Simultaneous, Collocated Rayleigh and Sodium Lidar Temperature Comparison

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Abstract

There are relatively few instruments that have the capabilities to make near continuous measurements of the mesosphere-lower-thermosphere (MLT) region. Rayleigh-scatter (RS) and resonance lidars, particularly sodium (Na) resonance lidar, have been the two dominant ground-based techniques for acquiring vertical temperature profiles from the mesosphere and MLT, respectively, for more than two decades. With these measurements, the dynamics and long-term temperature trends of the MLT region can be studied. For the first time, we will present simultaneous, night-time averaged temperatures acquired from the same observational site, on the campus of Utah State University (USU), using these two lidar techniques. This comparison is also unique in that this will be the first time that the Rayleigh and Na lidar profiles will cover the same altitude range (80-110 km). This altitude overlap has been achieved through upgrades to the existing USU Rayleigh lidar, which elevated its observational range from 45-90 km to 70-115 km, making it one of two Rayleigh lidars in the world that can extend into the thermosphere, and by the relocation of the Colorado State University (CSU) Na lidar to the USU campus. The comparison of the two sets of temperature measurements is important because the two lidar techniques derive temperature profiles using different observational techniques and analysis methods, each of which are based on different sets of physical assumptions and theories. Furthermore, previous climatological comparisons between Rayleigh and Na lidar, in the 80-90 km range, have suggested that significant temperature differences can occur. This comparison aims to extend the climatological studies by exploring the agreement and disagreement between the lidar techniques' temperatures with respect to altitude and season.

1. Motivation

Lidar systems remain the most advantageous method for acquiring temperature measurements in terms of vertical and temporal resolution. Two of the most widely used lidar techniques for the study the MLT are RS lidar and Na resonance lidar. However, the two techniques have yet to be compared with one another using simultaneous, collocated measurements that cover the same altitude range. Using the Na lidar and newly upgraded high-power, large-aperture RS lidar located at the same USU observatory, this work aims to make this temperature comparison for the first time.

2. Lidar system descriptions and 2014-2015 observations

Table 1. RS and Na lidar system parameters.

System Parameter	Rayleigh Lidar	Na Lidar
Emitted laser wavelength (nm)	532	589 ± Δλ
Laser energy (mJ/pulse)	1400	20-30 (per transmitted υ)
Total transmitted laser power (W)	42	~1 (per transmitted υ)
Laser rep. rate (Hz)	30	50
Transmitted beam divergence (mrad)	0.125	0.8
Receiving aperture (m^2)	4.86 (4 mirrors)	0.45(1 mirror)
Vertical resolution (km)	2	2
Maximal altitude range (km)	70-114	76-114
Estimated error at top (K)	19	10
Estimated error at midrange (~93 km; K)	1.1	0.3
Estimated error at bottom (K)	0.1	10

The Na lidar [*Krueger et al*., 2015] was moved from CSU to the USU campus and began operations there in 2010. The RS lidar was recently upgraded by a factor of 66 in order to extend its observational range from 45-90 km to 70-115 km and the new system began operations in 2014 [*Sox*, 2016].

The two lidars' system parameters are given in Table 1. Between 2014 and 2015, there were 19 nights when the two lidars made simultaneous measurements for at least four hours. Though these observations are sparse, they span one full annual cycle and cover all four seasons. A subset of the temperatures derived from these lidar measurements are given in Fig. 1.

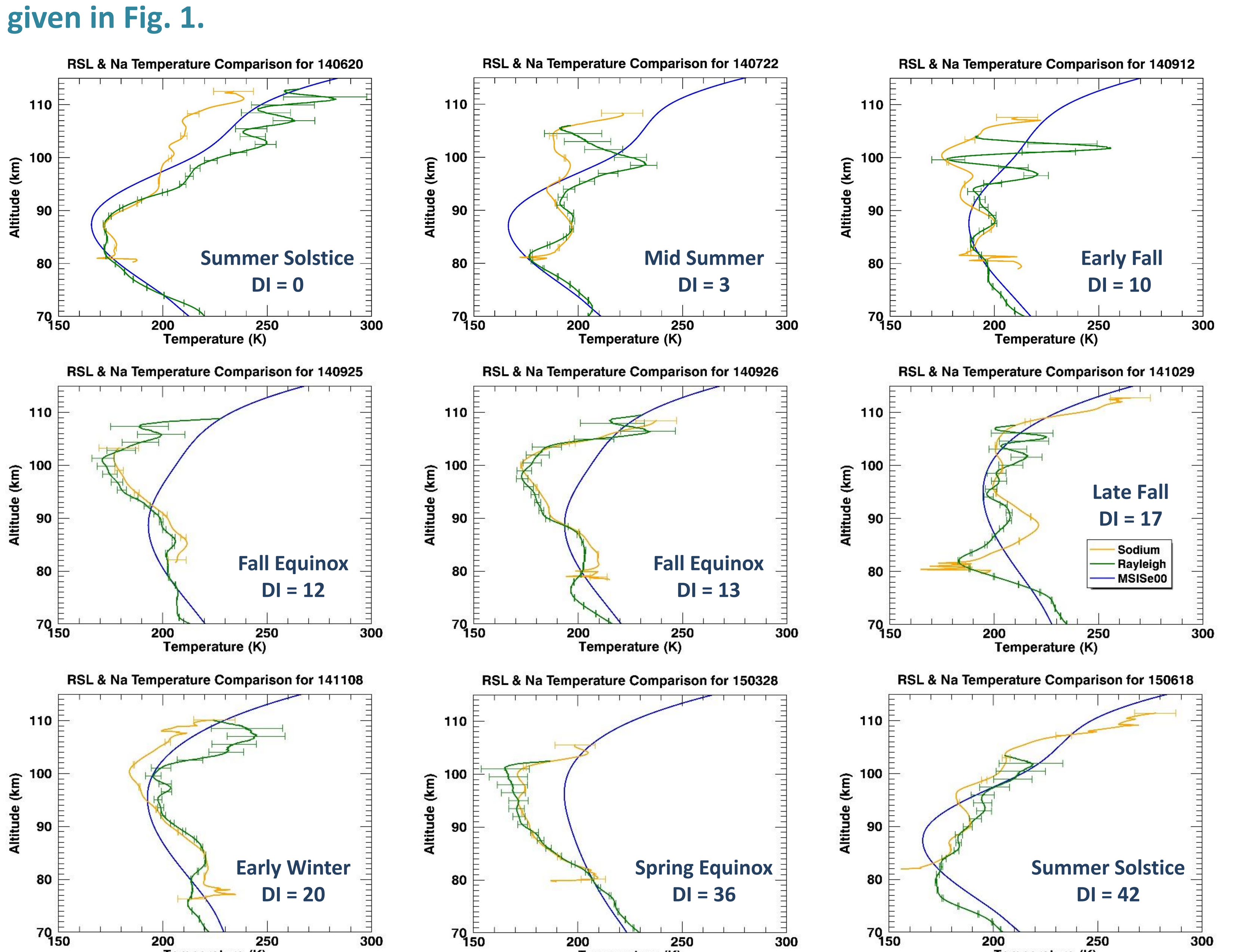

Figure 1. 2014-2015 temperature-altitude plots (9 of the 19 nights) for whole-night averages measured using the RS lidar (green curves) and Na lidar (orange curves). MSISe00 model temperatures (blue curves) for each date (YYMMDD) at 6 UT are also given. See Fig. 2 for explanation of date index (DI).

3. Results

The plots in Fig. 1 illustrate the differences between the two lidars' temperatures with respect to altitude and time of year:

- The best agreement between the two temperature curves occurs from 85 to 95 km
- RS temperatures are colder than Na temperatures below 90 km
- RS temperatures are warmer than Na temperature from 95 km and above
- RS temperatures show stronger vertical wave structure
- The best agreement, at all altitudes, occurs near equinoxes
- The worst agreement between the two temperature curves, at all altitudes, occurs in late fall-early winter, except where waves are present

3.1 Seasonal comparison

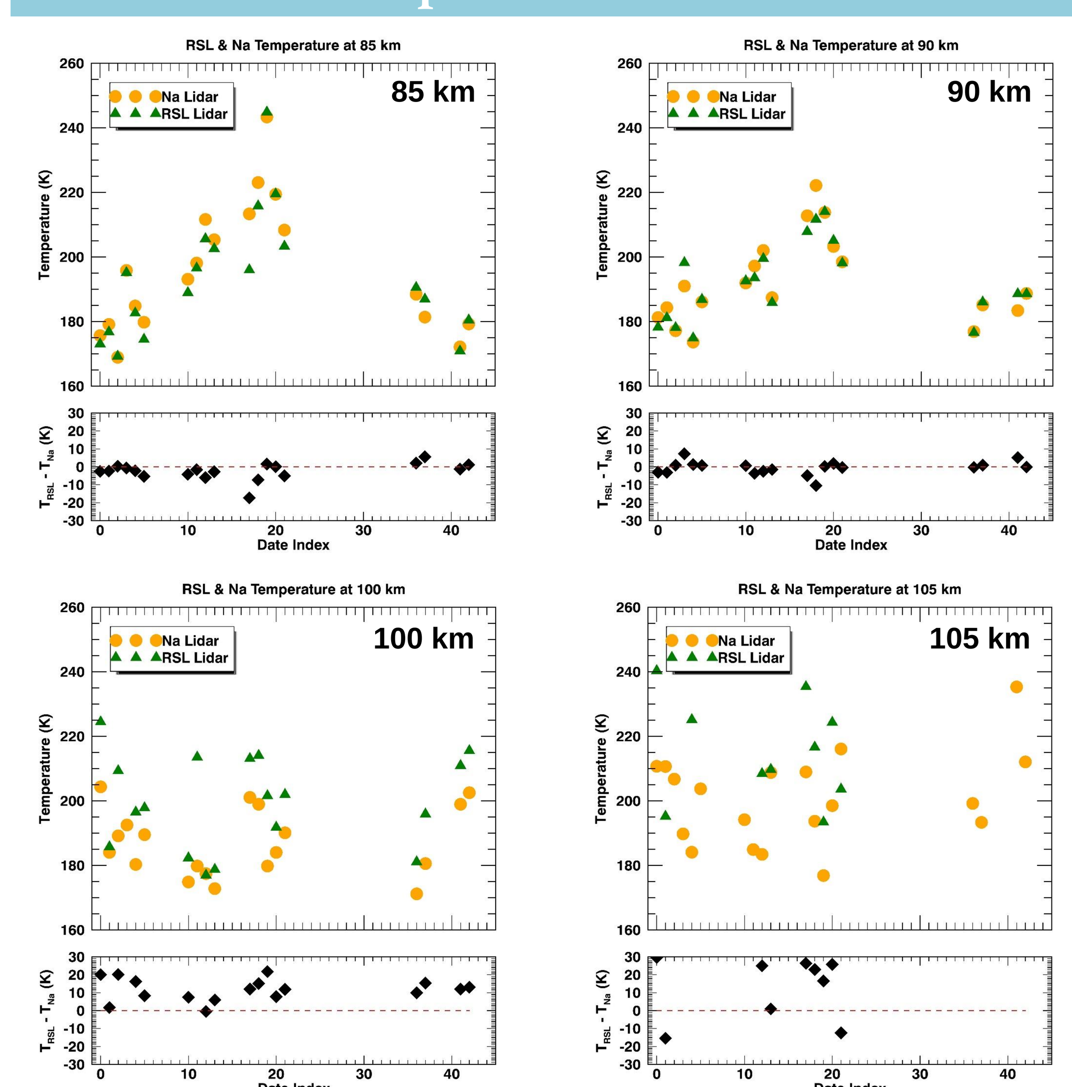

Figure 2. RS (green triangles) and Na (orange circles) lidar temperature time series plots for 85 km, 90 km, 95 km, 100 km and 105 km along with the differences between the two lidars' temperatures (lower panels, black diamonds). In order to show gaps in the data but still keep the plots visually legible, a date indexing (DI) system was applied to the actual calendar dates. For reference: DI 0 is 20 Jun 2014, DI 10 is 12 Sep 2014, DI 20 is 08 Nov 2014, DI 36 is 28 Mar 2015 and DI 42 is 18 Jun 2015.

Fig. 2 gives temperatures from the two lidars with respect to day of year for five altitudes. The differences between the two sets of temperatures are also given for each of the five altitudes. From these plots, we find that:

- At 85 and 90 km, RS temperatures are, on average, 1.5 K colder than Na temperatures
- At 95 km and above RS temperatures are warmer, on average, by about 13 K
- The best agreement between the two lidars' temperatures occurs near the equinoxes, the worst agreement between the two sets of temperatures occurs during the early winter

These results are corroborated by those seen in Fig. 1 and the other 10 profiles. In general, we observe that the RS lidar's temperatures are slightly colder than the Na temperatures below about 95 km and are much warmer above about 95 km. On a seasonal basis, the best agreement occurs during the equinoxes.

References

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3.2 Investigation of the two lidar techniques

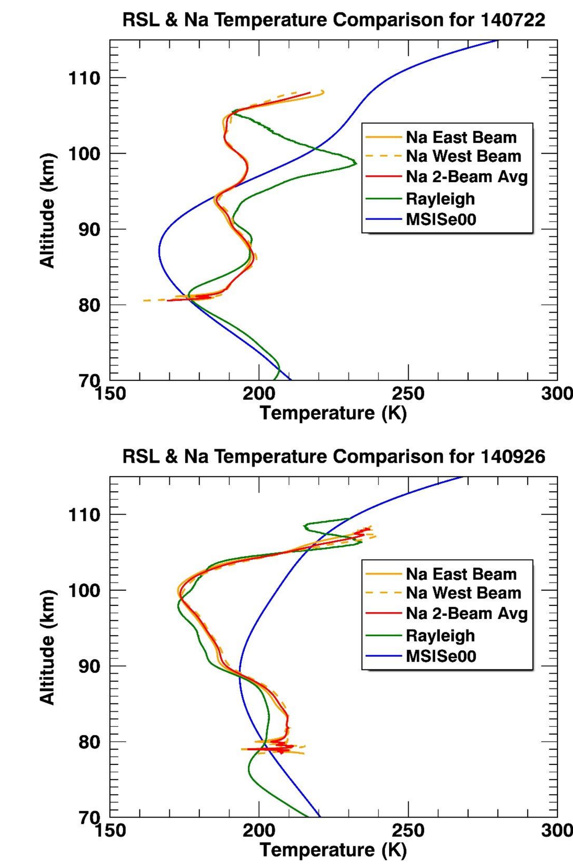

Figure 3. Temperature profile plots similar to those in Figs. 1 with Na lidar west-pointing beam temperatures (dashed orange curve) and the average of the east- and west-pointing beam temperatures (red curve) added.

The RS lidar transmits in the vertical whereas the Na lidar typically operates with a three-beam pointing configuration (20° east, west and north). The Na temperatures shown in Figs. 1 and 2 were calculated using east-pointing beam data. At higher altitudes (~110 km), this would separate the two lidar beams by about 40 km in the east-west direction. West-pointing data also available for 11 of the 19 nights, two examples are given in Fig. 3. They suggest that the pointing configuration of the Na lidar was not the cause of the discrepancy between the two temperature profiles at higher altitudes.

The RS lidar temperature retrieval [*Chanin and Hauchecorne*, 1980] has not previously taken changing atmospheric composition, due to diffusive equilibrium and dissociation of [*O*], into account. In *Sox* [2016], a method was developed to correct the RS retrieval for changing composition. Fig. 4 gives an example of these corrections, which are very small. This suggests that the effects of composition are not responsible for the high altitude RS and Na temperature differences.

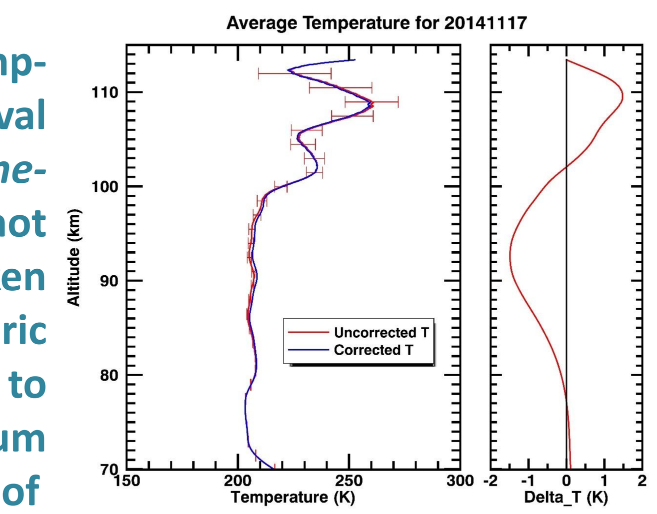

Figure 4. RS lidar temperatures, which were calculated by correcting (blue curve, left panel) and not correcting (red curve) the temperature retrieval for changing atmospheric composition. The difference between the corrected and uncorrected curves is given in right panel and shows less than 2 K magnitude change.

4. Discussion

Here, we have shown that RS lidar temperatures are colder than simultaneous and collocated Na lidar temperatures between 85 and 90 km. RS and Na observations were previously compared by *Argall and Sica* [2007] and *Leblanc et al.* [1998] using climatological data from different sites, which were at roughly the same latitude, but several hundred kilometers apart in longitude. They also covered a smaller overlapping altitude range, reaching at most 95 km (see Fig. 5).

They found that the RS temperatures were 7 K (from 80-95 km in *Argall and Sica* [2007]) and 2-6 K (from 80-88 km in *Leblanc et al*. [1998]) cooler. While our data show the Rayleigh temperatures being colder at these altitudes, our difference is not as large—having an average of only about 1.5 K.

At 95 km and above, our data shows that the RS temperatures are on average increasingly warmer as one goes up in altitude, reaching an average maximum temperature difference of about 13 K at 105 km (Fig. 2). This result, which was made possible with new high-power, large-aperture USU RS lidar, cannot be compared with the previous studies. Their overlapping measurements did not extend this high. The comparison between the three studies is summarized in Fig. 5.

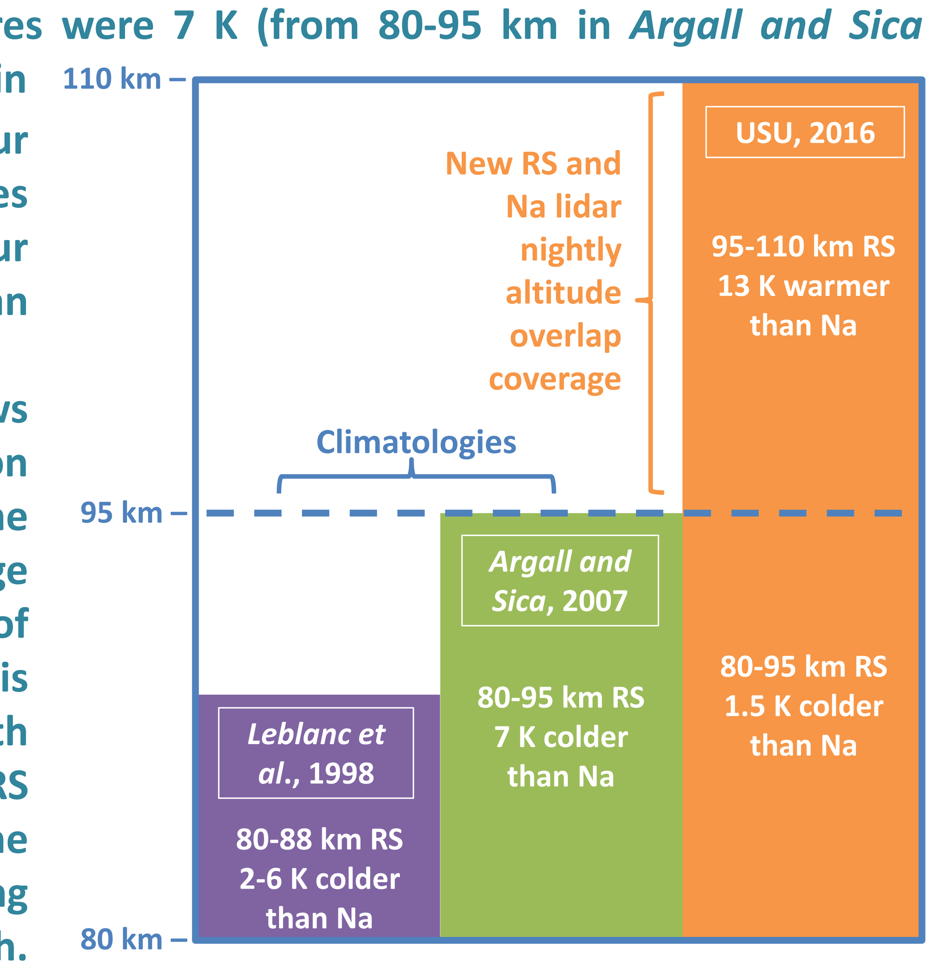

Figure 5. Infographic illustrating the comparison between the present USU, *Argall and Sica* [2007] and *Leblanc et al.* [1998] studies, which compared RS and Na lidar temperatures.

5. Conclusions and Future Work

For the first time, we present a comparison between simultaneous, collocated RS and Na lidar temperatures. In general, we found that the best agreement occurs between 85 to 95 km, the worst agreement above 95 km.

These results can be refined with continued simultaneous RS and Na lidar observations. The differences in temperature and detected wave activity need to be further investigated in order to discover if they suggest changes to our current understanding of atmospheric structure, composition and/or chemistry, particularly above 95 km.

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