed during the 1998 Leonid meteor shower, *Geophys. Res. Lett., 27,* 1807-1810, 2000.

Chu, X., C. S. Gardner, and G. Papen, Lidar observations of polar mesospheric clouds at South Pole: Seasonal variations, *Geophys. Res. Lett.,* 2001.

Chu, X., C. S. Gardner, and G. Papen, Lidar observations of polar mesospheric clouds at South Pole: Diurnal variations, *Geophys. Res. Lett.,* 20011.

Garcia, R. R., and S. Solomon, The effect of breaking gravity waves on the dynamics and chemical composition of the mesosphere and lower thermosphere, *J. Geophys. Res., 90,* 3850-3868, 1985.

Gelbwachs, J. A., Iron Boltzmann factor LIDAR: proposed new remote-sensing technique for mesospheric temperature, *Appl. Opt., 33,* 7151-7156, 1994.

Helmer, M., J. M. C. Plane, J. Qian, and C. S. Gardner, A model of meteoric iron in the upper atmosphere, *J. Geophys. Res., 103,* 10,913-10,926, 1998.

Huaman, M. M., and B. B. Balsley, Differences in near-mesopause summer winds, temperatures, and water vapour at northern and southern latitudes as possible causal factors for interhemispheric PMSE differences, *Geophys. Res. Lett., 26,* 1529-1532, 1999.

Kane, T. J., and C. S. Gardner, Structure and seasonal variability of the nighttime mesospheric Fe layer at mid-latitudes, *J. Geophys. Res., 98,* 16,875-16,886, 1993.

Lübken, F-J., M. J. Jarvis, and G. O. L. Jones, First in situ temperature measurements at the Antarctic summer mesopause, *Geophys. Res. Lett., 26,* 3581-3584, 1999.

Portmann, R. W., G. E. Thomas, S. Solomon, and R. R. Garcia, The importance of dynamical feedbacks on doubled CO_2-induced changes in the thermal structure of the mesosphere, *Geophys. Res. Lett., 22,* 1733-1736, 1995.

Roble, R. G., and R. E. Dickinson, How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?, *Geophys. Res. Lett., 16,* 1441-1444, 1989.

Rollason, R. J., and J. M. C. Plane, The reactions of FeO with O_3, H_2, H_2O, O_2, and CO_2, *Phys. Chem. Chem. Phys., 2,* 2335-2343, 2000.

Thomas, G. E., Mesospheric clouds and the physics of the mesopause region, *Rev. Geophys., 29,* 553-575, 1991.

von Zahn, U., G. von Cossart, J. Fiedler, and D. Rees, Tidal variations of noctilucent clouds measured at 69°N latitude by groundbased lidar, *Geophys. Res. Lett., 25,* 1289-1292, 1998.

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