MESOSPHERIC TEMPERATURE CLIMATOLOGY AND COMPARISONS ABOVE THE ROCKY MOUNTAINS

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Abstract

A Rayleigh-scatter lidar has been operated by the Center for Atmospheric and Space Sciences (CASS) at Utah State University (USU) since 1993. The lidar measures atmospheric temperatures between 45 and 90 km which are important for understanding the physics and chemistry of the middle atmosphere. The temperature profiles were used to create a multi-year temperature climatology. This climatology was used for comparisons with the temperature climatology from the Purple Crow Lidar at the University of Western Ontario, and nightly temperature profiles from the SABER instrument on board the TIMED satellite.

1. Introduction

The temperature structure of the mesosphere is the inverse of what we are use to in the troposphere. It exhibits lows during the polar summer and highs during the winter months. This temperature structure is a response of the atmosphere to the meridional component of the mesospheric circulation. The general circulation flows from summer to winter at high altitudes. In the summer mesosphere the air rises to flow toward the winter mesosphere and undergoes an adiabatic cooling. The winter mesosphere therefore undergoes a subsidence heating accounting for the temperature structure. To reproduce this temperature structure in circulation models it was found that a drag parameter was necessary. This drag was proposed to be caused by atmospheric gravity waves. The origin of these waves is believed to be in the troposphere from different sources such as orography, convective storms, and the jet stream. As these waves propagate up into the atmosphere conservation of energy causes the wave amplitude to grow until they become unstable and dissipate or break.

2. Rayleigh-Scatter Lidar

The Rayleigh-scatter lidar at USU is a co-axial lidar fixed in the zenith direction, Figure 1 [*Beissner*, 1997; *Herron*, 2004].
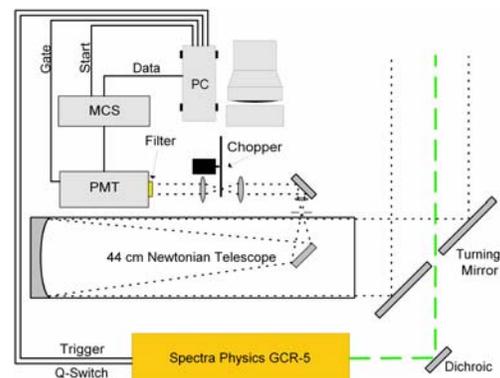
Figure 1 Simplified Lidar Diagram

The transmitter for the lidar system is a frequency doubled Nd:YAG laser (Spectra Physics GCR-5). The receiver consists of a Newtonian telescope with an aperture of 44-cm in diameter, and a red-sensitive bialkali photomultiplier tube (EMI 9954A). Returns from the lower altitudes are blocked from the

receiver by a mechanical chopper (New Focus) which is fully open by 20 km. In addition to the chopper the PMT is electronically gated to prevent saturation from the high intensity at lower altitudes. A small fast pre-amplifier is used to amplify the small pulses generated by the PMT. The returns are collected by a multi-channel scaler or MCS unit. The height resolution of the lidar is 37.5 m and the profiles are integrated for 2 minutes before a new integration starts. With 2 minute profiles it is possible to measure atmospheric waves down to the Brunt-Väisälä frequency.

The Rayleigh-scatter lidar is molecular or Rayleigh-scatter. With Rayleigh-scatter the incident radiation induces an electric dipole in the molecule. This induced electric dipole oscillates at the same frequency as the incident radiation. The Rayleigh-scattering is directly proportional to the produce of the atmospheric density and the Rayleigh backscatter cross-section.

Equation 1 Lidar Density

$$N(h) = \frac{N_0 A Q T^2(h)}{h^2}\left[n(h)\sigma_\pi^R\right]$$

Here h is the height above the lidar, $n(h)$ is the atmospheric number density, A is the telescope area, Q is the optical efficiency of the lidar system, N_0 is the number of transmitted photons, $N(h)$ is the number of backscattered photons, and $T(h)$ is the atmospheric transmittance. Since many of the quantities are unknown the lidar equation can be written in term of relaive density.

Equation 2 Relative density

$$n(h) = n(h_0)\frac{N(h)}{N(h_0)}\frac{h^2}{h_0^2}\frac{T^2(h_0)}{T^2(h)}$$

To derive absolute temperatures from the Rayleigh-scatter lidar returns (relative density) it is necessary to assume that the atmosphere is an ideal gas under hydrostatic equilibrium.

Equation 3 Hydrostatic Equilibrium of an Ideal Gas

$$k\frac{d(n(h)T(h))}{dh} = -n(h)m(h)g(h)$$

Here $P(h)$ is the pressure, $T(h)$ is the temperature, k is Boltzman's constant, $m(h)$ is the mean molecular mass, and $g(h)$ is gravity. This equation is easily integrated over the altitude region from h, the altitude of interest, to some particular reference altitude h_0.

Equation 4 Temperature Equation

$$T(h) = T(h_{max})\frac{n(h_{max})}{n(h)} + \frac{1}{k}\frac{n(h_{max})}{n(h)}\int_h^{h_{max}}\frac{n(h')}{n(h_{max})}m(h')g(h')dh'$$

Assuming a starting temperature T at a starting altitude h_{max} it is possible to integrate the relative densities downward in altitude to produce a temperature profile $T(h)$ [*Gardner et al.*, 1989].

The initial starting temperatures are taken from a nighttime temperature climatology from the Colorado State's sodium lidar [*She et al.*, 2000]. Any error in the starting temperature decreases as the temperatures are integrated downward. The lidar at CSU has been in operation over approximately the same time period and is located fairly close to the ALO lidar. By using a climatology instead of a model such as MSISe90 [*Hedin*, 1991] we hope to minimize the errors in the starting temperatures. The largest advantage for the Rayleigh-scatter lidar temperature technique is that while the measurements of density are relative the resulting temperatures are absolute.

3. Temperature Results

The Atmospheric Lidar Observatory (ALO) Rayleigh-scatter lidar database spans a period of 10 years. The temperature results have been calculated on hourly, nightly, monthly, and multi-year monthly profiles. A multi-year monthly average can be calculated by averaging the nightly temperature profile, Figure 2, or by average the raw data and using the average to calculate the temperatures, Figure 3.
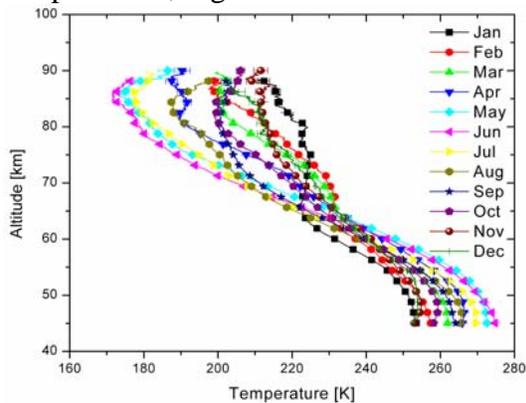
Figure 2 Multi-Year Temperature Average of Nightly Temperatures.
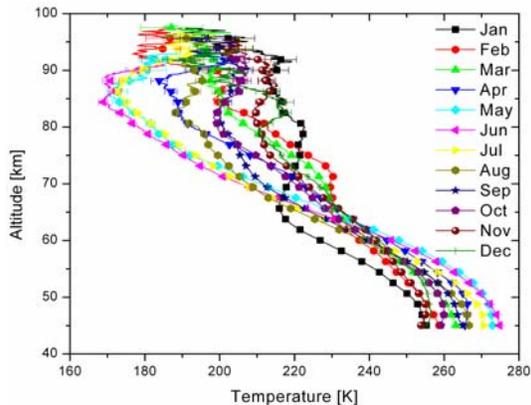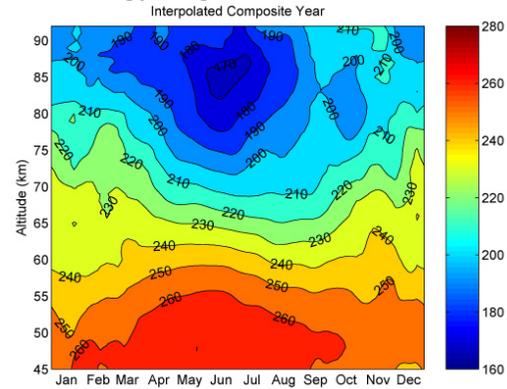

Figure 3 Multi-Year Temperature Average from Average of Raw Data

The similarities between the two averaging techniques show that the data reduction technique used was correct. The resulting summer temperatures near the stratopause region are 20 K warmer than during the winter period. The

winter temperatures near the mesopause are 50 K warmer than the summer temperatures.

4. Comparison with PCL

The Purple Crow Lidar (PCL) is a Rayleigh-scatter lidar operated by Bob Sica at the University of Western Ontario [*Sica et al.*, 1995]. The lidar system has been in operation since April of 1994 and is located at approximately the same latitude as ALO. The temperature climatology provided by Bob Sica and his group has been provided for comparison with the ALO climatology, Figure 4.

Figure 4 Multi-Year Temperature Climatology from the PCL lidar.

For comparisons the nightly temperature results from ALO were averaged using a 28 day boxcar average, Figure 5.
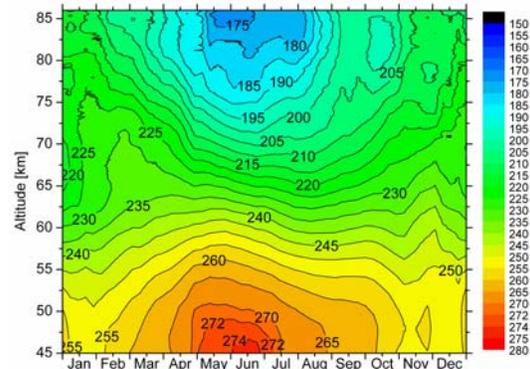
Figure 5 Temperature Contour of 28-day Boxcar Average of Nightly Temperature Profiles.

Comparing the temperatures from the two lidar systems in the stratopause region we see that the maximum from the PCL lidar is a small contour in mid May of 270 K. The maximum temperature from the ALO lidar is approximately the same at 274 K, but the 270 K contour extends from mid-April to mid-July which is a significant difference between the two systems when the error in the temperature measurements are their smallest.

The mesopause region can be clearly seen in the PCL climatology with a minimum mesopause temperature of 170 K centered about 85 km in June. In comparison the minimum in the ALO mesopause temperatures is 175 K centered at 85 km also. While they do agree in altitude and temperature the minimum starts approximately two weeks before the PCL minimum. The subtle difference suggests that there may be some longitudinal difference in the temperature structure of the atmosphere.

One interesting aspect of the temperature structure that is seen with both lidars can be seen in the equinox periods. The mesosphere is typically characterized by a constant decrease in temperature with altitude or a negative lapse rate. At certain times of the year the temperature structure increases or stays constant with altitude for a certain distance and is typically called an inversion. Inversions are seen with both lidars from February to March and from October to November. The cause of these inversion layers is not well understood and is believed to be linked to gravity waves and tides [*Hauchecorne et al.*, 1987; *Meriwether et al.*, 1998].

5. Comparisons with SABER

With the launch of the TIMED satellite mesospheric temperature measurements have been carried out by the SABER instrument it carries. Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) looks at Earth-limb emissions with a 10-channel radiometer. The data from the instrument must be mathematically inverted to provide vertical profiles. The primary data product from the SABER instrument is temperature derived from CO_2 from 10 to 130 km. The instrument was built by the Space Dynamics Lab at Utah State University, but is operated by James Russell at Hampton University who provided the data for the comparison.

To make comparisons with the SABER instrument it was necessary to derive a coincidence parameter for the measurements. For the comparison nights where there were measurements from SABER were taken within a 300 km of Logan. The SABER results were compared to the all night averages from the ALO lidar. These nightly temperature comparisons showed very good agreement as can be seen in Figure 6.
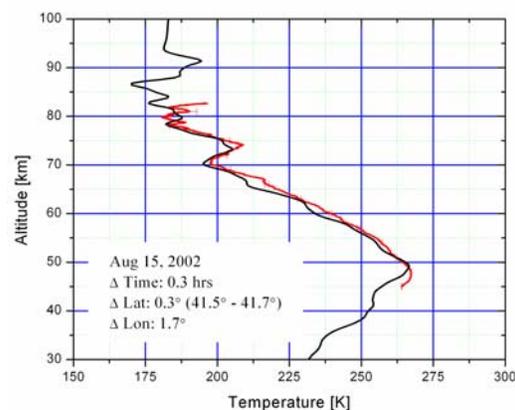

Figure 6 SABER vs ALO, August 15, 2002

For this comparison the two temperature profiles are with a half hour and also very close in latitude and longitude. As the distance between the SABER measurements and the nightly average from ALO increased the agreement suffered, but can give insight into the structure of the atmosphere, Figure 7.

Mar 09, 2002
Δ Time: 3.2 hrs
Δ Lat: 6.4° (35.4° - 41.7°)
Δ Lon: 3.5°
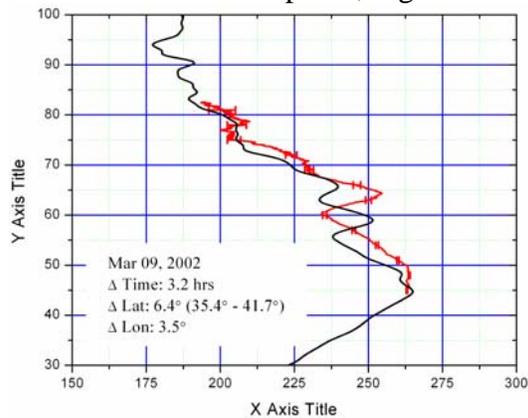
Figure 7 SABER vs ALO, Mar 09, 2002

There is a 6.4° difference in the latitude and a 3.2 hour difference in time for this comparison and the increased spacing shows how atmospheric waves can change the temperature structure.

7. Future Work

With the completion of the temperature climatology it is now possible to use the resulting temperature for studies of gravity waves, tides, inversion layers, and solar cycle effects to name a few. Some of these are currently being done by other members of the lidar group at USU.

All of the observations to date have been made with a 44 cm telescope. To improve our signal a much larger four barreled telescope is under construction. We have recently taken delivery of the four parabolic mirrors that were the last major component for the new telescope and will be couple it into the lidar system this summer. With the addition of the new telescope we will be able to make more accurate temperature measurements to higher altitudes. This will enable temperature comparisons between PCL and ALO possible on an hourly basis as the two systems will be very comparable at this point.

References

Beissner, K.C., Studies of mid-latitude mesospheric temperature variability and its relationship to gravity waves, tides, and planetary waves, Ph.D. thesis, Utah State University, Logan, UT, 1997.

Gardner, C.S., D.C. Senft, T.J. Beatty, R.E. Bills, and C.A. Hostetler, Rayleigh and sodium lidar techniques for measuring middle atmosphere density, temperature and wind perturbations and their spectra, in *World Ionosphere/Thermosphere Study, WITS HANDBOOK*, edited by C.H. Liu, pp. 148–187, SCOSTEP Secretariat, University of Illinois, Urbana, IL, 1989.

Hauchecorne, A., M.L. Chanin, and R. Wilson, Mesospheric temperature inversion and gravity wave breaking, *Geophys. Res. Lett.*, *14*, 933-936, 1987.

Hedin, A.E., Extension of the MSIS thermosphere model into the middle and lower atmosphere, *J. Geophys. Res.*, *96* (A2), 1159-1172, 1991.

Herron, J.P., Mesospheric Temperature Climatology Above Utah State University, Masters Thesis thesis, Utah State University, Logan, 2004.

Meriwether, J.W., X. Gao, V.B. Wickwar, T.D. Wilkerson, K.C. Beissner, S.C. Collins,

and M.E. Hagan, Observed coupling of the mesosphere inversion layer to the thermal tidal structure, *Geophys. Res. Lett.*, *25*, 1479–1482 & 2127, 1998.

She, C.Y., S. Chen, Z. Hu, J. Sherman, J.D. Vance, V. Vasoli, M.A. White, J.R. Yu, and D.A. Krueger, Eight-year climatology of nocturnal temperature and sodium density in the mesopause region (80 to 105 km) over Fort Collins, CO (41 N, 105 W), *Geophys Res. Lett.*, *27* (20), 3289-3292, 2000.

Sica, R.J., S. Sargoytchev, P.S. Argall, E.F. Borra, L. Girard, C.T. Sparrow, and S. Flatt, Lidar measurements taken with a large-aperture liquid mirror. 1. Rayleigh-scatter system, *Appl. Optics*, *34* (30), 6925–6936, 1995.

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