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Rayleigh-Lidar Observations of Mesospheric Mid-latitude Density Climatology above Utah State University

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Abstract. Data from Rayleigh lidars have been used extensively to derive temperatures in the mesospheric region of the atmosphere. However, these data have not been used extensively in a similar way to derive neutral densities. We report on one such mid-latitude, density climatology between 45 and ~90 km, based on nearly 600 good nights of observations carried out since 1993 at the Atmospheric Lidar Observatory (ALO) at Utah State University (41.7°N 111.8°W). They produce relative density profiles that are then normalized at 45 km to an empirical model, in this case the MSISe00 model. Despite this normalization, significant differences are found between the observations and the model starting as low as 50 km. For instance, the lower mesosphere is denser than the model in summer and less dense in winter. In contrast, the upper mesosphere is denser near the equinoxes and less dense at other times. Differences between the climatology and the model reach ±11%. The normalized observations show a large seasonal variation, with the summer densities in the 65-75 km region being approximately 55% greater than the winter densities. At both lower and higher altitudes, the seasonal variation is less.

INTRODUCTION

The absolute neutral densities in the middle atmosphere, especially between the stratopause and the lower thermosphere, are important for a number of reasons. These include

- the reference for minor constituents whose concentrations are given as so many parts per million or per billion
- the concentrations available for chemical reactions giving rise to heating or airglow emissions
- the mass that causes meteorites to disintegrate
- the mass that rockets, the Shuttles, or future hypersonic airliners will pass through
- the mass used for aero breaking of orbital transfer vehicles

Yet the neutral densities are not well known. Below 30 km and above ~170 km, measurements are regularly made by balloons, satellite-borne accelerometers, measuring satellite drag, or are derived from incoherent scatter radar. Between 30 and ~170 km, however, measurements are more difficult to make. Some have been obtained from rockets, low altitude satellites, the Shuttles, satellite observations of Rayleigh limb extinction, and the decay of meteor trails. However these represent very few measurements. Most of the observational information has been brought together into empirical models like NRL-MSISe00[1].

Considerably more high quality density information is available, though. By normalizing the relative densities derived from Rayleigh lidar observations to a lower altitude absolute density, an extensive new data resource becomes available in this altitude region. Since 1993 a large database of nearly 600 good nights of Rayleigh-scatter data from the mesosphere between 45 and ~95 km been acquired at the Atmospheric Lidar Observatory[2] (ALO) (www.usu.edu/alo). These are the same data used in the ALO temperature climatology[3]. They are from zenith observations. They have been carefully scrutinized to identify and retain only the good data, about 65% of the total.

REDUCTION & ANALYSIS

The observations were carried out with a frequency-doubled Nd:YAG laser (532 nm). The signal was sampled every 37.5 m (250 ns) and integrated for 2-minutes (3600 laser pulses). Each of the observations was carefully examined for data quality with emphasis on high-altitude background. The background was subtracted, the signal was multiplied by range squared, the altitude scale was adjusted for the 1.47-km ALO altitude, and the profile was normalized to unity at 45 km using a 3-km least-squares fit.

Depending on the problem being addressed, individual profiles can be averaged together to obtain integrations over various time scales. Examples used here include an all-night average, *D*1; a (multi-year) climatological, all-night average, <*D*1>; a climatological 41-night, average, <*D*41>; and a climatological, 12-month average, <*D*yr>. For this work, all profiles were normalized to the MSISe00 model at 45 km. The comparison model integrations include a climatological 41-night average, *DM*41, and a 12-month average, *DM*yr. The 41-night average takes the form of a truncated triangle with a 41-night base and a 15-night top. No end-point problems occur because the data are treated as being annually periodic. In addition, because densities change by almost four orders of magnitude between 45 and ~95 km, the relative differences to the model 12-month averages *DM*yr are shown instead of the actual densities.

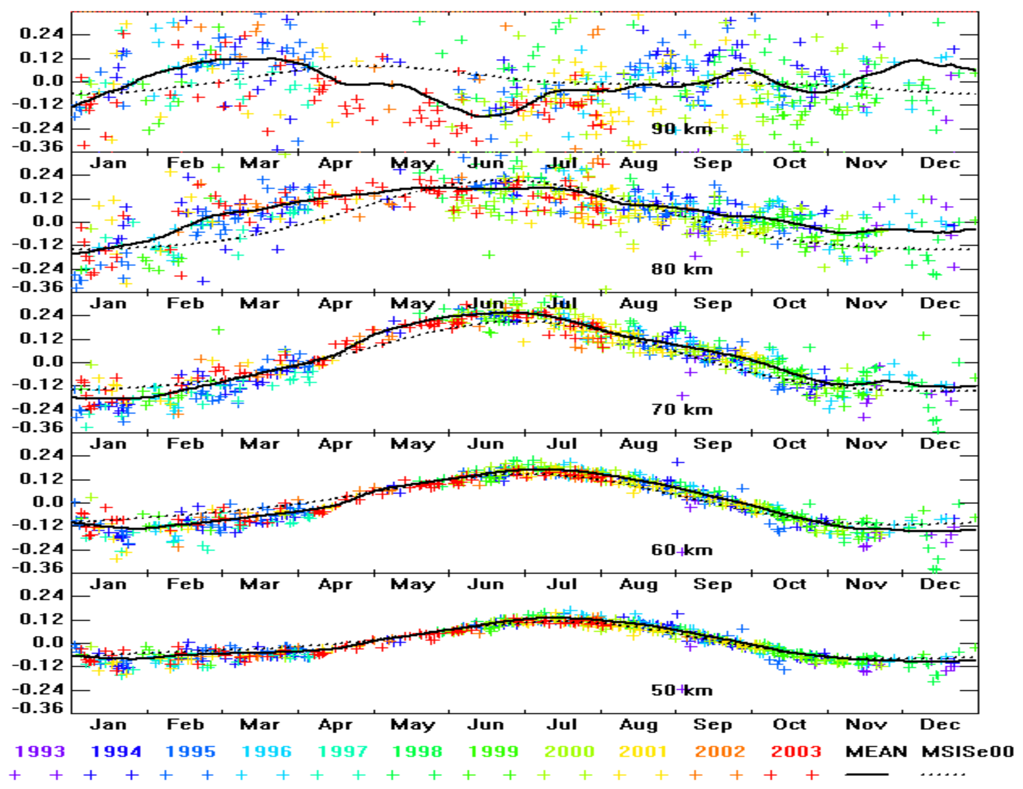

Figure 1. Density variations at 10-km intervals between 50 and 90 km. The crosses show the basic data, the all-night density averages relative to the MSISe00 annual density, [*D*1−*DM*yr]/*DM*yr. They are color-coded to show the year in which they were observed. The heavy solid lines show the climatological 41-night average relative to the annual model average, [<*D*41>−*DM*yr]/*DM*yr. The dashed line shows the 41-night model average relative to the annual model average, [*DM*41−*DM*yr]/*DM*yr.

RESULTS

The time variations in the density are shown in **Figure 1** at five altitudes. The crosses show basic nightly data colored to each year and are relative to the MSISe00 annual density, [*D*1−*DM*yr]/*DM*yr. The solid line is the 41-night data average, [*D*41−*DM*yr]/*DM*yr. The dashed line is the 41-night MSISe00 average, [*DM*41−*DM*yr]/*DM*yr. Differences between the observations and the model begin to appear at even 50 km and, where they exist, increase with increasing altitude. Some interesting points to note include

- Daily variability is greater in winter and spring then in the summer.
- From 50 km to 70 km, the spring/winter values are smaller than MSISe00.
- Above 70 km, the spring/winter values are greater than MSISe00.
- There is a 24% density depletion at 90 km during the summer.

Figure 2 shows how the observed densities vary during the year relative to the model average annual density, [<*D*41>–*DM*yr]/*DM*yr. Noise above ~93 km makes judging densities problematic in that region. The most noticeable structure is the annual variation. In particular

- Near 70 km, the densities vary from 19% below *DM*yr in January. to 24% above it in June. This is a large 55% density increase in summer relative to winter.
- Near 92 km, the maximum density is near the equinoxes with values ~16%.
- Densities at 92 km drop to 25% below *DM*yr in June.
- A tongue of enhanced densities of ~3% forms in November and December between 70 – 80 km.
- Spring depletions are 5% greater than fall depletions in the lower mesosphere.

Figure 3 shows, for comparison, the variability of MSISe00 compared to its average, [*DM*41–*DM*yr]/*DM*yr. The patterns are similar to Figure 2, but the observed density depletions and enhancements are smaller in magnitude than the data.

- The area of maximum density near 70 km in the model is higher in altitude and more later than in the data.
- The depletion beginning at ~90 km in the data starts in the model later in the year and 7 km higher.
- The winter tongue of enhanced densities is not found in the model.
- The densities at 50 km increase more slowly in spring within the model.

Figure 4 shows how the density climatology compares directly to the MSISe00 model densities, [<*D*41>−*DM*41]/*DM*41. Many features are apparent with just a casual look. One feature is the "Y"-shaped structure centered on the summer solstice in the lower mesosphere. The two "arms" show densities greater than the model, with maxima at about 85 km.

- The maximum is 16% in early March and 17% in November.
- Between these "arms" at ~90 km is the depletion discussed in depth earlier in Figures 1 and 2.
- The depletion is ~7 km lower than the model predicts and is 24% deeper than *DM*41 at ~90km.
- Below the "arms" in spring and fall, the densities are 8% and 5% below *DM*41, respectively.
- <*D*41> varies annually ~11% from January through July in the lower mesosphere.
- The upper mesosphere around 90 km varies 55% from spring to summer.
- In general, there are deeper depletions than MSISe00 in spring and winter in the lower mesosphere, particularly in spring.

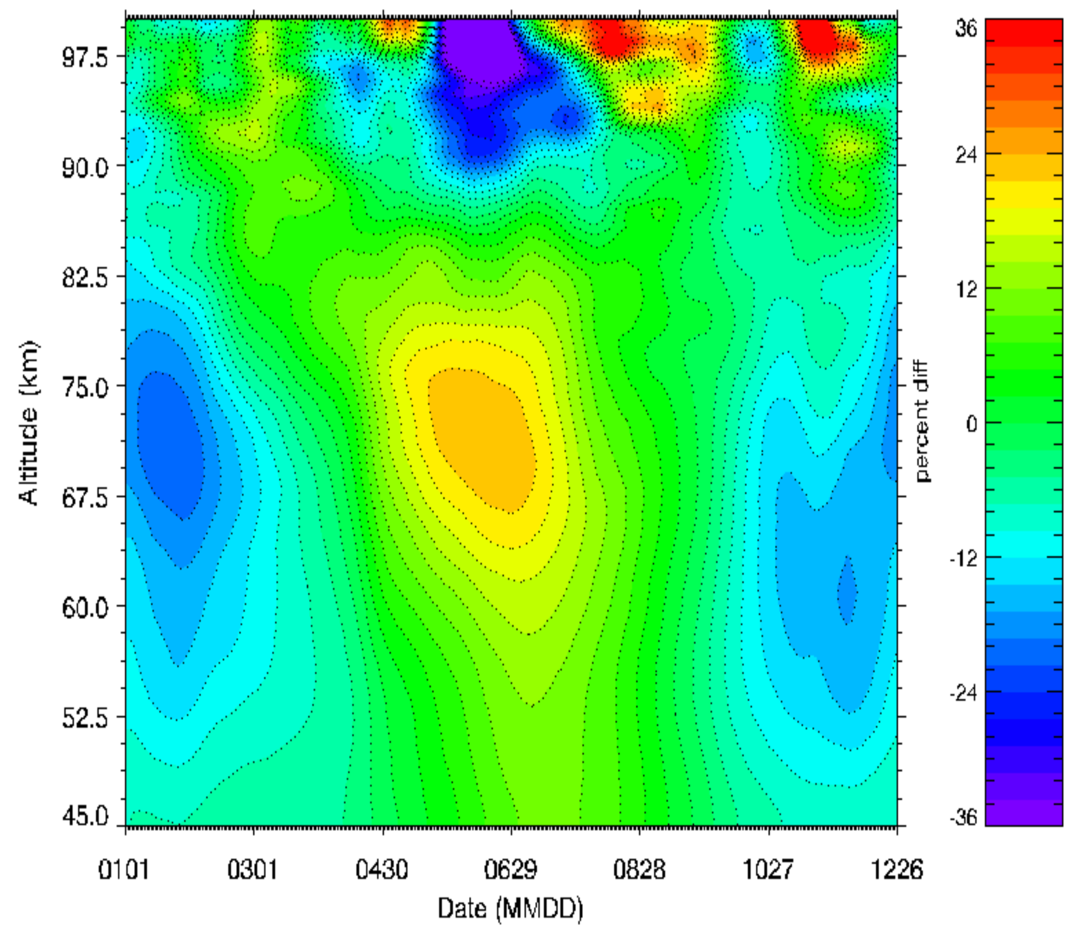

Figure 2. Relative differences between the 41-night climatological density average and the model annual density average, [<*D*41>–*DM*yr]/*DM*yr.

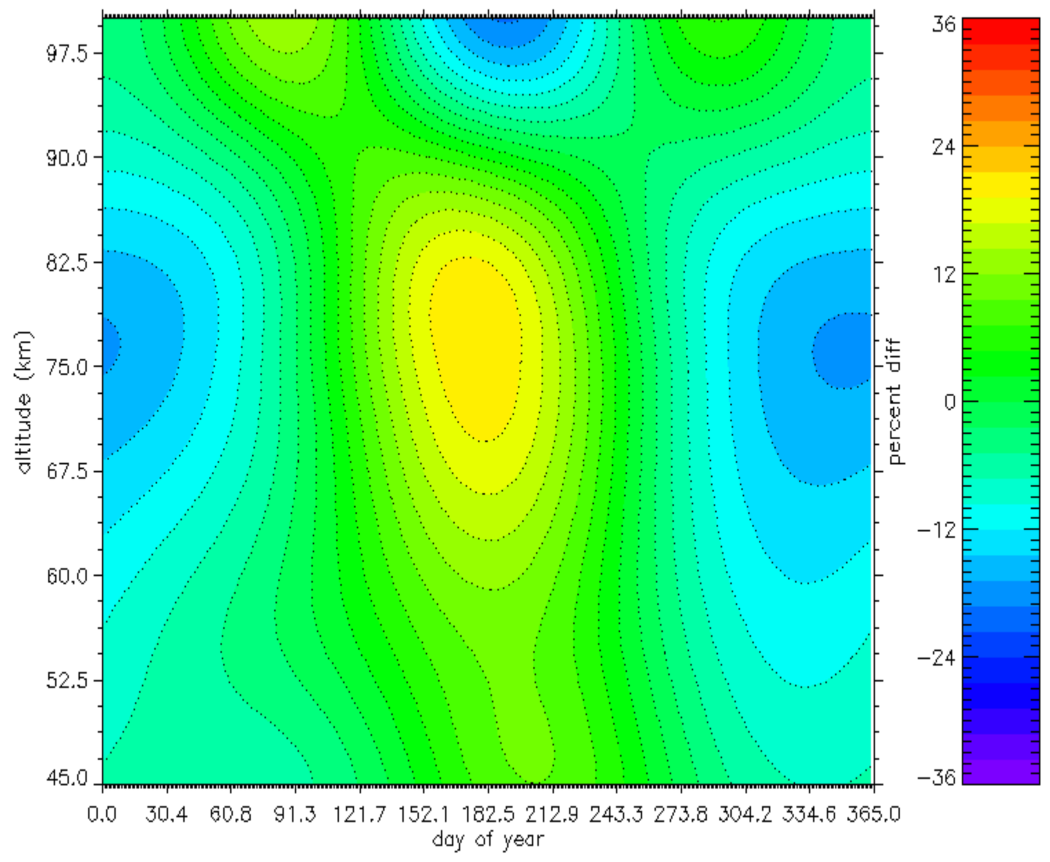

Figure 3. Relative differences between the 41-night model density average and the model annual density average, [*DM*41-*DM*yr]/*DM*yr. For ease of comparison, this is the same format as Figure 2.

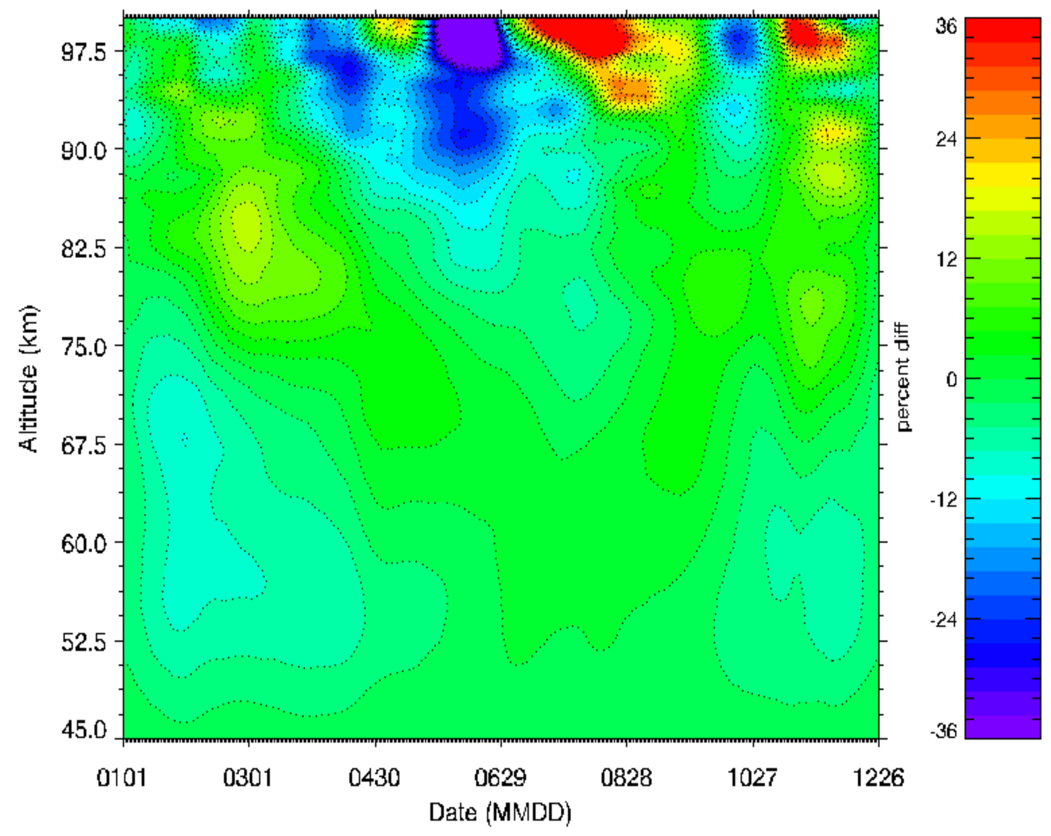

Figure 4. Relative differences between the climatological 41-night density average and the model 41-night density average, [<*D*41> −*DM*41]/*DM*41.

CONCLUSIONS

A mesospheric density climatology has been derived from 10 years of ALO Rayleigh-scatter lidar data. Here, it is normalized to MSISe00 absolute densities at 45 km. In general the following points can be made:

- The averaged 41-night density climatology shows differences from MSISe00 of up to 55% in the upper mesosphere.
- The summer densities in the upper mesosphere of the 41-night climatology are 53% larger than the winter densities.
- In particular, there is considerable annual variability in the 41-night climatology: 19% depletions in winter and 24% enhancements in summer within the middle region compared to the annual MSISe00 value.
- There is a 25% depletion in the climatology at ~90 km during the summer months. The depletion is 7 km lower than MSISe00.
- Also of note is the sudden density enhancement between 70 and 80 km in late fall.

While the MSISe00 model is a good approximation to the real geophysical structure of the mesosphere, this comparison shows that at least at mid latitudes there are significant differences with observations. In particular, the density structures (depletion and enhancements) occur at a significantly lower altitude than in the model. Most occur earlier, but the winter depletion starts later. A fall/winter enhancement occurs between 70 and 80 km that is not in the model. In the future, the densities could be examined further by normalizing the ALO relative densities to other purported sources of absolute density.

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