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Rayleigh-LIDAR Observations of Mesospheric Densities

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By Lucas R. Priskos
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Project Contributors

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Abstract

The goal of this project is to take relative densities of the mesosphere (altitude 45-90 km) from data that has been collected and convert them into absolute densities. It is then possible to look at how these densities vary with altitude and season. The data was collected using a Rayleigh-scatter LIDAR at the Atmospheric LIDAR Observatory. This is a part of the Center for Atmospheric and Space Sciences and is located on the Utah State University Campus. It spans a total of 11 years beginning in 1993 and ending in 2004. The collected data is used to create a composite year and is then normalized to a constant at an attitude of 45 km. It is then compared to an absolute density measurement at 45 km that is calculated using the European Reanalysis 20th Century (ERA-20C) model. This density is then used to convert all of the relative mesospheric densities into absolute densities.

Motivation

Few people would probably dispute the importance of studying the atmosphere, its behavior, and the physics governing that behavior. Studying climatology allows for weather predictions which many people rely upon. In the past few decades, the importance of studying the atmosphere has grown tremendously in importance. Global Warming has caught the attention of the public as scientists try to determine the extent to which humans have contributed to climate change and political governing bodies discuss what can and needs to be done about it. These are a couple of examples that illustrate the importance of atmospheric physics, but why specifically study the densities of the Mesosphere? While a lot of research has gone into studying temperatures in the atmosphere and how they vary with season and altitude, little research has been done regarding densities. Modeling these density variations could give insights into certain atmospheric behaviors that temperatures cannot. In addition to this, knowing the absolute densities at higher altitudes is valuable to space programs as this information allows them to more successfully conduct launches, reentries, and orbits.

Using LIDAR to collect the relative density measurements in the Mesosphere has several advantages. It is one of the few instruments that can be used to gather data in the middle atmosphere. Other forms of atmospheric data collection, such as weather balloons and satellites, can gather data in the lower and upper atmosphere, respectively, but are not able to collect Mesospheric data. LIDAR also has the advantage of being ground based. It addition to being able to see how the densities vary with altitude, this allows us to see how densities vary with time. The variations can be seen in as short of a time period as a single day or night. RADAR is another ground based instrument that can collect Mesospheric data, but it is more difficult to use for measuring atmospheric densities than is LIDAR. RADAR is used mostly for collecting data pertaining to winds.

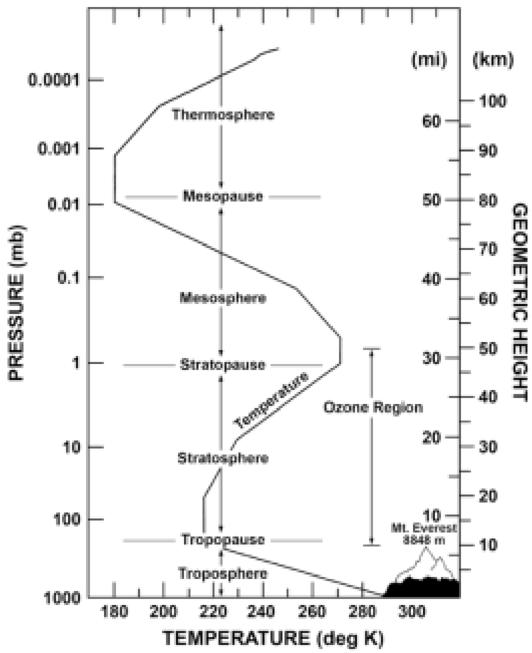

Fig. 1. This illustrates the well-document variation of temperature with altitude throughout the atmosphere. Temperature is given as a function of both pressure (on the left) and geometric height (on the right). It also depicts what altitude ranges each level of the atmosphere covers. (ie Mesosphere ranges from about 45-90 km)

Background

Fig. 2. Upgraded Rayleigh LIDAR

Originally, the Rayleigh scatter LIDAR consisted of Neodymium laser with a wavelength of 532 nm. During part of the 11 year period analyzed in this paper, an 18 W laser was used and during the remainder of the 11 year period a 24 W laser was used. A single telescope consisting of a 44 cm mirror was used to collect the backscattered light. However, several upgrades have since been made to the LIDAR. It now uses both lasers and the telescope system consists of 5 mirrors. Here is a more detailed description of the upgraded system.

The LIDAR uses a green (532 nm) laser beam that is directed vertically into the atmosphere. Some of the light is Rayleigh scattered back toward the earth. There is a telescope system consisting of 4 mirrors each with a diameter of 1.25 m (as well as a separate smaller telescope that was added very recently and will be used for collecting data in a lower portion of the atmosphere than was previously possible with the original system). Each mirror focuses the light onto an optical fiber. The photons travel through the fiber to an optical system. The light is focused to a small spot coincident to the location of a chopper. It is like a miniature fan that is rotating at 105 Hz. The fan has two openings in the wheel. Accordingly, light can pass through 210 times a second. It is timed with the laser pulses using an Arduino microprocessor so that it only accepts light that is scattered back between approximately 45-90 km in the atmosphere. After going through the chopper the light is sent through an interference filter that only allows 532 nm light through. This helps to eliminate noise from things like starlight, airglow, moonlight and city light. The light then enters a photomultiplier tube which converts the photons to photoelectrons via the photoelectric effect and amplifies them by 10^7. The resultant pulses of electrons are sent to a counter and measured every 250 ns, which corresponds to altitude intervals of 37.5 m. More photons will be scattered back when the density is higher and vice versa. So we can deduce the relative atmospheric density from the number of photons that were scattered.

Procedure

The goal is to convert the relative atmospheric densities from the data collected by the LIDAR into absolute densities. This is done by comparing the data to the European Reanalysis 20th century (ERA-20C) model which has absolute calculations for the density. These reanalysis models are created by using weather balloons that can collect atmospheric data up to an altitude of about 30 km as well as other methods of collecting atmospheric data. This data is then used to build a model of the atmosphere for higher altitudes. ERA-20C takes their model up to approximately 46 km. The LIDAR collects data down to an altitude of 45 km so this overlap with the reanalysis model allows for a comparison in the densities at 45 km. The relative densities are normalized to a constant at 45 km. Then some conversions need to be made in the ERA-20C data to get it into densities. First, the geopotential height is converted to geometric height using

$$Z = \frac{g * z}{9.80} \qquad (1)$$

where Z is geometric height in meters, z is geopotential height, and g is the acceleration of gravity at the height of interest. The geopotential height treats gravitational acceleration as a constant as altitude increases and is commonly used in atmospheric modeling. Whereas geometric height takes into consideration the variation of gravitational acceleration with altitude. This conversion is done to put the reanalysis model values and the LIDAR data on the same altitude because the data collected by the LIDAR is in geometric height.

Next, it is necessary to convert the data in the reanalysis models into number densities. The reanalysis model gives the atmospheric temperature at certain pressure levels. This data can be used to get the number density. Start with the ideal gas law:

$$PV = Nk_BT \qquad (3)$$

Where P is the pressure, V is the volume, N is the number of molecules in the volume, k_B is Boltzmann's constant, and T is the temperature. Rearranging the terms, this can be written as

$$\frac{N}{V} = \frac{P}{k_BT} \qquad (3)$$

The quantity $\frac{N}{V}$ has units of molecules per volume which is the desired number density. The ideal gas law can now be expressed as

$$\rho = \frac{P}{k_BT} \qquad (4)$$

where ρ is the number density. This is the equation that was used to convert the ERA-20C data into a number density.

A composite year is then created from the ERA-20C data using only the days that correspond to the days for which we have collected LIDAR data. The reanalysis model has pressure levels at 1 hPa, 2 hPa, 5 hPa, 10 hPa which correspond to the following approximate altitudes: 46 km, 41 km, 35 km, and 30 km.

We are interested in getting a density measurement at 45 km so we ran a regression through the reanalysis model. This regression allows us to obtain a good approximation of the model density at 45 km. Using this as the true density at 45 km, the relative densities from the LIDAR data can be converted to absolute densities by normalizing them at 45 km.

In order to do this analysis, it was necessary to create a composite year out of the 11 years of LIDAR data that had been collected. First, data from days that were deemed to be "bad" was eliminated from the data set. This left approximately 700 days of good data spanning the 11 years. From here, a composite year can be created by averaging 15 days before and after each data point and finally averaging these 31 days over the 11 years.

After doing this, we were left with a composite year consisting of 320 days. A 365-day composite year could not be created because there were some days for which no data had been collected. Most of these days occurred around December and January where various factors such as weather, students studying for finals, and the winter break prevented data from being collected. This resulted in the analysis being a slightly imprecise representation of what was truly going on with the density variations during those months. However, we are still able to get a decent picture of the density variation throughout the year.

The ERA-20C data was then reduced down to only the days for which we had LIDAR data. A composite year was then created in the same manner as was used for the LIDAR data. After running the regression through the ERA-20C data, an absolute measurement for the density at 45 km was obtained. Comparing this to the LIDAR data normalized at 45 km allowed all of the LIDAR data to be converted into absolute density measurements.

Analysis

Looking at figures 3-10, several things can be noted about how the mesospheric densities vary throughout the year. It is worth looking at when the absolute maximum occurs at each altitude, which corresponds to the coldest time of the year. At altitudes 45 km, 50 km, 55 km, and 60 km this peak occurs at the beginning of July. As altitude increases, this peak begins to occur earlier in the year. At 65 km it occurs at the end of June and at 70 km its closer to the middle of June. At 75 km and 80 km, this peak occurs around the middle of May. All of these are consistent with the coldest period in the mesosphere occurring around the end of Spring and the start of Summer. In figures 3-6, there is a noticeable local maximum that occurs around the end of January. This local maximum becomes less and less prominent as altitude increases signaling a difference in mesospheric behavior at higher altitudes than at lower altitudes. This local maximum is followed by a rapid drop in the density that also becomes less apparent at the higher altitudes. It is worth noting that December and January were the months where the fewest data points were collected so we should be weary of drawing too many conclusions from that portion of the graphs. There is another local maximum that occurs around the end of September that is quite noticeable in the lower altitude graphs. As with the other local maxima, it becomes less obvious as altitude increases. Although the graphs are not nearly as smooth at the higher altitudes as they are at the lower altitudes. It is possible that having more data could help to smooth out the higher altitude graphs so that better comparisons can be made. None of the graphs are symmetrical. The way and rate at which the mesosphere cools down is not the same as when it warms up.

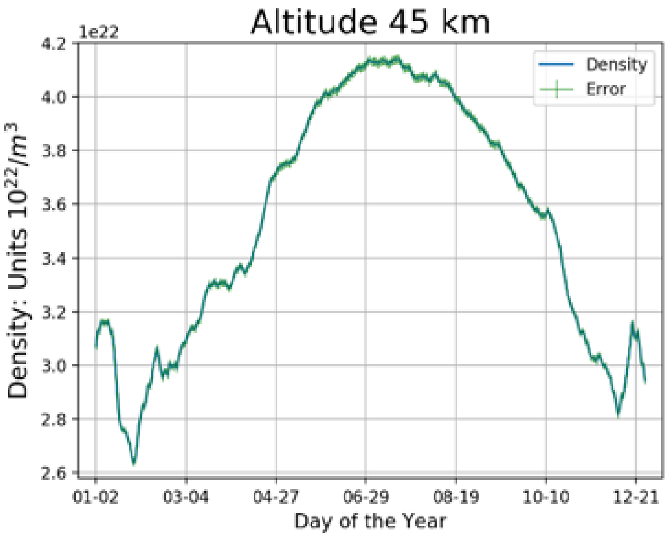

Fig. 3. Absolute density annual variations at an altitude of 45 km.

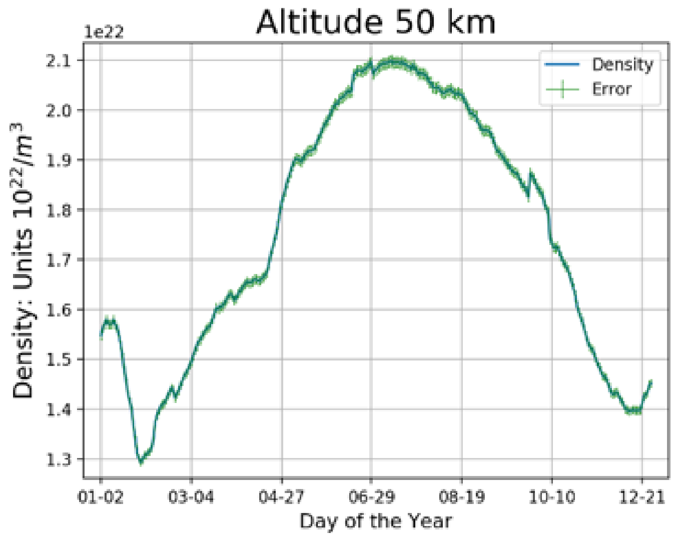

Fig. 4. Absolute density annual variations at an altitude of 50 km.

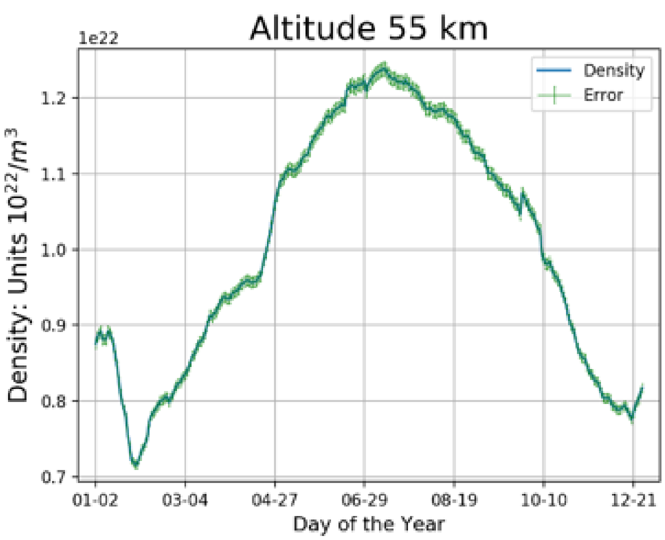

Fig. 5. Absolute density annual variations at an altitude of 55 km.

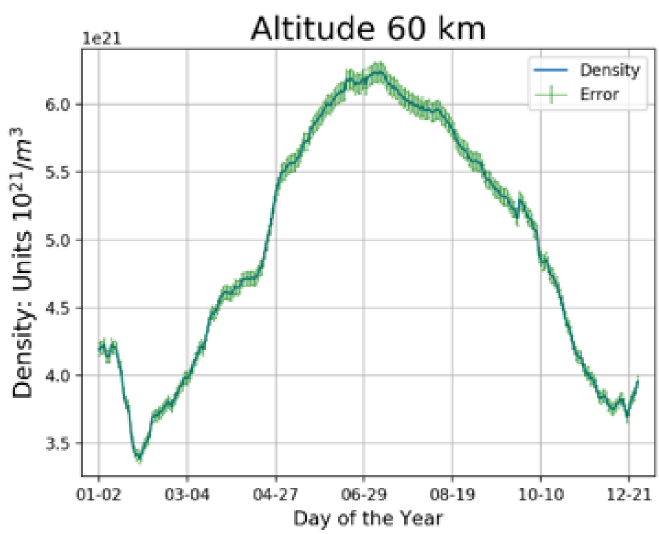

Fig. 6. Absolute density annual variations at an altitude of 60 km.

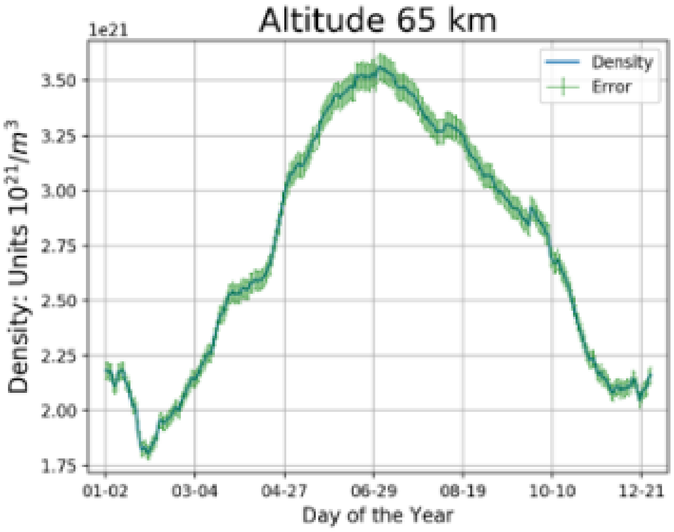

Fig. 7. Absolute density annual variations at an altitude of 65 km.

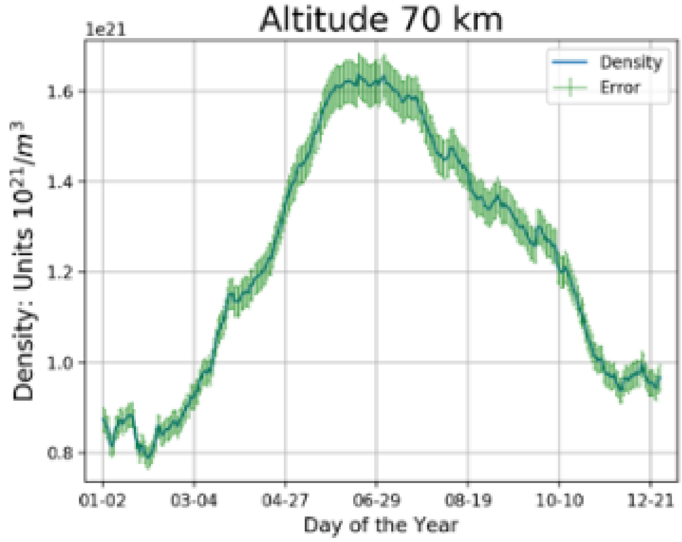

Fig. 8. Absolute density annual variations at an altitude of 70 km.

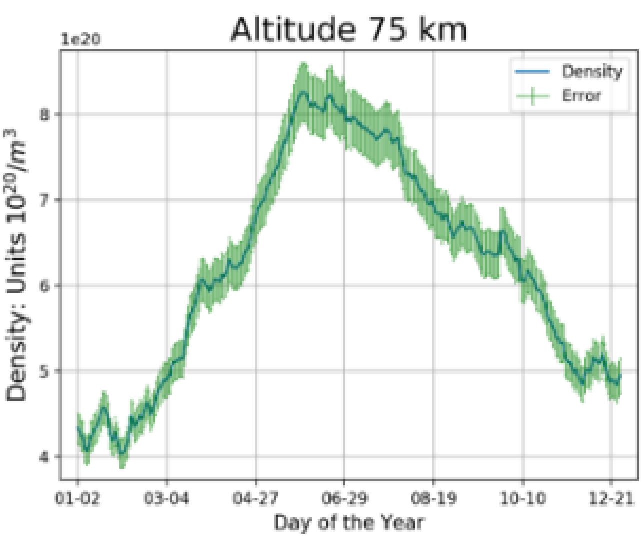

Fig. 9. Absolute density annual variations at an altitude of 75 km.

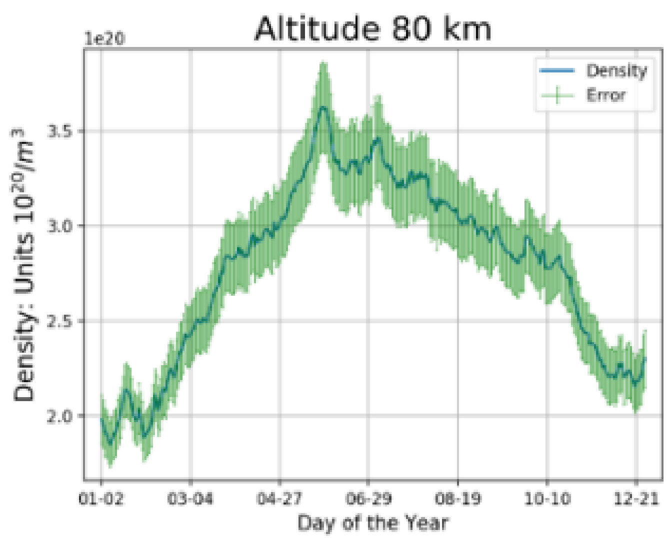

Fig. 10. Absolute density annual variations at an altitude of 80 km.

Conclusion

This paper is, by no means, meant to be a final and/or comprehensive analysis on the topic of mesospheric densities. This project is meant to provide some insight into the analysis that can be done using Rayleigh LIDAR combined with data from reanalysis models. More LIDAR data should be collected and more reanalysis models should be used in order to draw further conclusions about mesospheric density variations. Having more data in the December-January time period would allow for a better composite year to be constructed, which, in turn, would result in more accurate graphs. There is a considerable amount of continued research and future work that can be done to expound upon the ideas and analysis that were used in this project.

Future Work

This project could be continued by comparing the LIDAR data to other reanalysis models using this same methodology. There are several other reanalysis models that could be used. A couple of them are: NASA's Modern-Era Retrospective Analysis for Research and Application, Version 2 (MERRA-2) and the Japanese 55-year Reanalysis (JRA-55). These models could be used in the same manner that the ERA-20C model was used in this project and the results could then be compared.

The recent upgrade to the LIDAR (such as adding a smaller telescope as mentioned earlier) will allow for data to be collected in a lower region of the atmosphere. Additional upgrades would allow the LIDAR to collect data in higher regions of the atmosphere. Since many of the reanalysis models are restricted in how high they can collect data for building their models, being able to use the LIDAR to collect data in a lower part of the atmosphere could potentially reduce errors that may result from the reanalysis models not being perfect at 45 km. Normalizing the LIDAR densities to 35 km, rather than 45 km, could reduce these potential errors. Collecting data at higher altitudes would put the LIDAR data into the lower portion of the thermosphere. Knowing the densities in this region of the atmosphere is especially useful to space programs for things such as safe reentries.

Acknowledgements

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