Study of Gravity Wave Activity and Monochromatic Waves in the Polar Middle Atmosphere using Rayleigh Density and Temperature Lidar (RDTL)

Satyaki Das[(1)], **Richard L. Collins**[(1)], **Jintai Li**[(1)]
[(1)] *University of Alaska, Fairbanks, Alaska, USA*

MLTL-1
Email: sdas8@alaska.edu

1. Introduction and Motivation :

- SSW-induced temperature changes can modify chemical reaction rates, which is particularly important for upper stratospheric ozone.
- Previous studies [Randall et al., 2006] has shown a downward transport and subsequent increased level of NOx in the Arctic middle atmosphere following a sudden stratospheric warming (SSW) event which contributes to the formation of ozone holes in the stratosphere.
- Interaction between the wave forcing and mean winds causes the strong wave forcing and upper mesospheric NOx to descend in altitude.
- In this study, we analyze the wave activity during SSW and non-SSW periods to get a better understanding of the polar middle atmosphere and and how the filtering of the waves during SSW modulates the dynamics and circulation in that region. The study focusses on answering two major questions :

1) **Does the wave activity show any seasonal cycle in the Arctic middle atmosphere and if there is any change in specific potential energies of the waves during SSW?**
2) **Are these waves dissipating with altitude? What is the instability associated with the waves?**

2. Methodology :

Instruments/ Model used :

1) Rayleigh Density and Temperature Lidar (RDTL)
2) MERRA-2. **Better estimation of SPE at higher altitudes**

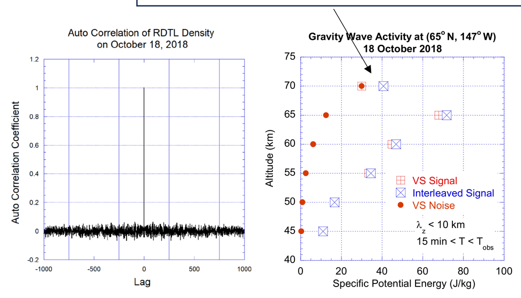

Figure 1

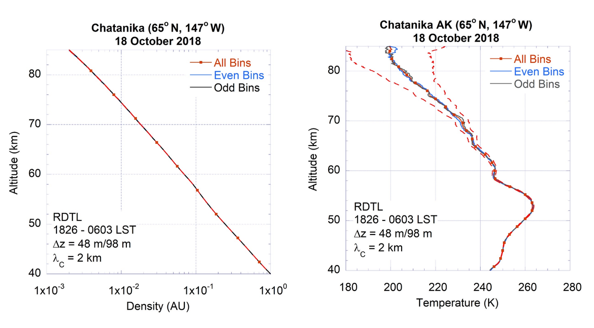

Figure 2

Altitude-based interleaved method is applied to the RDTL photon counts (50 s, 48 m resolution)

Density and temperature profiles are obtained from RDTL

$$T(z) = T(z_0)\frac{N(z_0)}{N(z)}\left(\frac{z_0}{z}\right)^2 + \frac{M}{R}\int_z^{z_0}\frac{N(r)}{N(z)}\left(\frac{r}{z}\right)^2 g(r)\,dr$$

Specific potential energy (SPE) associated with the waves is calculated

$$E_p = \frac{1}{2}N^2\xi^2 = \frac{1}{2}\left(\frac{g}{N}\right)^2 \mathrm{cov}(r_e, r_o)$$

Correlation analysis of the waves
1) With winds.
2) Between SPEs.

3. Background :

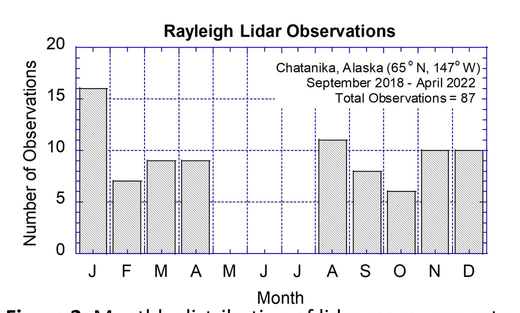

Figure 3. Monthly distribution of lidar measurements.

A major SSW in January 2019
A minor one in January 2021.

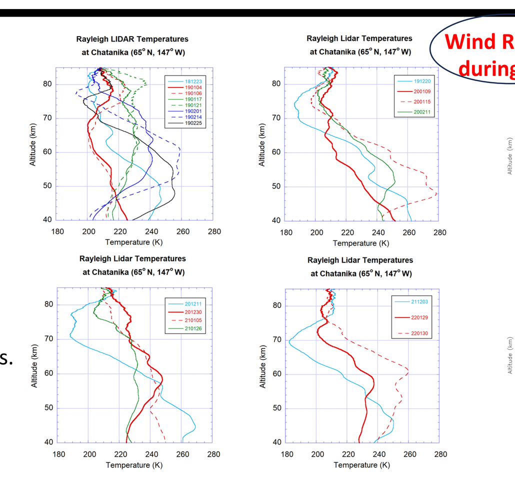

Figure 4. Rayleigh lidar temperature profiles on nights from the winters of 2018-19 (Top left), 2019-20 (Top right), 2020-21 (Bottom left) and 2021-22 (Bottom right).

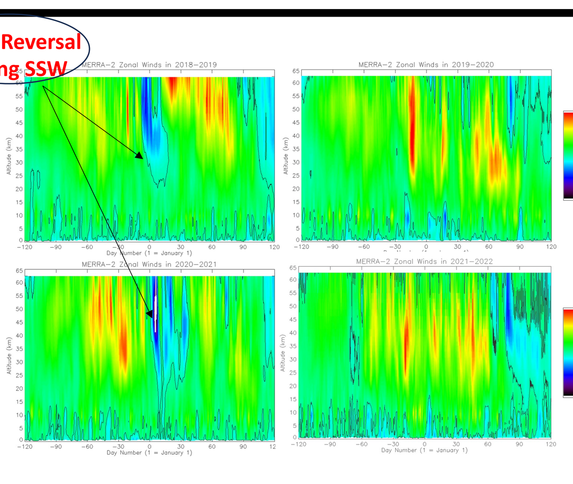

Figure 5. Zonal winds over from MERRA-2 over Chatanika 2018-19 (upper left) 2019-20 (lower left), 2020-21 (upper right), 2021-22 (lower right).

- The SSWs are evident in the winds over Chatanika as determined from the Modern-Era Retrospective analysis for Research and Applications (MERRA-2)
- The lidar temperature profiles reflect the synoptic meteorology over Chatanika. In 2018-2019 the evolution of the temperature profiles follows the disturbance due to the SSW with the formation of an elevated stratosphere and subsequent recovery of the middle atmosphere.

4. Gravity Wave Activity :

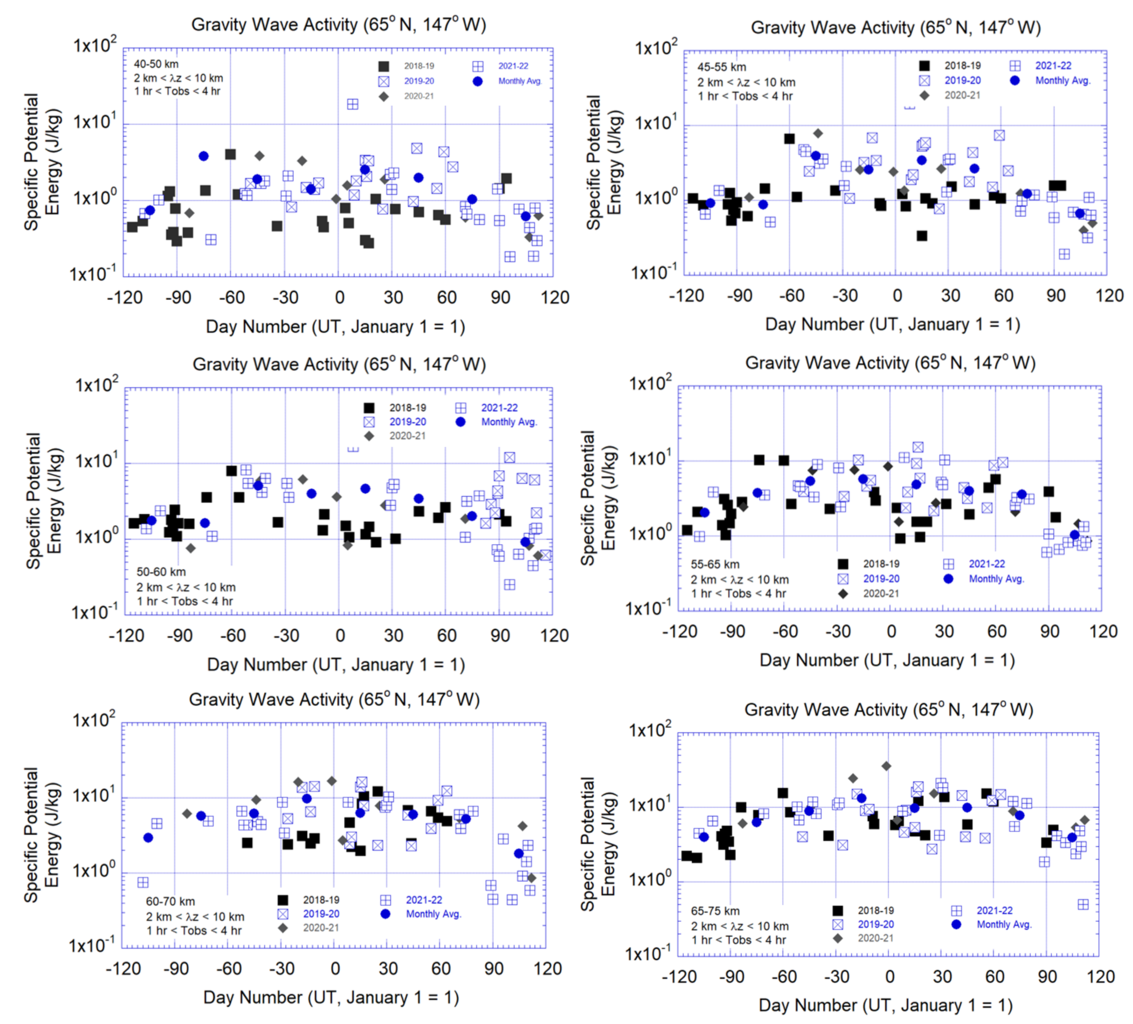

Figure 6. Specific potential energy as a function of day number at different altitudes.

- In the winter of 2018-2019, the gravity wave activity is lower in November through February than in the other years. This difference is most obvious in the 40-50 km altitude range and becomes less obvious as we increase in altitude.
- The data shows higher values of SPE in winter. However, the relative difference between these winter values and the spring and fall values decreases with altitude, suggesting that the seasonal cycle in gravity wave activity becomes less pronounced as altitude increases.

5. Correlation between Winds and Waves :

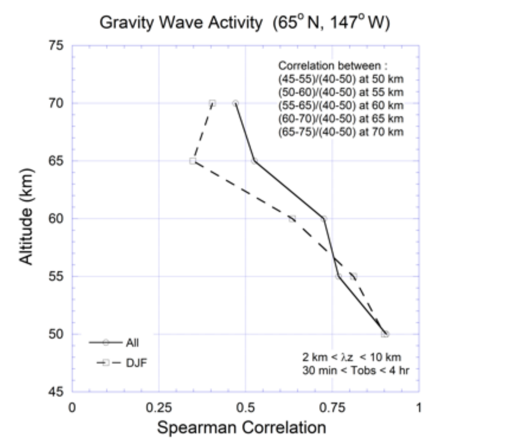

Figure 7. The correlation between the gravity wave activity at 40-50 km and other altitude ranges.

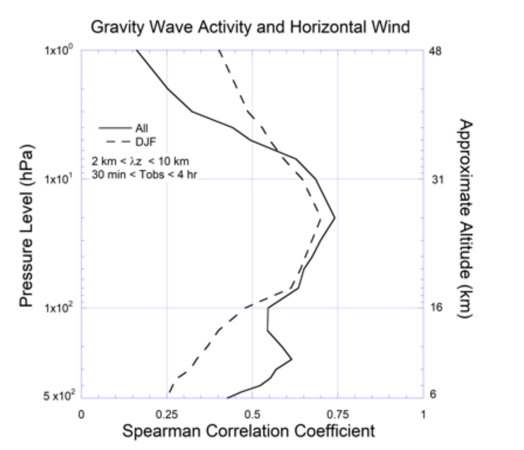

Figure 8. Correlation between the gravity wave SPE and horizontal winds

- The correlation coefficient between the SPE at all altitudes (45-55 km, 50-60 km..) relative to that at 40-50 km decreases with altitude.
- The correlation coefficient shows that the winds near 30 km are the most correlated with the gravity wave activity suggesting that the winds in the mid-stratosphere have the greatest influence on the gravity wave activity.
- Freely propagating waves should grow with altitude inversely proportional to the density of the atmosphere. Thus, the ratio of SPE at 50-60 km to 40-50 km should be ~3. Normalizing the ratio by the atmospheric densities yields a ratio of 1. We find that for the 76 nights the average density normalized ratio at 50-60 km to 40-50 km is 0.67. This average is 0.65 for the density normalized ratio at 60-70 km to 50-60 km indicating that the waves are dissipating uniformly in the mesosphere only growing by a factor of ~65% relative to freely propagating waves.

6. Monochromatic Waves:

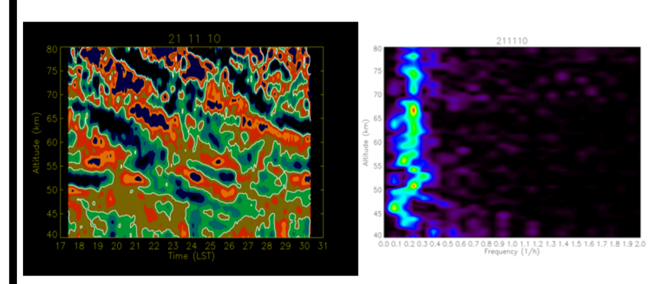

Figure 9. Relative density fluctuation on November 10, 2021 (Left) and the frequency spectrum in altitude.

1) For our analysis we choose the 51 nights out of the 76 nights of observation when the time-period of observation is greater than 8 hours. We only consider wave periods of less than 8 h. The night of 10-11 November 2021 shows the presence of a persistent wave with a spectral signature near 5.0 h (0.2 hr^{-1}) that is present in the mesosphere.

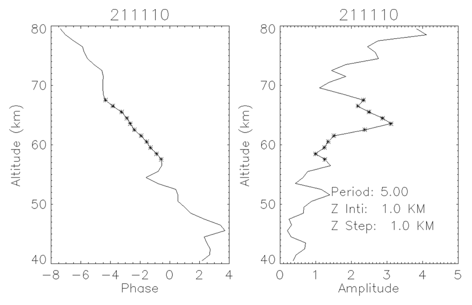

Figure 10. Phase and amplitude of the 5.0-hour wave with altitude

2) An altitude range is identified where the phase varies linearly with altitude and the amplitude of the wave is significant. This range is shown in figure 10 where the phase progression associated with the 5.0 h wave is evident over the 58-68 km altitude range. The fitting of the vertical phase progression yields a vertical wavelength of 13.8 km ± 0.4 km.

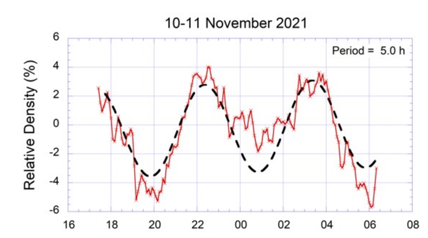

Figure 11. Relative density perturbation with 5.0 h harmonic fit.

3) The density perturbations are averaged over 1 km slices, and the best harmonic fit is determined at each altitude. The 63-64 km slice with the 5.0 h harmonic fit is shown in figure 11.

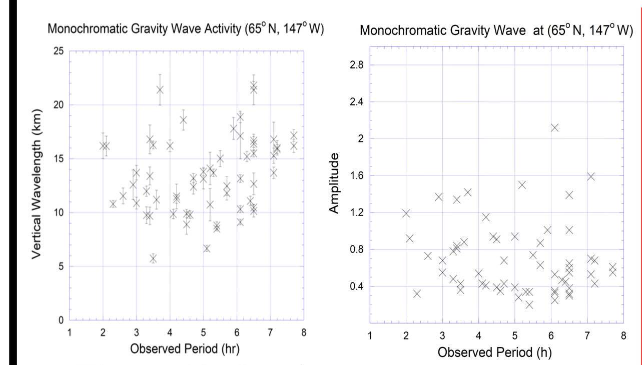

Figure 12. Gravity wave parameters detected by Rayleigh lidar at Chatanika, AK

We find 60 waves associated with downward phase progressions and with observed periods between 2.0 and 7.7 h and vertical wavelengths between 5.7 and 21.8 km. All the fits are confirmed with visual inspection of the density fluctuations.

7. Conclusions and Future Work :

- The interleaved method has been applied to the Rayleigh lidar data. This improves the estimation of gravity wave activity at higher altitudes where there is low signal to noise ratio.
- We find that the gravity wave activity shows a seasonal cycle and is strongest in mid winter and early spring. The wave activity is low during the period of SSW.
- We find waves are not propagating freely and dissipating with altitude.
- We find that monochromatic waves in the upper stratosphere and mesosphere are relatively common. Coherent wave signatures are detected in time and height and have similar scales to waves reported in the upper mesosphere but differ from those reported in the lower stratosphere.
- Future work includes a detailed study of the dissipation of the waves with altitudes and if there is a particular region where the wave breaking occurs rapidly. We are also interested to look at the instability associated with the identified monochromatic waves using the polarization relations.

8. Acknowledgement :

The authors thank the staff at Poker Flat Research Range (PFRR) for their ongoing support of our observations at the lidar research lab. **This work is supported by NSF grants 829161 and 1651464.** PFRR is operated by the Geophysical institute of the University of Alaska, Fairbanks with support from NASA.