EARLY RAYLEIGH-SCATTER LIDAR TEMPERATURE MEASUREMENTS FROM THE LOWER THERMOSPHERE

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ABSTRACT

Rayleigh-scatter lidar observations were made on many clear nights at the Atmospheric Lidar Observatory (ALO) at Utah State University (USU) from 1993 to 2004 in the altitude range 45–90 km. An upgraded facility, 66 times more sensitive, has been brought on line. It has resulted in temperature measurements with maximum altitudes that extend into new territory—the lower thermosphere. All-night temperature averages have been recorded up to an altitude of 114 km. Temperatures from each month, starting in June 2014, are presented and discussed. They are compared to each other, to the ALO-USU climatology from the original lidar, and to temperatures from the NRLMSISe00 empirical model.

1. INTRODUCTION

The original ALO-USU lidar covered the altitude gap between the highest weather balloon measurements (~30 km) [1] and the lowest radar [2,3], airglow [4] and resonance lidar measurements [5] (~80 km). A similar ground-based observational gap exists in the lower thermosphere above about 100 km.

The intent of the redesign of the ALO lidar is to extend Rayleigh observations up to about 120 km. The upgrade has involved a big increase in both laser power and telescope collecting area. So far the upgraded system has reached 114 km.

One general point of making ground-based Rayleigh observations is to observe the time evolution of various aspects of the middle atmosphere. Another is to observe the coupling among regions: between the stratosphere and mesosphere and between the mesosphere and thermosphere.

A more specific and detailed statement about the science to which Rayleigh lidar contributes comes from the list of past and ongoing studies carried out using data from the original ALO Rayleigh lidar. Studies taking advantage of much of the 11-year data set include: a midlatitude mesospheric temperature climatology [6], an extensive gravity wave study [7], a detailed examination of possible climate or solar cycle changes [8], a study of the midlatitude mesosphere during Sudden Stratospheric Warmings [9], and an exploration of neutral density variations [10].

In addition, there are unexpected results that arise from observing as frequently as possible. These include midlatitude observations of noctilucent clouds [11,12] and their association with large-amplitude waves, and an all-night observation of a thin layer descending from the mesosphere into the stratosphere.

Furthermore, Rayleigh lidar observations are complementary to observations from satellites, such as those from SABER on TIMED [13]. While satellites take global measurements that can show latitudinal and longitudinal variability, Rayleigh lidars obtain data from a fixed point on the globe, which enables them to acquire valuable information on time evolution and about local atmospheric variability. Rayleigh lidars are also complementary to resonance lidars, which have a more limited altitude range, roughly 80–105 km, though they have better altitude and time resolution. At USU, either on campus or at the nearby Bear Lake Observatory, the ALO Rayleigh lidar observations overlap with those from a cluster of other instruments making mesospheric observations. These include a sodium resonance lidar; all-sky cameras imaging OH, O(^{1}S), and O_2 Atmospheric bands; a meteor wind radar; an ionosonde for measuring D and E region ionization; and a magnetometer for measuring E-region currents.

It is expected that the extremely sensitive ALO Rayleigh lidar will continue the types of studies described above, extending them in time and from the mesosphere into the lower thermosphere.

The format of this paper is as follows: Section 2, on methodology, discusses the acquisition and temperature reduction of the early data from the upgraded system. Section 3, on results, shows these early temperatures and their relation to climatological and model temperatures. Section 4 gives conclusions and indicates future directions.

2. METHODOLOGY

2.1 USU Rayleigh Lidar System Upgrades

Many upgrades to the original lidar have been made in order to extend its measurements to higher altitudes. The new Rayleigh lidar system operates with two lasers, with a combined 42 W of transmitted power; a four-mirror telescope with a combined receiving area of 4.9 m^2; and one photomultiplier tube (PMT) detector. This gives the new instrument a Power-Aperture Product (PAP; figure of merit and sensitivity for Rayleigh lidar systems) of nearly 206 Wm^2. This means the new Rayleigh lidar is about 66 times more sensitive than the previous ALO-USU Rayleigh lidar with a PAP of 3.1 Wm^2. We will show that the large increase in PAP improves data acquisition and extends the measurement range of the lidar upward in altitude. The two Nd:YAG lasers are pulsed at 30 Hz and transmit at a wavelength of 532 nm. The emitted photons have significant Rayleigh scatter off of nitrogen and oxygen molecules (N_2 and O_2) throughout the atmosphere and atomic oxygen (O) beginning at about 90 km.

2.2 Data Acquisition and Analysis

Considerable data were acquired with the upgraded system starting in the summer of 2014. The raw data (photon counts) were acquired during periods typically ranging from 2 to 10 hours. The data were averaged in time over these whole periods and smoothed 3 km in altitude. The analysis used the standard Chanin-Hauchecorne [14] method, slightly modified to use temperatures instead of pressures, which assumes hydrostatic equilibrium and employs the ideal gas law to give,

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

From Equation 1, one finds that the derivation of absolute temperature at a given altitude, $T(h)$, is based on the ratio of densities from one altitude bin to the next, $n(h')/n(h)$. This allows us to use relative densities (which are proportional to the lidar signal times range squared) in place of absolute densities.

For this early work, the mesospheric composition was extended upward unaltered, giving rise to a constant backscatter coefficient and mean molecular mass. The initial value for the temperature integration at the highest altitude for

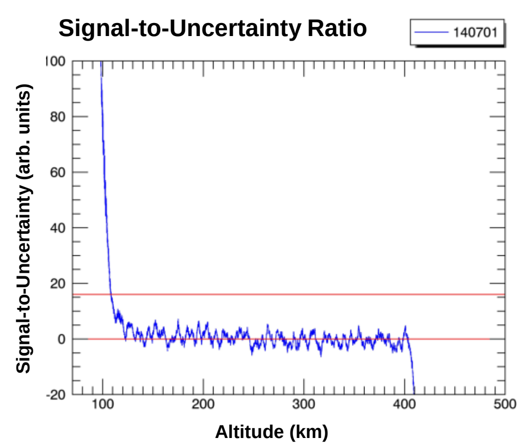

Figure 1. Plot of signal-to-uncertainty ratio versus altitude (on the horizontal axis) for the night of 01 July 2014. This ratio is given in blue and the red curves indicate where the ratio equals 16 and 0.

each night was taken from the Naval Research Laboratory's MSISe-00 model [15]. With this technique, the temperatures are highly accurate 10 to 20 km below the highest altitude because the first term in Equation 1 becomes very small. The highest altitude for each night is taken to be where the ratio of signal-to-uncertainty drops below 16. An example of this is given in Figure 1, which

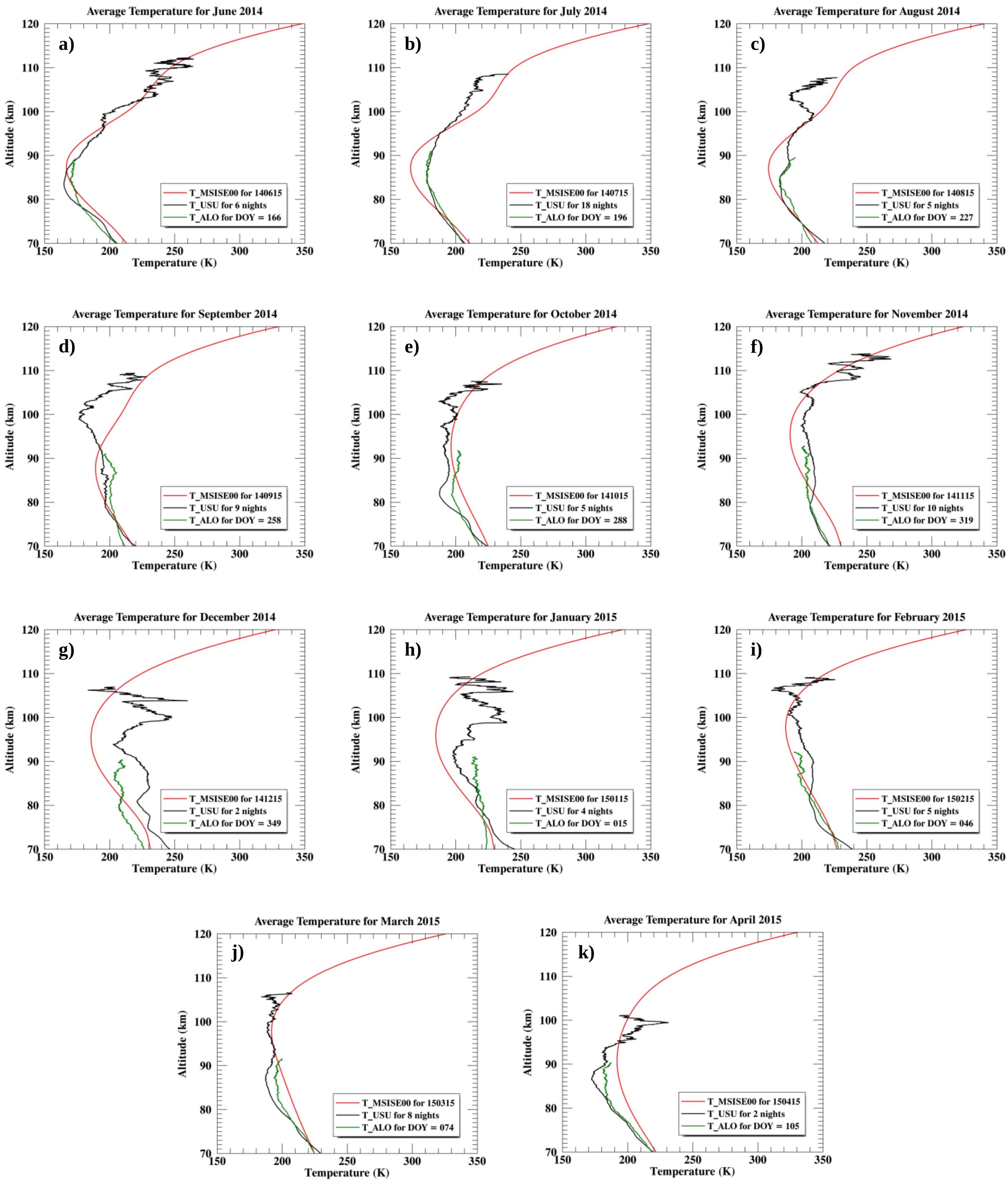

Figure 2. Monthly averages of USU Rayleigh lidar temperatures (black curves) from June 2014 to April 2015 (a-k). Temperature curves from the ALO Climatology (green curves) and the NRLMSISe-00 model (red curves) for the 15th of each month are also given.

displays a blue curve for the ratio of background subtracted signal, averaged over the whole night, to its uncertainty at each altitude bin. The uncertainty from Poisson statistics, at each bin, includes a term for uncertainty in the measured signal and the uncertainty in the background, and is given by,

$$\sigma_{\overline{\langle S\rangle_{IJ}}} = \sqrt{\frac{1}{JI}\overline{\langle (S+N)\rangle_{IJ}} + \frac{1}{JK}\overline{\langle (N)\rangle_{KJ}}} \tag{2}$$

In Equation 2, measured signal, (S+N), and background, N, are both averaged over J number of profiles for the night, and I number of altitudes for measured signal and K number of altitudes for background, respectively. For a given night, the temperature uncertainties derived from Poisson statistics are far less than 1 K at 70 km and ~12 K at the highest altitude.

The data coverage for each month is variable due to weather which obstructs lidar operation (clouds and precipitation). Each of the 11 months presented in Figure 2 (a-k) has data from between 2 and 19 nights.

3. RESULTS

Figure 2 shows eleven temperature plots, one for each month, from June 2014 to April 2015 between 70 and 120 km. The black curves give the monthly averages from the new ALO-USU Rayleigh lidar. At 70 km, it is the average of all the nights in the observed period. At the highest altitudes of these curves, the top 5 km or so, the number of nights in the average decreases rapidly to only 1 or 2. Because of the effects of geophysical variability and the decreasing number of profiles at the highest altitudes, these curves become noisier towards their tops. Also shown in Figure 1 is a green curve between 70 and 90 km that represents the climatological average found with the earlier Rayleigh lidar [6] for the 15th of each month. That value is an average over 31 nights, the center night ±15 nights on either side, over 11 years. The initial temperature value, at the highest altitude, for the data reductions for these curves was taken from the 8-year temperature climatology from the nearby Na lidar at Colorado State University (CSU) [5]. Finally, a red curve is shown between 70 and 120 km. It is calculated from the NRLMSISe-00 model [15] for the 15th of each month at 6:00 UT, midnight Mountain Daylight Time.

In general, the temperature curves obtained with the new Rayleigh lidar agree with both the NRLMSISe-00 and ALO Climatology's curves, though there is some variation month-to-month.

Agreement of the 2014–2015 averages and the 1993–2004 ALO climatological temperatures from 70–90 km is remarkably close in summer, especially considering that the new averages are from only a few days in one year, while the climatology is from many days over 11 years. In fall, winter and spring the differences approach 10 K. The largest differences between the 1993–2004 and the 2014–2015 temperatures exist in December and are about 20 K throughout the whole 70–90 km region. This could be due to there being only 2 nights in the 2014 average, which are both from later in the month (24 and 31 December 2014), whereas the 1993–2004 temperatures were selected for the middle of the month. Excluding the month of December, all of the differences between the 1993–2004 and 2014–2015 temperatures are within the geophysical variability found for the climatology. This means these new results support the original ALO climatology that, with the same caveats, means they also support reasonable agreement of Rayleigh and Na temperatures at 90 km during these months. At that altitude, the new temperatures are good because the downward integration started ~20 km higher. The initial values near 90 km for the ALO climatology, in contrast, are based on the CSU Na climatology.

There is less agreement between the 2014–2015 USU Rayleigh lidar temperatures and the NRLMSISe-00 model temperatures. June is the only month where the Rayleigh lidar temperatures and the NRLMSISe-00 temperatures are in good agreement throughout the whole overlapping altitude region. Between about 70–80 km, for all months, the two sets of temperatures are within 10 K of each other. Above 80 km, things become very different. In July, August and September, the Rayleigh lidar temperatures are warmer than the model temperatures from 80–90 km and colder above 90 km. It should also be noted that the agreement between the two sets of temperatures at the highest observed altitudes is somewhat artificial in that the initial temperature (at the maximum altitude) for each night was taken from the NRLMSISe-00 model. In November, December and January, Rayleigh temperatures are warmer than the model temperatures from about 80–105 km. In January, the upper altitudes (80–90 km) of the ALO Climatology temperatures are also higher than the NRLMSISe-00 temperatures. There appears to be a transition between February and March temperatures as the Rayleigh temperatures go from being slightly warmer than the model temperatures in February to slightly colder than the model temperatures in March. Due to poor weather conditions, there have been only two nights of observations in April (at the time of this paper's submission). However, the Rayleigh lidar data in April does seem to be carrying on the trend from March of being colder than the model temperatures.

4. CONCLUSIONS

From this study several conclusions can be made based on the first year's worth of temperature measurements made with the upgraded Rayleigh scatter lidar at ALO-USU:

- Increasing the PAP of the Rayleigh lidar improved the data acquisition capabilities, enabling observations to be extended upward in altitude by about 25 km, into the lower thermosphere.
- For nearly every month, the 1993–2004 and 2014–2015 USU Rayleigh lidar temperatures are within 10 K of one another in their overlapping region of 70–90 km. This agreement between with the new temperatures tentatively validates the old Rayleigh lidar temperatures and therefore tentatively corroborates the CSU sodium lidar climatology, which provided the initial temperatures for the integration for the Rayleigh temperatures. (This agreement is "tentative" because the data in this initial comparison are from only one year and the number of nights is limited.)
- There is less agreement between the Rayleigh lidar temperatures and the NRLMSISe00 model temperatures. The differences between measured and model temperatures appear to have a seasonal variation: observed temperatures are about the same as model temperatures in the summer, colder in the fall, warmer in the winter and colder again in the spring.

In the future, upgrades to this new ALO-USU Rayleigh lidar will further raise the top altitude and regular observations will continue. The bottom altitude will be lowered with continuing system improvements, including more detector channels. Extensive comparisons will also be carried out with observations from the other instruments in the USU mesospheric cluster and any available data from stratospheric probes, such as radiosondes.

While this lidar opens the mesosphere and lower thermosphere to ground-based observations at one midlatitude location, it suggests the future importance of developing more affordable and simpler Rayleigh systems with comparable sensitivity that can be operated as part of a global network at many locations around the world.

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REFERENCES

[1] Allen, S. J. and R. A. Vincent, 1995: Gravity Wave Activity in the lower atmosphere: Seasonal and latitudinal variations, *J. Geophys. Res.*, **100(D1)**, 1327-1350.

[2] Nakamura, T., T. Tsuda, M. Tsutsumi, K. Kita, T. Uehara, S. Kato, and S. Fukao, 1991: Meteor wind observations with the MU radar, *Radio Sci.*, **26(4)**, 857–869.

[3] Manson, A. H. and C. E. Meek, 1985: Middle atmosphere (60-110 km) tidal oscillations at Saskatoon, Canada (52°N, 107°W) during 1983-1984, *Radio Sci.*, **20(6)**, 1441-1451.

[4] Baker, D. J. and A. T. Stair Jr, 1988: Rocket measurements of the altitude distributions of the hydroxyl airglow, *Phys. Scr.*, **37(4)**, 611-622, doi:10.1088/0031-8949/37/4/021.

[5] She, C. Y., et al., 2000: 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.

[6] Herron, J.P., 2007: *Rayleigh-Scatter Lidar Observations at USU's Atmospheric Lidar Observatory (Logan, UT) — Temperature Climatology, Temperature Comparisons with MSIS, and Noctilucent Clouds*, PhD Dissertation, 156 pp, Utah State University, Logan, UT.

[7] Kafle, D. N., 2009: *Rayleigh lidar observations of mesospheric gravity wave activity above Logan, Utah*, PhD Dissertation, 209 pp, Utah State University, Logan, UT.

[8] Wynn, T. A., 2010: *Statistical analysis of the USU lidar data set with reference to mesospheric solar response and cooling rate calculation, with analysis of statistical issues affecting the regression coefficients*, PhD Dissertation, 232 pp, Utah State University, Logan, UT.

[9] Sox, L, V. B. Wickwar, C. Fish, J. P. Herron, 2015: Temperature deviations in the midlatitude mesosphere during stratospheric warmings as measured with Rayleigh-scatter lidar, *Proceedings of the 27th International Laser Radar Conference*. (Submitted), New York City, New York

[10] Barton, D. L., V. B. Wickwar, J. P. Herron, L. Sox, L. A. Navarro, 2015: Variations in Mesospheric neutral densities from Rayleigh lidar observations at Utah State University, *Proceedings of the 27th International Laser Radar Conference*, (Submitted), New York City, New York.

[11] Wickwar, V. B., M. J. Taylor, J. P. Herron, B.A. Martineau, 2002: Visual and lidar observations of noctilucent clouds above Logan, Utah, at 41.7°N, *J. Geophys. Res.*, **107(D7)**, 4054–4059, 10.1029/2001JD001180.

[12] Herron, J. P., V. B. Wickwar, P. J. Espy, and J. W. Meriwether, 2007: Observation of a noctilucent cloud above Logan, Utah (41.7ºN, 111.8ºW) in 1995, *J. Geophys. Res.*, ***112*** **(D19203)**, doi:10.1029/2006JD007158.

[13] Mertens, C. J., et

al., 2004: SABER observations of mesospheric temperatures and comparisons with falling sphere measurements taken during the 2002 summer MaCWAVE campaign, *Geophys. Res. Lett.*, **31 (L03105),** doi:10.1029/2003GL018605.

[14] Hauchecorne, A., and M. L. Chanin, 1980: Density and temperature profiles obtained by lidar between 35 and 70 km, *Geophys. Res. Lett.* **7**, 565–568.

[15] Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin, 2002: NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, **107(A12)**, 1468–1483, doi:10.1029/2002JA009430.