Atmospheric Composition and the Retrieval of Rayleigh Lidar Temperatures in the Lower Thermosphere

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Abstract

Rayleigh-scatter lidar (RSL) measurements have provided relative density and absolute temperature measurements of the middle and upper atmosphere (35-90 km) for over three decades. The data acquired with these instruments have been used to study the thermal structure, dynamics and long-term trends on atmospheric regions. Recently, the Rayleigh lidar on the campus of Utah State (42°N, 112°W) has been upgraded to include more transmitted power (42 W) and a larger receiving aperture (4.9 m²), which has enabled observations to be regularly made from 70 to above 110 km. Inherent in the current Rayleigh lidar temperature retrieval method is the assumption that the neutral atmosphere is a thermally mixed combination of nitrogen (N₂) molecular oxygen (O₂) and atomic oxygen [O]. This is a good approximation up to 95 or 100 km. This assumption allows one to take the Rayleigh-backscatter cross-section (RBCS) and mean molar mass (MMM) to be constant over the altitude range of the Rayleigh lidar measurements, which previously did not extend much above 90 km. However, above 100 km, photodissociation breaks molecular oxygen to produce atomic oxygen (O) along with the mixture of N₂, O₂, and Ar. Due to this change in atmospheric composition, the temperature retrieval method used for new Rayleigh lidar measurements above 100 km has to be examined. In this work, we will make corrections to the Rayleigh lidar data reduction procedure in order to account for changing RBCS and MMM with altitude. The corrections will be developed using the NRL-MSISE00 (MSIS) empirical model and will then be applied to examples of the USU Rayleigh lidar data obtained in 2014-2015. The applied corrections give differences in temperature of less than 2 K.

1. Motivation

Modern RSL systems can obtain good signal up into the lower thermosphere (~115 km). In order to calculate temperatures from this high-altitude signal, the current RSL temperature retrieval must be amended to account for the changing atmospheric composition in the upper mesosphere and lower thermosphere.

2. Atmospheric Composition

The Earth’s atmosphere is dominated by a mixture of molecular oxygen, molecular nitrogen and atomic argon from about 30 km to 100 km. Above 80 km, oxygen molecules undergo photochemical dissociation by ultraviolet radiation to form two atomic oxygen particles [1].

Atomic oxygen has a lifetime, above 90 km, of much longer than one day [2]. For Rayleigh lidars that can obtain good signal above ~90 km, atomic oxygen needs to be taken into account.

3. Rayleigh-backscatter Cross-sections

The lidar signal equation can be given by:

\[ S(h) = \sum n_i(h) \sigma_{iR} h^2 \]  

where the sum is being taken over species \( i \). Below ~80 km, N₂, O₂, and Ar contribute to the sum. Above that, O starts to contribute. The cross sections for 532 nm are given in Table 1 [3].

4. Current RSL Temperature Calculation

The Rayleigh-scatter lidar temperature retrieval assumes that the observed atmospheric region is:

- A thermally mixed combination of \( N_2, O_2, \) and \( Ar \) (MMM and RBCS are constant)
- An ideal gas
- In hydrostatic equilibrium

By assuming hydrostatic equilibrium, integrating from a given altitude \( A \) to a top altitude \( h_{max} \), and then substituting into the ideal gas law, we get the Rayleigh lidar temperature retrieval equation [4]:

\[ T(h) = T(h_{max}) \frac{n_0(h_{max})}{n_0(h)} + \frac{s h^2}{n_0(h) h^2} \frac{m(h)}{m(h_{max})} \frac{n_0(h_{max})}{n_0(h)} M(h) h^4 \]  

Rayleigh lidar signal, \( S(h) \), multiplied by range squared is proportional to number density, which allows one to substitute relative density measurements into the equation above and retrieve absolute temperature. \( T(h_{max}) \), in the first term, is the seed temperature at the highest altitude, \( h_{max} \). It comes from a model, a climatology, another instrument, or a detailed calculation. It has little effect 10-20 km below \( h_{max} \).

5. Corrections to the RSL Temperature Retrieval

Two corrections to the current temperature retrieval will be applied to extend RSL temperatures from 90-100 km to 115-120 km:

1. Signal correction, which will account for a fall off in the Rayleigh signal relative to the total number density, \( n_{tot}(h) \), because the mean RBCS falls off with altitude due to the increasing proportion of atomic oxygen.

2. MMM correction, which will account for the decrease in MMM with altitude due to the increasing proportion of atomic oxygen.

5.1 Signal Correction

\[ n_{sig}(h) = \frac{n_{sig}(h_{max})}{n_{tot}(h_{max})} \frac{n_{tot}(h)}{n_{tot}(h_{max})} \]  

This correction takes the number density obtained from measured lidar signal, \( n_{sig}(h) \) using the MSIS [5] model, and multiplies each given number density by its corresponding RBCS given in Table 1.

5.2 MMM Correction

The equation for the MMM of a mixture of \( N_2, O_2, \) and \( O \) with respect to Altitude is given by:

\[ M(h) = \frac{n_0(h)}{n_0(h_{max})} \left( \frac{N_2 + O_2 + O}{N_2 + O_2 + Ar} \right) \]  

MSIS was used to verify the use of Eq. 6 in place of constant MMM in Eq. 3. In Figure 3, the blue line is the MSIS temperature, the red line is the RSL calculated temperature with constant MMM, and the dotted gold line is the RSL calculated temperature with the MMM determined from the simulation. The agreement of the blue and dotted gold curves is to be expected where diffuse equilibrium still dominates.

References


6. In the above, the effects of the RBCS and MMM corrections were shown separately. Here, they are combined on observed data. The composition profiles are still based on the initial temperatures come from the MSIS model. Both the signal and MMM corrections (using Eqs. 5 & 6) were applied in the temperature reduction of 2014-2015 data from the large-aperture, high-power Rayleigh lidar on the USU campus. Figures 4(a)-(d) compare the temperatures calculated by using constant composition (red) and by using both the RBCS and MMM corrections (blue). The same seed temperature was used in both cases. Several notable effects arise:

• In keeping with Figure 1, there is a difference between the temperatures from constant composition (red) and variable composition (blue) when the integration is initiated above ~100 km, Fig 4(b)-f, and hardly any when initiated below 100 km, Fig 4(a).

• In keeping with Figure 2, there is a bigger difference between the temperatures with constant composition (red) and variable composition (blue) when the MSIS composition change is greatest, i.e. in winter, Fig 4(f).

• Combining these two effects, the biggest differences occur in Fig 4(b), which starts at the highest altitude and is in early winter.

7. Conclusions and Future Work

In this study, we used the MSIS model to estimate the effect of neutral composition changes on the calculated temperatures when the RSL observations are extended beyond 90 km to the vicinity of 115-120 km. When the RBCS and MMM are both allowed to vary with altitude, the effect appears to be small. This is based on the temperature difference between no correction and correction being at most 2K. The biggest uncertainty comes from the initial temperature, which is currently being taken from the MSIS model. This work could be furthered with independent temperature and composition measurements.

Acknowledgments

Leda Sox would like to acknowledge financial support from the USU Physics Department’s Keith Taylor Summer Scholarship. The data were obtained through the work of many students: Todd Amaro, Jason Baumann, Ryan Bingham, Joe Constantine, Ben Covington, Patrick Curley, James David, Max Davison, Joe Davison, Matt Davison, David Moos, Luis Navarro, Lance Peterson, Rebecca Patrick, Warner Schwaigert, Patrick Sharp, Joe Slomsky, and Bryce Ward.