# New Observations of Noctilucent Clouds (NLCs) and their environment over Alaska

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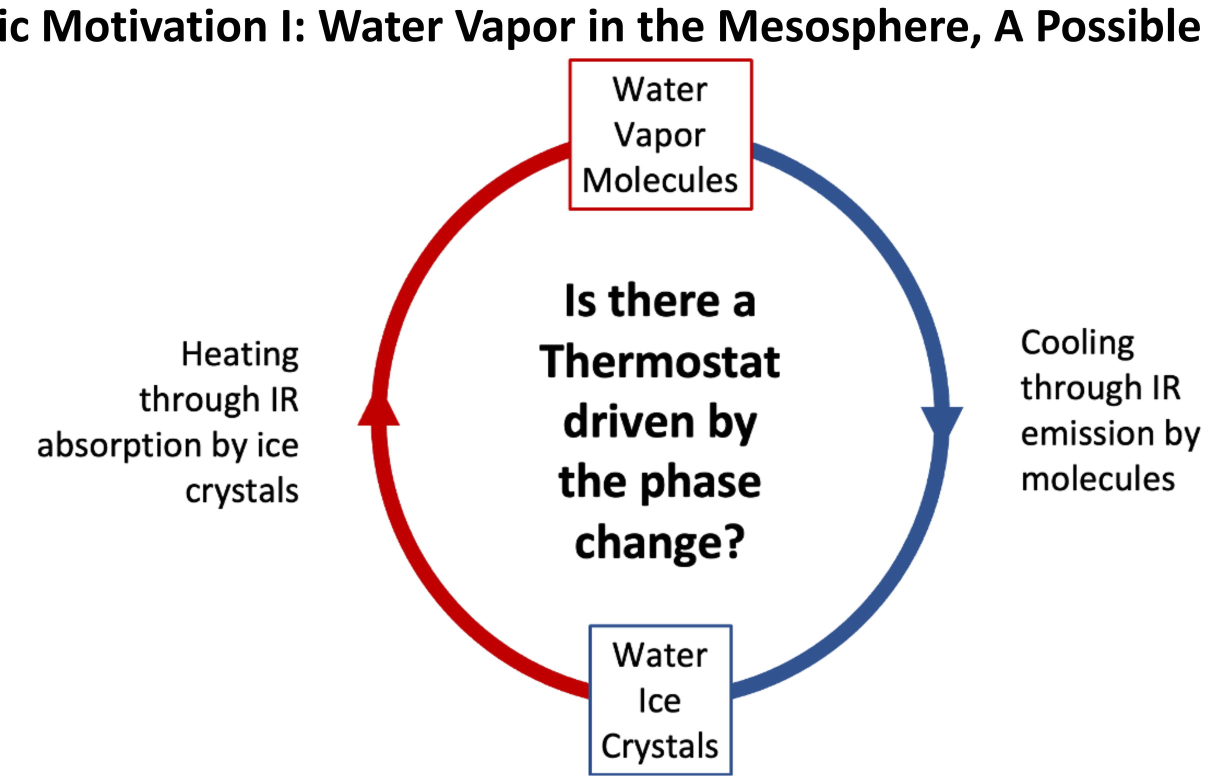
## Abstract

We present new observations of noctilucent clouds (NLCs, or polar mesospheric clouds, PMCs) and their environment made with collocated Rayleigh and resonance lidars at Poker Flat Research Range (PFRR), Chatanika, Alaska (65°N, 147° W). The Rayleigh Density Temperature Lidar (RDTL) at PFRR has been extended to a three-channel system and yields measurements with signals a factor of 3-4 higher than the previous single-channel systems. This higher signal yields NLC measurements at higher resolution and neutral density measurements above the altitude of the clouds. This allows us to determine the neutral density profile over altitudes above, spanning, and below the NLCs. The Sodium Resonance Wind Temperature Lidar (SRWTL) provides measurements of temperature and wind above the NLCs. Combining the RDTL neutral density profile and the SRWTL temperature measurements, we determine the temperature profile over the altitude range of the clouds. We present a case study of NLC observations made during the 11-12 of August 2019. We examine the temperature in the NLCs in the light of recent investigations of water releases in the mesosphere.

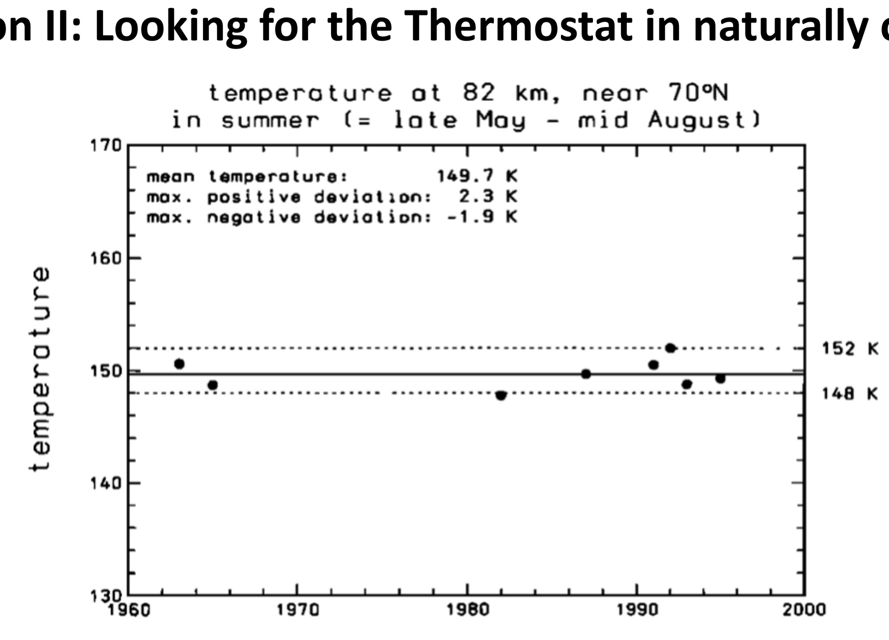
## Scientific Motivation I: Water Vapor in the Mesosphere, A Possible Thermostat?




In the troposphere, water vapor acts as a greenhouse gas where water molecules take up energy from collisions, and warm up the atmosphere. The warmer atmosphere allows for more water vapor to be present, and thus provides a positive feedback to the warming, leading to a runaway effect. In the mesosphere, the atmosphere is very thin and therefore collisions are infrequent. This allows water molecules to re-radiate their energy to space before the next collision occurs and cools the atmosphere. As the atmosphere cools, ice crystals form and cause warming through the absorption of infrared (IR) radiation, thus providing a negative feedback to the cooling. Due to this battle between IR cooling and IR heating effects, the water oscillates between transitioning to a gaseous phase and an ice phase maintaining a nearly unchanged local temperature near the frost point. Therefore, through the introduction of water vapor, the surrounding atmosphere will cool to a point where there is just enough cold for the ice to exist, but not enough ice to cause heating. Theoretically, it is speculated that a thermostat is maintaining the environment at a controlled temperature.

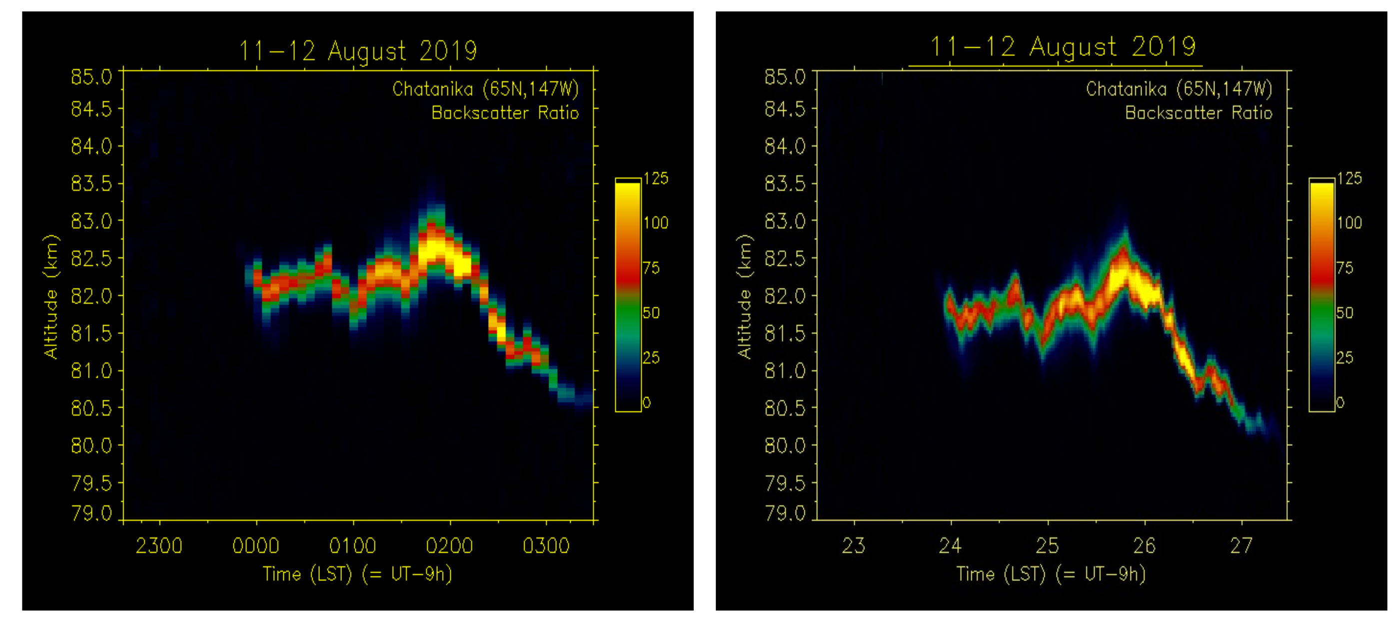
This idea of a thermostat mechanism was originated by Michael Stevens at NRL. It was prompted by the earlier work of Lübken (Lübken et. al., 1996) and explicitly comes out of the work on the Super Soaker experiment (Collins et al., 2021). During this experiment, the localized release of water vapor into the upper mesosphere resulted in rapid radiative cooling and an increase in frost point temperature generating an artificial NLC. In other words, the thermostat mechanism appears to be governing the stability of this equithermal submesopause allowing clouds to exist.

## Scientific Motivation II: Looking for the Thermostat in naturally occurring NLCs




This thermostat mechanism is consistent with Lübken et al. (1996), which demonstrated with rocket measurements that the lower edge of naturally occurring NLCs are found in remarkably repeatable temperatures of 150K +/- 2K around 82 km. We are now re-exploring this idea as we have developed a method for successfully looking at temperatures within naturally occurring NLCs using lidar.

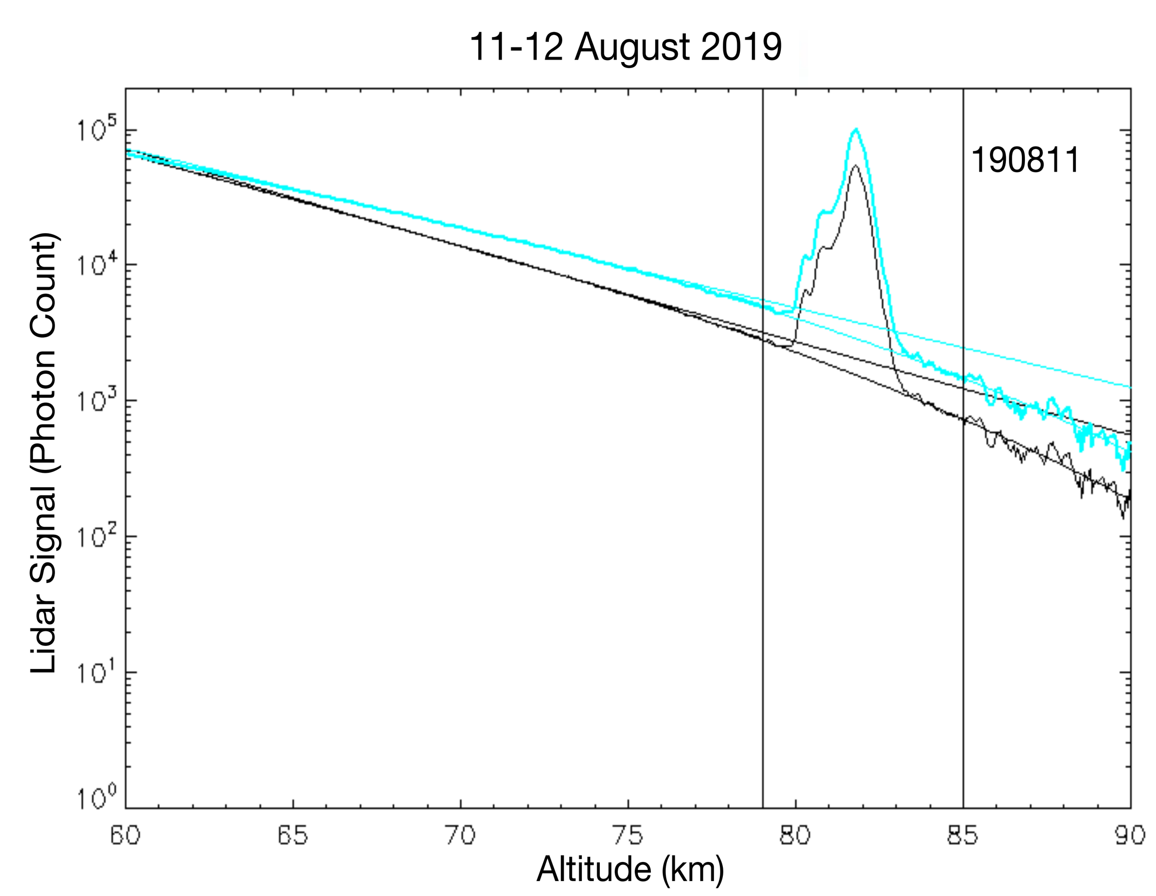
## Three Channel Rayleigh Lidar System




The Rayleigh lidar system at PFRR has made NLC observations over several decades (Alspach, 2020). The system has recently been improved to a three-channel configuration. In this system, the returned signal is optically split into three channels and goes to separate detectors and data acquisition systems. The splitting allows us to avoid saturation in the lower range, and combining the three channels yields more signal in the upper range. This extends the dynamic range of the lidar system and allow us to obtain observations above NLC altitudes.

To the left are 2D false color plots of the backscatter ratio over the entire night of 11-12 August 2019 when a bright shining NLC was detected. The backscatter ratio represents the measure of relative brightness of the NLC compared to the molecular atmosphere at each given altitude. This particular cloud was 125 times more reflective than the surrounding air. Implementing the three-channel Rayleigh lidar system, this NLC had a maximum backscatter ratio of 167.114 at 81.94 km. A comparison is made between the old single-channel system and the updated three-channel system in the two figures. The plot on the far left is the backscatter ratio retrieved by one of the three single channels at PFRR. In contrast, the three-channel system is 3-4 times more powerful both visually to the eye and in terms of backscattered signal. This improved Rayleigh lidar system returns echoes from above the NLCs which opens up the possibility to interpolate the temperatures across the clouds.

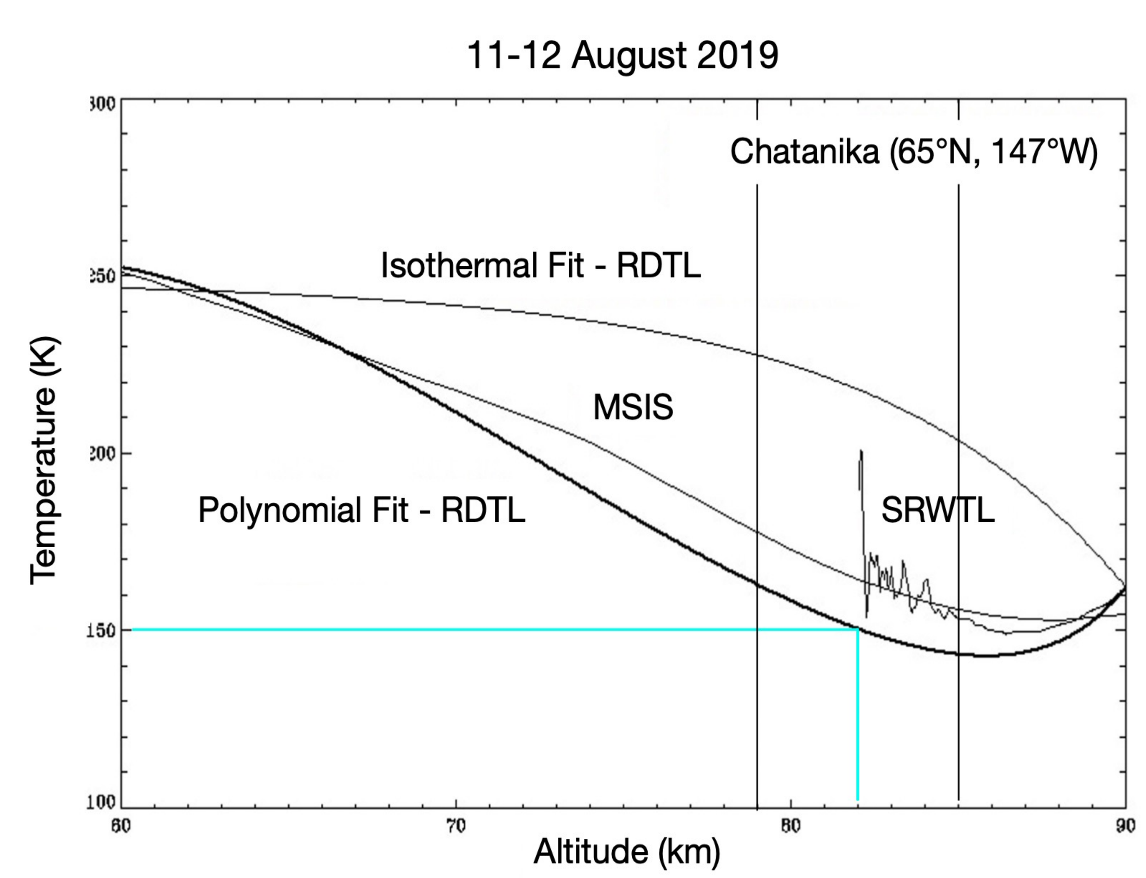
## Density measurements through the cloud




The lidar echoes above the clouds allow us to interpolate the atmospheric density across NLCs/PMCs and provides the opportunity to yield temperatures within the clouds.

The figure to the left shows the lidar signal plotted against height. The black curves are the lidar echoes integrated over the night, with the background removed. The blue curves are the range scaled lidar echoes and are thus proportional to the density of the atmosphere. This provides a more accurate representation of the signal, especially at higher altitudes.
There are two fits to the black and blue curves, respectively: a straight line in the log domain, which is the equation of an isothermal atmosphere, and a 3rd order polynomial fit, which deviates just slightly at higher altitudes. The cloud range (79-85 km) is excluded in the fitting.

## Temperature measurements through the cloud




How fast the density falls off with height depends on the scale height, and the scale height itself depends on temperature. Therefore, by integrating the interpolated density profiles, a continuous measurement of temperature is achieved through the cloud.

In the figure to the left, temperature profiles are plotted against the altitude range 60-90 km for the NLC observed on the 11-12 of August 2019. The SRWTL data is used as a seed temperature at 90 km. The narrow line is the linear fit and converges after about 10 km, which is what we should expect. The bold line is a polynomial curve fit, which shows significantly different and more accurate results. There is about a 75K difference in these temperatures around 80 km. Between the stratopause and mesopause, there is a difference of about 100K which is not unreasonable during the summer.

As expected, the data is slightly colder than MSIS at this time of year. The SRWTL temperature profiles are more consistent with MSIS than the polynomial fit. However, it is important to note that when the cloud is present, there is less sodium present. As a result, the SRWTL data is biased toward the warmer, less cloudy part of the night. This could be a possible explanation for the warmer temperatures seen in the SRWTL data. Overplotted in blue, are two lines demonstrating that our lidar observations confirmed the remarkably repeatable temperature of 150 K at 82 km within the NLC.

## Conclusions and Future Work

The three-channel Rayleigh lidar system has 3-4 times more signal than the previous single-channel systems. This enhanced signal allow us see above NLCs/PMCs and estimate the signal through the cloud with fitting. Linear and polynomial fitting yield significantly different temperatures (~75 K) within the cloud. The temperatures from the third order polynomial fit are in better agreement with the MSIS and SRWTL temperatures but colder (~20K). However, based on the polynomial fit, the temperature at the peak of the cloud (82 km) is 150 K, which is consistent with both the rocket measurements (Lübken et. al., 1996) and the thermostat mechanism.

To our knowledge these are the first temperature measurements of NLCs by lidar. This method is currently being refined and we are addressing ambiguities in the first retrievals introduced here. However, this is a strong foundation for the measurement of temperatures through NLCs by lidar. In the future, we will be incorporating the Cloud Imaging and Particle Size Instrument (CIPS) and using the meteor wind radar at PFRR to look at the wind regimes in which these clouds are forming. An MRI proposal is under establishment to upgrade the Rayleigh lidar with a new high-power laser. Furthermore, an iron resonance lidar is being developed, and a "cloud burst" proposal has been submitted by Brentha Thurairajah to further explore the effect of water vapor in the mesosphere with rocket borne water release, lidars and other ground-based instruments.

## References

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