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## Middle Atmosphere Temperature Results from a New, High-powered, Large-Aperture Rayleigh Lidar

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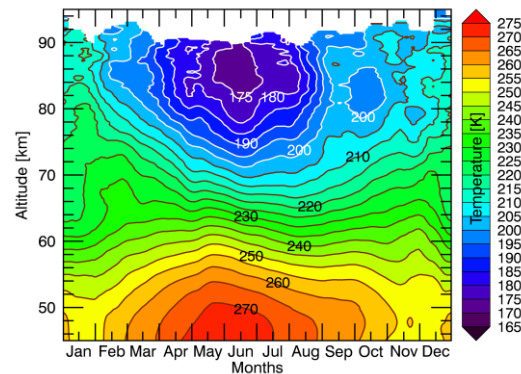
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**Abstract.** In June–July 2012, observations were carried out using the recently upgraded, large-aperture, Rayleigh-scatter lidar system located at the Atmospheric Lidar Observatory (ALO) on the campus of Utah State University, in Logan, UT (41.7° N, 111.8° W). This time period was significant because it enabled us to observe the annual temperature minimum in the upper mesosphere-lower thermosphere region. The data collected during the campaign were analyzed for temperatures between ~70–109 km. The results above ~95 km are the first obtained with a Rayleigh-scatter lidar, extending the technique well into the lower thermosphere. A great deal of variability from night-to-night is evident in these temperature profiles and in the mesopause altitude. The profiles also show considerable wave activity from large amplitude waves. The temperatures are compared to those from the MSISE90 model and from the 11-year ALO temperature climatology. This new capability for the ALO Rayleigh lidar, like any new observational capability, opens the potential for new discoveries in this hard-to-observe region.

### I. INTRODUCTION

Rayleigh lidar observations opened the region 30–90 km to ground-based study. The upgraded system at ALO is showing that this ground-based study can be extended to 109 km, with the goal of reaching 120 km. The resultant study of short and long-term

temperature trends contributes immensely to our overall understanding of the properties and dominant physical processes in the middle atmosphere. Climatological studies of temperatures can help predict global change throughout the atmosphere, while temperature variations on shorter scales, from minutes to days, give insight into the effects of waves (gravity waves, tides, planetary waves).



**Figure 1.** USU Rayleigh lidar temperature climatology constructed from the 11-year data set from the original Rayleigh lidar system

The original Rayleigh lidar system at the Atmospheric Lidar Observatory (ALO) on the campus of Utah State University in Logan, UT, ran for 11 years. A temperature climatology was developed using the 11 year data set showing seasonal trends throughout the mesosphere from 45–90 km (Fig. 1).<sup>1</sup> Mesospheric properties that stand out in these data include the annual temperature maximum at lower altitudes (~45–50 km) and the annual temperature minimum at higher

**Table 1. USU Large-Aperture, Rayleigh lidar system specifications**

<b>Transmitter</b>		<b>Receiver</b>		<b>Signal Processing</b>	
<b>Lasers</b>	Spectra Physics GCR-5 (GCR-6)	<b>4-mirror Receiving Area</b>	4.9 m <sup>2</sup>	<b>Photon Counting System</b>	Ortec Turbo Multichannel Scaler
<b>Laser Crystal Type</b>	Nd:YAG	<b>Single Mirror Diameter</b>	1.25 m	<b>Max Count Rate</b>	1 Million CPS
<b>Wavelength</b>	532 nm	<b>Focal Length</b>	236 cm	<b>Range Bin</b>	37.5 m
<b>Pulse Width</b>	7 ns (7 ns)	<b>Fiber NA</b>	0.39	<b>Number of Range Bins</b>	14,005
<b>Pulse Energy</b>	600 mJ (800 mJ)	<b>Fiber Diameter</b>	1.5 mm	<b>Integration Time</b>	2 min
<b>Average Power</b>	18 W (24 W)	<b>Photomultiplier Tube</b>	ET 9954B		

altitudes (~80–90 km) that both occur during the summer months of June and July. It is these temperatures near summer solstice that are of particular interest, because the new observations reported here show the capability to extend the temperatures upward into the lower thermosphere.

When the first of a series of hardware upgrades to the original Rayleigh lidar were completed by mid-June 2012, an observing campaign was launched to better examine this temperature minimum. An 18-day data set was collected from June 13 to July 12. These data covered the region from 60 to 109 km. This data set is significant in that it extends the previous Rayleigh lidar observations significantly above 90 km. This takes the observations from the mesosphere, through the mesopause, and well into the lower thermosphere.

## II. SYSTEM UPGRADES

This first step in a series of hardware upgrades, which will transform the original ALO Rayleigh lidar into a Rayleigh-Mie-Raman (RMR) scatter lidar, was completed in June 2012. This portion of the upgrade

increased the sensitivity by a factor approaching 70, which is how we were able to improve the highest altitude data. A detailed description of this large-aperture, high-powered, Rayleigh lidar's specifications is given in Table 1.

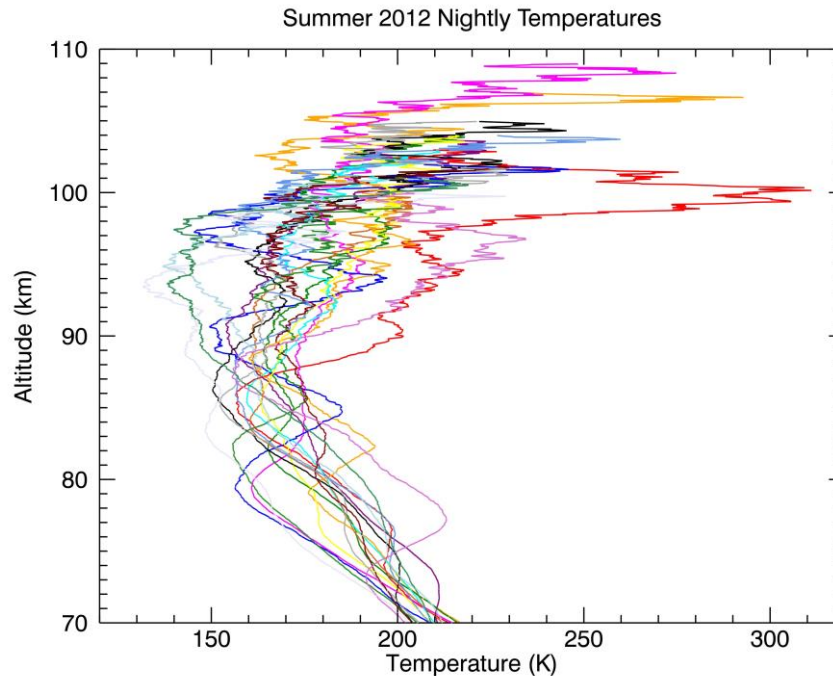
Upgrades of note include the use of two pulsed Nd:YAG lasers operating at 532 nm giving an overall transmitted power rating of 42 W; the use of four coaligned 1.25-m diameter parabolic mirrors as a single receiving telescope (the equivalent of a 2.5-m diameter telescope) to give a receiving aperture area of about 4.9 m<sup>2</sup>; and the development and use of a new optical system to combine the light from the four optical fibers into one beam in order to get the full return signal into a single detector. Except for the details of how this is done, the receiver part of the lidar system is equivalent to having one large telescope to collect backscattered light and send it to one detector. Other upgrades had to do with the computer and equipment timing systems, as well as the plumbing and air systems in the lidar laboratory.

The signal processing used in the summer 2012 campaign remained mostly unchanged from that of the original ALO Rayleigh lidar. A multichannel scalar (MCS) and its accompanying software, installed on a PC, were used to count photons and save data

adding more, lower sensitivity, detector channels as described in Section VI.

### III. MLT TEMPERATURES

During the summer 2012 data campaign, observations were made over a month long



**Figure 2.** Nighttime temperature profiles for the 18 nights of data taken during the summer 2012 campaign. The data were averaged over 3 km in altitude and 1–6 hours in time

profiles every two minutes with a range bin size of 37.5 m. These are the minimum resolutions for the observations. However in the data processing, the data were usually averaged over 3 km in altitude and 30 minutes to all night in time.

The data processing system was set up to begin taking good data at 60 km. However, the PMT was receiving so much light at altitudes below 70 km, that its response to light became nonlinear. That limited the lowest altitude results presented here to 70 km. We plan to solve this “problem” by

period (June 13–July 12). Some nights were devoted to improving the system, and some to observing. Eighteen of those nights gave good temperature profiles in the mesosphere-lower thermosphere (MLT) region from 70 km up to a maximum of 109 km. Temperatures were reduced using the classic Chanin-Hauchecourne (CH) method<sup>2</sup> developed in 1980 and modified to use temperatures instead of pressures as the initial condition at the top altitude. The initial temperatures were taken from the MSISe90 model<sup>3</sup> for each night. For a single temperature profile the altitude resolution

was 3 km and the integration time was typically a full night (about 5–6 hours). However, after working on the system in the early evening, it was sometimes shorter, even as short as 1 hour.

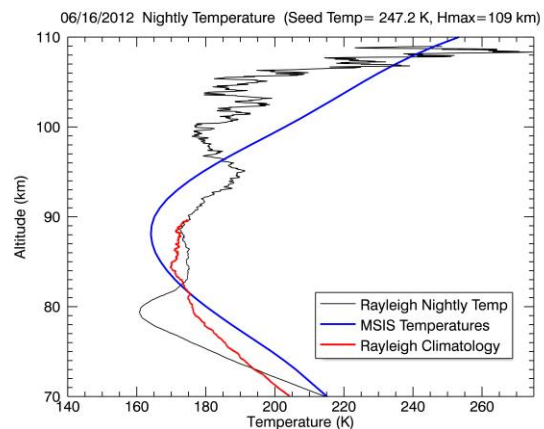
In Figure 2, all eighteen nighttime temperature profiles are plotted together. With this representation, one of the striking features is the variability from night to night. Some of this variability is due to wave activity, i.e., gravity waves, tides and/or planetary waves. In particular, the dark blue profile, a one-hour profile from June 22, 2012, stands out. It shows three minima and two maxima for a wave with a 9 km vertical wavelength and an amplitude that grows with altitude from 10 K near 80 km to 25 K near 100 km. Waves with large amplitudes similar to this one produce particularly low temperatures at altitudes near the minima of the waves. This can affect the deduced mesopause temperature and its altitude. Low temperatures in the mesosphere produced in this way have been implicated in the formation of mid-latitude noctilucent clouds.<sup>4</sup> Other nights show smaller waves.

As expected, temperatures in this region during this period are quite low. Ignoring obvious wave structures, there is an underlying average of approximately 165 K near 87 km, which would be the mesopause. However, four individual nights, exhibiting what appear to be wave like variations, clearly show temperatures only slightly greater than 150 K between 79 and 84 km. Three additional nights show minima of approximately 140 K near 94 km. This illustrates the fact that, from night-to-night the mesopause can appear to change altitudes or not even be clearly present.

On average the highest altitude limit of these temperature plots is approximately 103 km. This limit can vary from night to night depending on the number of data files

acquired, atmospheric transmission, mirror alignment, laser power and other instrumental parameters. Our highest altitude for temperature determination was on June 16, 2012, with a height of 109 km. This is the highest that Rayleigh lidar temperature data has gone thus far. In fact, all of the data from the summer 2012 campaign reached into new territory for Rayleigh lidar systems, which have historically had an upper altitude limit of 95 km.<sup>5</sup>

A comparison of these new Rayleigh lidar temperatures with the major empirical model and our previous temperature climatology illustrates the need for more observations in this atmospheric region. Figure 3 picks out the June 16 temperature profile specifically (black curve), and plots it against the MSISe90 model temperatures for the same night (blue curve) as well as the ALO temperature climatology (red curve) for the same night of the year.



**Figure 3. Comparison of new Rayleigh lidar temperatures from the night of June 16, 2012 with those from the MSISe90 model and original ALO Rayleigh lidar temperature climatology.**

There is broad agreement between the Rayleigh and MSISe90 temperatures. They are both hot at 70 and 109 km, and cold near 90 km. However they differ greatly in

between. They tend to differ ( $T_{\text{Lidar}} - T_{\text{MSIS}}$ ) from each other by +10 K centered on 90 km to between -20 and -35 K over much of the rest of the altitude range. Some of this difference is undoubtedly due to wave effects in the Rayleigh observations, while waves have been effectively removed from MSIS. However, some of these differences may represent real limitations in the model because of the paucity of middle atmosphere data at the time when the model was developed. To determine that, the averaging of many more nights of observations will be required. In turn, Rayleigh lidar temperatures such as those in Figure 1 and new ones from the upgraded Rayleigh lidar should be included in a new formulation of the empirical model.

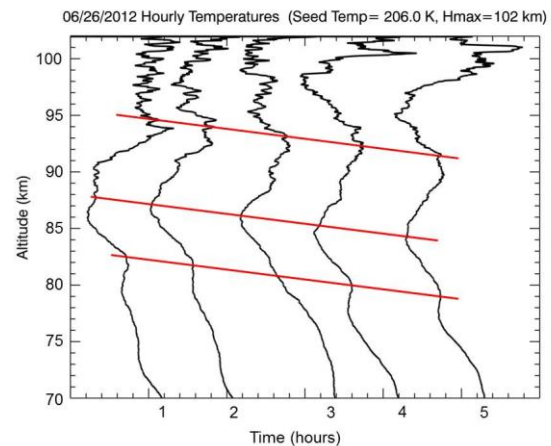
Returning to wave-like differences, this is where good observations are important. They enable, for instance, the analysis of temperatures to find waves of any type, heating and cooling events, the conditions under which noctilucent clouds occur, and the effects of instabilities.

Looking now at the comparison between the new Rayleigh lidar temperatures and those of the original Rayleigh lidar's climatology there appears to be a bit more agreement. There are significant differences at 70 and at 79 km, which might reflect wave activity. Again, more comparisons would be needed to be sure. However, the main take away of this comparison is how much higher the new system is able to go.

#### IV. WAVE ACTIVITY

As seen in Figure 2 and already discussed, some of the summer 2012 campaign's temperature profiles show strong evidence of wave structures. However, even more can be learned about these waves. The night of June 26, 2012, has been chosen to illustrate this. The data were reanalyzed in

one-hour intervals. The resultant hourly temperature profiles are plotted with 50 K offsets, Figure 4. (One hour corresponds to 50 K.) Lines have been drawn connecting peaks and valleys to help direct the eye. In this plot, we see evidence of waves with a downward phase progression. The dominant wave appears to be monochromatic with a wavelength of 12 km and a phase speed of -1 km/hr, giving an approximate 12 hr period. Other waves are also present, but they have smaller amplitudes. With further analysis, the horizontal wavelengths and phase velocities could also be found using the densities or temperatures measured with this Rayleigh lidar system.<sup>6</sup>



**Figure 4. Evidence of gravity wave activity in the temperature measurements from June 26, 2012. Each curve is integrated over 1 hour in time and offset successively by 50 K. The temperatures are integrated over 3 km in altitude.**

Data from the region now observable with the upgraded ALO Rayleigh lidar will be very significant to wave studies. Part of this is because we will be able to follow the waves from lower altitudes, where their pattern is simpler, into this region where there may be some filtering, more wave breaking, reflections, and ducting. Collecting a great deal of observations of such

phenomena will be a great help in furthering our overall understanding of wave dynamics in the atmosphere.

## V. CONCLUSIONS

In sum, the new large-aperture, high-powered, Rayleigh lidar system at Utah State is now acquiring good temperature data in a fairly uncharted portion of the MLT (70–109 km—especially above 90 km). The emphasis on completing this first step of the lidar upgrade was to be able to make observations to the highest possible altitudes.

Measurements in this region in 2012 during the annual temperature minimum about the summer solstice did indeed show very low temperatures. They also showed complications to simple interpretations of the MLT region due to a significant portion of the nights having large-amplitude wave activity. The mesopause was also observed in the temperatures from some of the nights during the campaign, while it was obscured by wave activity on other nights.

This variability was further illustrated with two comparisons. First, a comparison was made with the MSISe90 model for the same day. The data showed the occurrence of big waves while the model did not. Second, wave activity was examined in more detail by integrating temperature plots over shorter time intervals, one-hour intervals instead of all night. The plot's successive one-hour profiles for one night clearly showed the vertical wavelength, downward phase speed, and period of a monochromatic wave.

Additionally the comparison between one night's temperatures, those of the MSISe90 model and the original ALO Rayleigh lidar's climatology illustrated the importance of the new lidar's data in that (1) it captures variations in temperature structure from night to night, hour to hour and possibly even on smaller time scales whereas a model

cannot, and (2) it goes well above previous Rayleigh lidar systems, acquiring Rayleigh lidar data above 90 km.

## VI. FUTURE WORK

As mentioned previously, the high-powered, large-aperture, Rayleigh lidar used to conduct the summer 2012 campaign is really one step in a series of upgrades to the original ALO Rayleigh lidar. The completion of these upgrades will transform the Rayleigh scatter lidar into a Rayleigh-Mie-Raman (RMR) scatter lidar. As is described in its name, the RMR lidar will measure Rayleigh, Mie and Raman scattering interactions between the transmitted laser pulses and atmospheric constituents.

To do this, instrumentally, three more detector channels must be added to the system. These channels have already been designed and will be put into place in the summer of 2013. They include an second channel to measure Rayleigh scatter down to 45 km, a third channel to measure both Rayleigh and Mie scatter down to 15 km and a fourth channel to measure Raman scatter from  $N_2$  molecules below 35 km, which is then used in the data reduction to separate the Rayleigh and Mie signals from each other.

The new RMR lidar will have an overall altitude range of ~15 to 120 km after the installation of the new detector channels, more precise optical alignment of the telescopes, selection of the most sensitive PMT for the highest altitude channel and fine tuning of the lasers' power output. This range will cover most of the stratosphere, all of the mesosphere and well into the lower thermosphere. Analysis of the data acquired with this unique system will provide a better understanding of the whole atmosphere as one complete system.

## VII. ACKNOWLEDGMENTS

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