MESOSPHERIC TEMPERATURE CLIMATOLOGY AT THE USU/CASS ATMOSPHERIC LIDAR OBSERVATORY (ALO)

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Abstract

The Center for Atmospheric and Space Sciences (CASS) at Utah State University (USU) operates the ALO for the study of the middle atmosphere. Mesospheric observations between 45 and 90 km have been carried out on an "observe when possible" philosophy at night from 1993 to present. The location of ALO is unique as its mid-latitude location places it well within the Rocky Mountains which are a major orographic source for gravity waves. The lidar facility is located on the Utah State University campus, where it is very accessible to students. The relative observations from the lidar are reduced to provide absolute temperature profiles, 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 to examine secular, annual, seasonal variations, to compare with other temperature observations, and with modeled temperatures.

Introduction

The temperature structure of the mesopause exhibits lows during polar summer and highs during the polar 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. In circulation models it was found that to reproduce this temperature structure a drag parameter was necessary [*Leovy*, 1964]. The source of this drag was proposed to be caused by atmospheric gravity waves [*Hines*, 1960]. Gravity waves are believed to originate in the troposphere from different sources such as orography, convective storms, and the jet stream. As the gravity waves propagate conservation of energy causes the wave amplitude to grow exponentially with altitude until they dissipate or "break."

ALO's Rayleigh Lidar

Measurements made from the Rayleigh-scatter lidar are valuable for providing not only the mesospheric temperature structure, but also for correlative measurements with instruments at the Bear Lake Observatory (BLO) [*Choi et al.*, 1997; *Shepherd et al.*, 2000; *Taylor et al.*, 1991; *Wickwar et al.*, 1997b], and gravity wave studies. The current Rayleigh lidar is a co-axial lidar fixed in the zenith direction. 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 PMT (Electron Tubes 9954B). Returns from low altitudes are blocked from the receiver by a mechanical chopper (New Focus) which is fully open by 20 km. The mechanical chopper was necessary as the electronic gating (Products for Research) proved not to provide enough of a reduction of the intense low altitude returns. A small pre-amplifier located next to the PMT housing amplifies the output pulses by 200, which are sent to a multi-channel scaler with a built in discriminator (EG&G). The gate width is 250 ns (37.5 m) and 14000 gates (525 km) are sampled. The returns from 3600 laser pulses are summed creating a time resolution for the lidar of 2 minutes. The maximum range of the lidar is 525 km to provide a diagnostic of the PMT behavior.

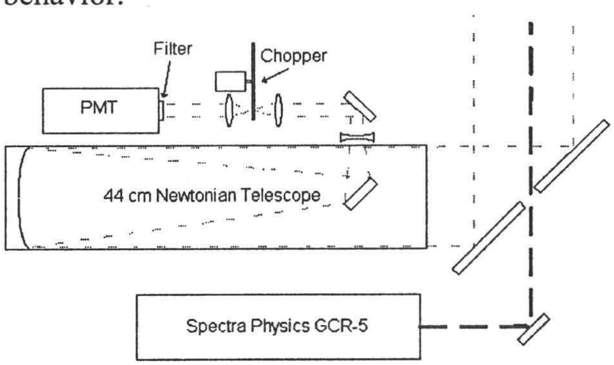

Figure 1 Simplified optical layout of the Rayleigh lidar system

The operation philosophy for the lidar has been to observe whenever possible. This is facilitated by the location of the lidar on the USU campus. This convenient location has enabled the nightly observations to be carried out by a group of both undergraduate and graduate students. The major portion of the observations is made by the undergraduate students. On average the lidar is in operation for 10 nights in a typical month.

Data Reduction

The basis for Rayleigh lidar is molecular or Rayleigh scatter from which it derives it name. In Rayleigh scattering the incident radiation induces an electric dipole in the molecule. This induced electric dipole oscillates at the same frequency as the incident radiation. Furthermore theory states that the scattering is directly proportional to the product of the atmospheric density and the Rayleigh backscatter cross-section. Since the incident radiation is produced with a laser, the backscatter cross-section can be assumed a constant, so the return profiles are a measure of relative density.

To derive absolute temperatures from the Rayleigh lidar returns (relative density), it is necessary to assume that the atmosphere is an ideal gas under hydrostatic equilibrium. Assuming a starting temperature T at a starting altitude h_{max}, it is possible to integrate down in altitude and produce a temperature profile. We choose h_{max} to be the altitude in which the signal is 16 standard deviations above the background noise. The initial starting or seed temperature for the data reduction has been taken from a nighttime climatology of a resonance-scatter lidar located at Ft. Collins, Colorado[*She et al.*, 2000]. As such the climatological temperatures should be valid to a higher altitude than if we used initial values from another source such as an atmospheric model. The largest advantage for the Rayleigh temperature technique is that while the measurements of density are relative the resulting temperatures are absolute.

The highest time and spatial resolution for the lidar are typically not used to make temperature measurements. The spatial resolution is dependent upon the scale height $H = \frac{kT}{\langle m \rangle g}$ which is ~ 7 km for the middle atmosphere. As such the 37.5 m resolution of the lidar is a high resolution measurement. Typically a 3 km boxcar average is taken to smooth the return profiles. One of the assumptions for making temperature measurements with the lidar is that the atmosphere is in hydrostatic equilibrium, and the atmospheric mixing in this region is due to eddy diffusion. The time constant for eddy diffusion is $T \approx \frac{H^2}{D}$, where D is the eddy diffusion coefficient. This time constant is on the order of 15 minutes in the middle atmosphere. For temperature measurements the shortest period used is typically an hour. However, when the returns from the lidar are analyzed for spectral components the limiting factor is the Brunt-Väisälä frequency typically has a period of 4 minutes compliments the two minute resolution of the Rayleigh lidar.

Lidar Model

To provide a means of testing the temperature reduction used with the Rayleigh lidar a simple model was created. The MSISe90 atmospheric model [*Hedin*, 1991] was used as a basis for the model. The density profile from the lidar model was used to create artificial lidar returns. Given the density profile it is possible to calculate the corresponding temperature profile and compare this with the temperature profile from MSIS. Using the algorithm from the lidar reduction it was possible to derive the same temperature profile as given by the MSISe90 model see Figure 2.

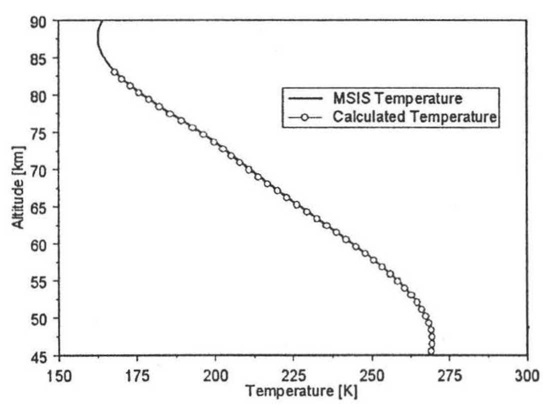

Figure 2 Comparison between the MSISe90 model temperatures and those calculated from the models density profile.

Given that the temperature reduction is producing the correct temperature structure it is possible to test some of the sources of error that can enter into the lidar model. The first error that enters into the lidar reduction is that of the initial starting temperature. As we cannot accurately know the actual initial temperature any error in this profile will cause errors in the resulting temperature profile. In testing the effects of the starting temperature various starting temperatures were used over a range from -20 to 20 K. As shown in figure 3 the effects from the error in the starting temperature decreases as the temperatures are integrated downward. Looking closer as the plus 20 K case the error in the temperature profile is reduced to ~ 3 K after 10 km and ~ 1 K at 70 km. While initial thoughts were to add a sodium lidar, for simplicity it was decided to add a potassium resonance lidar to the facility to provide temperature measurements between 80 and 110 km. The addition of this system will provide an accurate initial temperature measurement to seed the Rayleigh reduction.

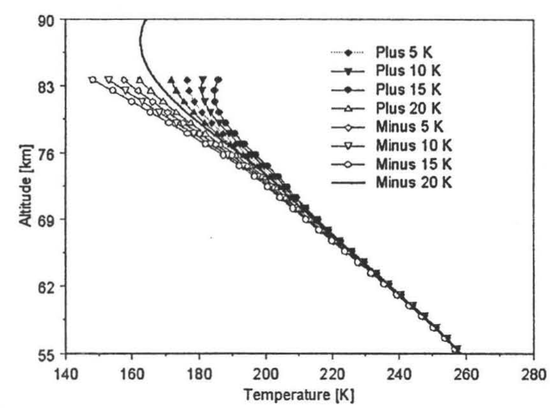

Figure 3 Errors in the temperature profile due to incorrect starting temperature.

The effect of non-linearities in the background region on temperature was also modeled. As the lidar records the return up to an altitude of 525 km an extensive background region is available. A measurement of the background is necessary to separate the Rayleigh signal from the total. When the lidar returns become non-linear it becomes difficult to find the correct background level to be removed from the total returns. Using the lidar model the background level that was removed was varied ± 5 % from the correct level. Overestimating the background level will produce a lower than normal density profile and an underestimation will produce a higher density Profile.

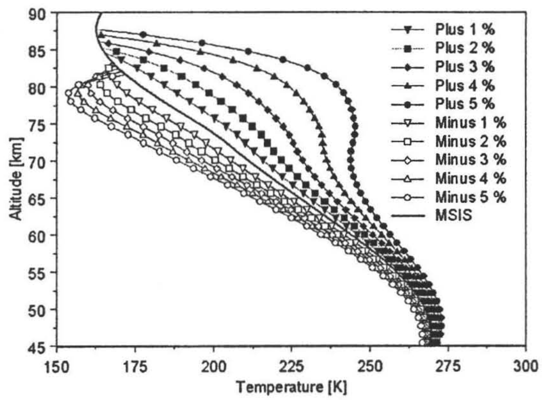

Figure 4 Temperature errors due to small variations in the background level

The effects of these underestimation and overestimation of the density profiles causes dramatic deviations from the correct temperature structure, especially at high altitude. Unlike errors in the starting temperature the effects of errors in the background measurements cause persistent deviations for the entire profile. This can clearly be seen in Figure 4. Fortunately the deviations from the normal temperature profiles have a characteristic shape that provides a good diagnostic for correcting the background level.

Mesospheric Temperatures

The ALO Rayleigh lidar database spans a period of 10 years starting from 1993. Temperatures have been calculated in a variety of different time resolutions. Typically a night of observations is reduced to one hour temperature profiles, and a single profile for a nighttime average. The monthly temperature profiles can be calculated in two distinct ways. Figure 5 is based upon a monthly average of the one hour temperature profiles. For a profile to be considered for the average it must contain 40 minutes of data. Figure 6 shows the results of the second way. It is a monthly average of the raw two minute return from the lidar. This averaged density profile is used to calculate the monthly average. Both figures show the results from th 12 month averages combing 10 years of measurements.

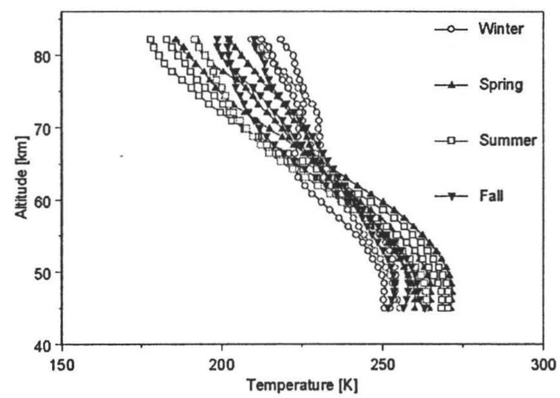

Figure 5 Monthly temperature averages created from hourly temperature profiles.

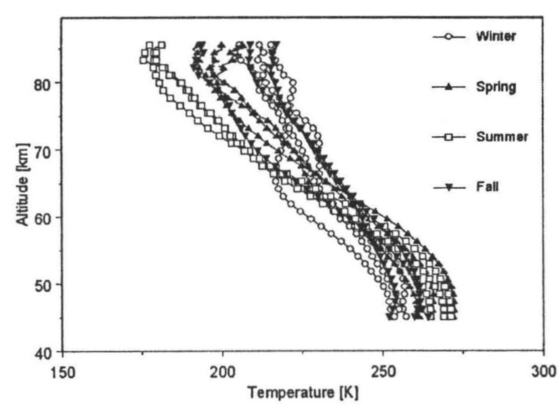

Figure 6 Monthly temperature averaged created from averages of the raw Rayleigh returns.

Small differences are present between the two. These differences can partly be contributed to the method of averaging the data. In averaging the nightly temperature profiles, hourly profiles were centered on the hour which left some hourly bins with much less than an hours worth of data. These profiles were not included in the averaging of the hourly profiles as they do not satisfy the necessity of having hydrostatic equilibrium. In addition to the start and stop times there are also data sets where clouds were removed causing short hours also. The second reason for the two plots to show differences in the resulting temperatures is that by averaging the raw two minute Rayleigh returns together the signal-to-noise ratio is higher. The net result of this is for the temperature reduction to start at a higher altitude. As such any error due to the starting temperature has less of an influence at the lower altitudes than with the hourly averages. The overall similarities between the two contour profiles while slightly different show large similarities ensuring that the data reduction technique used was correct. The resulting summer temperatures near the stratopause region are 15 K warmer than during the winter period.

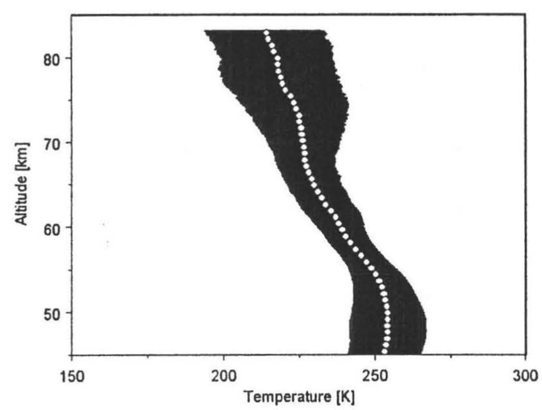

Figure 7: Geophysical variation of winter temperatures about the average temperature profile

The hourly temperature profiles were used to calculate the geophysical variation of the temperature profiles used for the monthly averages. These geophysical variations are more dramatic during the winter months. Temperature fluctuations in the winter months can easily approach levels of 40 K. Figure 7 depicts a winter (December) month long temperature profile with the black region depicting the geophysical variation. Figure 8 likewise depicts a summer (June) temperature profile. In both plots the dotted line down the center of the geophysical noise is the average temperature profile. The measurement error of these averaged profiles is on the order of a fraction of a degree.

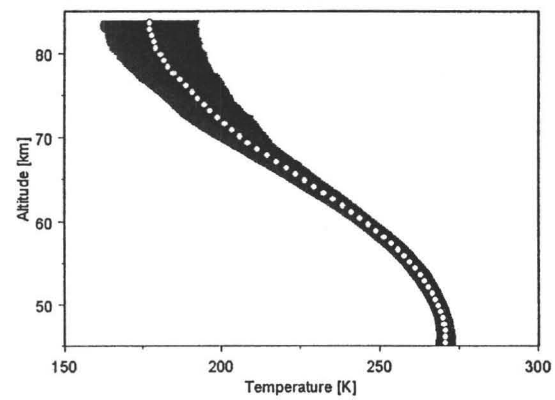

Figure 8 Geophysical variation of summer temperatures about the average temperature profile.

Future directions

The analysis of the temperature data from the ALO Rayleigh lidar has primarily been analyzed for its temperature structure and a few interesting phenomena *Wickwar et al.*, 1997a] a large database is available for additional analysis. Further work can be done on analysis of the gravity waves that propagate in the mesosphere, and currently work is being done on tidal motions.

All of the observations made to date have been made with a 44 cm Newtonian telescope. To improve our signal a much larger four barrel telescope is currently under construction. The design of the telescope is to use four separate primary mirrors to create a total collecting area of 5 m^2 or equivalent to a single 2.5 m primary. The multiple mirror telescope is the most economical way to achieve the larger collecting area that we desire. All of the mirrors have been made, ground, and polished, but only one primary has been coated. This first telescope has been installed and is currently undergoing optical testing. The other primaries will receive their final polishing and coating once we are satisfied with the optical properties of our first telescope.

The addition of the new telescope will significantly increase the abilities of the ALO facility. The collecting area of the new system will be 33 times that of the current one. This increased capability will be used to reduce the integration times need for temperature measurements, and to increase the maximum altitude. The shortest time that the atmosphere is still in hydrostatic equilibrium is 15 minutes. Using the new telescope temperature measurements over 15 minute intervals would have the same accuracy as those that currently take 8 hours of observations. The new telescope is not only increasing the collecting area of the lidar, but also providing a capability of pointing the lidar in azimuth and elevation. The pointing of the telescope is limited by the structure of observatory, and the lower limit is 45° off zenith.

With the increased range of the new system a new data acquisition system was necessary. Currently we are limited to the dynamic range possible with one channel. The new acquisition system will have four channels. With three channels it is possible to cover the entire altitude range in which the assumptions for Rayleigh lidar hold from approximately 30 to 110 km. The temperature profiles can then span across both the stratosphere and the mesosphere as well. Measurements of both the stratopause and the mesopause are important as they mark regions of the atmosphere where changes in both the chemistry and the physics are occurring. In the case of the stratopause the transition is between heating due to ozone and cooling due to CO_2. The mesopause region is measurably less understood than the stratopause. It marks the shift in the atmosphere from a region where eddy diffusion dominates to a region that is dominated by molecular diffusion.

The fourth channel of the new data acquisition system will be used for a second lidar. An alexandrite laser, at 770 nm, will be used as a resonance scatter lidar measuring the potassium layer between 80 and 110 km. The resonance lidar technique provides measurements of the temperature structure by measuring the spectrum with its shape being indicative of the neutral temperature. This addition will also provide the initial seed temperatures for the Rayleigh temperatures that, as was seen in Figure 2,will significantly increase the accuracy at higher altitudes. At lower altitudes there will also be a significant Rayleigh scatter from the 770 nm signal. Having the two wavelengths measure of the Rayleigh returns at lower altitudes will provide the ability to detect the presence of aerosols. If there is an abundance of aerosols at the lower altitudes Mie scatter will also be present in the return creating significant errors in the Rayleigh temperatures.

As the potassium lidar has to measure the spectrum to derive temperature we will also be able to detect Doppler shifts. This combined with the steering capability of the new telescope will enable measurements of winds in the upper atmosphere. Measurements of winds with a Rayleigh lidar are possible but would require the addition of a new detector system.

Acknowledgements

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