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Gravity Wave Activity in the Arctic Middle Atmosphere during the winters 2018-2022

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Abstract: We report Rayleigh Density and Temperature Lidar (RDTL) measurements of gravity waves activity in the 40-80 km region at Chatanika, Alaska (65^0 N, 147^0 W). We use density profiles measured by the lidar to characterize gravity wave fluctuations. We consider both ensemble of waves as well as monochromatic waves. We present the wave activity from 76 nights in terms of specific potential energy over 10 km altitude ranges from 40 to 75 km. We find that the wave activity in winter 2018-2019 is reduced relative to the other winters. We discuss the propagation of wave energy with altitude. We analyze the correlation between gravity wave activity obtained from RDTL and horizontal winds. We also characterize the wave activity in terms of monochromatic waves. Furthermore, these waves are characterized in terms of vertical wavelength and time period from 51 nights where the observations length exceeded 8 hrs. We find waves with periods between X and Y hours, and vertical wavelengths between Z and W km.

1. Introduction

Atmospheric gravity waves are an essential component of the atmosphere, coupling the lower and upper atmosphere, and impacting the variability and circulation of the middle and upper atmosphere [1]. The Arctic wintertime middle atmosphere provides a natural laboratory for understanding the role of gravity waves in the general circulation. When the middle atmosphere is disturbed during a stratospheric sudden warming (SSW) event, breaking planetary waves reverse the circulation resulting in filtering of gravity waves which impacts the recovery of the circulation [2].

In this study we present 76 nights of Rayleigh lidar measurements of the gravity wave activity in the upper stratosphere and mesosphere during the winters of 2018-19, 2019-20, 2020-21 and 2021-22 at Poker Flat Research Range (PFRR), Chatanika, Alaska. We also present the correlation between MERRA winds and RDTL gravity wave activity in this study. Furthermore, we identify monochromatic gravity waves by distinguishing observed periods and vertical wavelengths and report the vertical wavelengths and time periods of the waves over 51 nights where the observation period is greater than 8 hours.

2. Rayleigh Lidar Density Perturbations

The RDTL yields an average density and temperature profile for the night as well as a sequence of temperature and density profiles. The average temperature and density profile for the night is calculated from 40 to 85 km. Then the sequences of temperature and density profiles are calculated at 5-minute resolution averaged over 15 minutes from 40 to 80 km. The average temperature profile is used to provide the initial temperature for the temperature sequences. We use the relative density fluctuation rather than the temperature fluctuations to characterize the wave activity to avoid biases in the fluctuations due to the constant initial temperature at 80 km. The relative density fluctuations are calculated relative to the average density profile for the night.

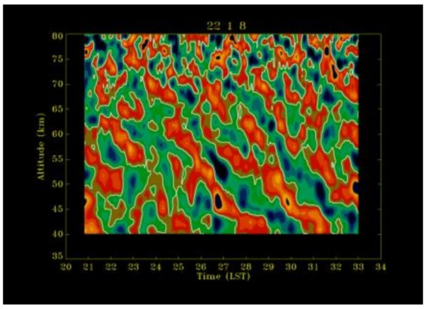

Figure 1. Perturbations in relative density as a function of time and altitude.

The relative density fluctuations are plotted in figure 1 for the night of 8-9 January 2022. The data has been filtered to remove all fluctuations with periods greater than 4 h. The fluctuations are of several percent. Downward phase progressions are clearly visible indicating the presence of upwardly propagating gravity waves.

To characterize the gravity wave activity, we determine the specific potential energy of the waves from the variance of the density fluctuations and the buoyancy period for the night. We use the interleaved method to determine the unbiased variance of the density data [3]. On the night of 8-9 January 2022, the rms density fluctuations at 40-50 km are 1.9 % corresponding to a rms vertical displacement of 392 m, and specific potential energy (SPE) of 35 J/kg. The buoyancy period is 293 s.

3. Gravity Wave Activity

We present the gravity wave data over the four years at each altitude range in figure 2. 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.

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.

We consider the coupling of the gravity wave activity with altitude by determining the Spearman correlation coefficient between the SPE at all altitudes (45-55 km, 50-60 km, ..) relative to that at 40-50 km. We plot the correlation in figure 3. We find that the correlation coefficient decreases with altitude when we consider all the 76 data sets. When we limit ourselves to those nights in December through February (DJF) we find the correlation coefficient decreases more rapidly with height. This decrease of correlation with altitude reflects the fact that over a single site the fluctuations detected at higher altitudes may reflect waves that have originated from further away. The decrease in correlation in DJF may reflect the larger variability in the wintertime wave activity.

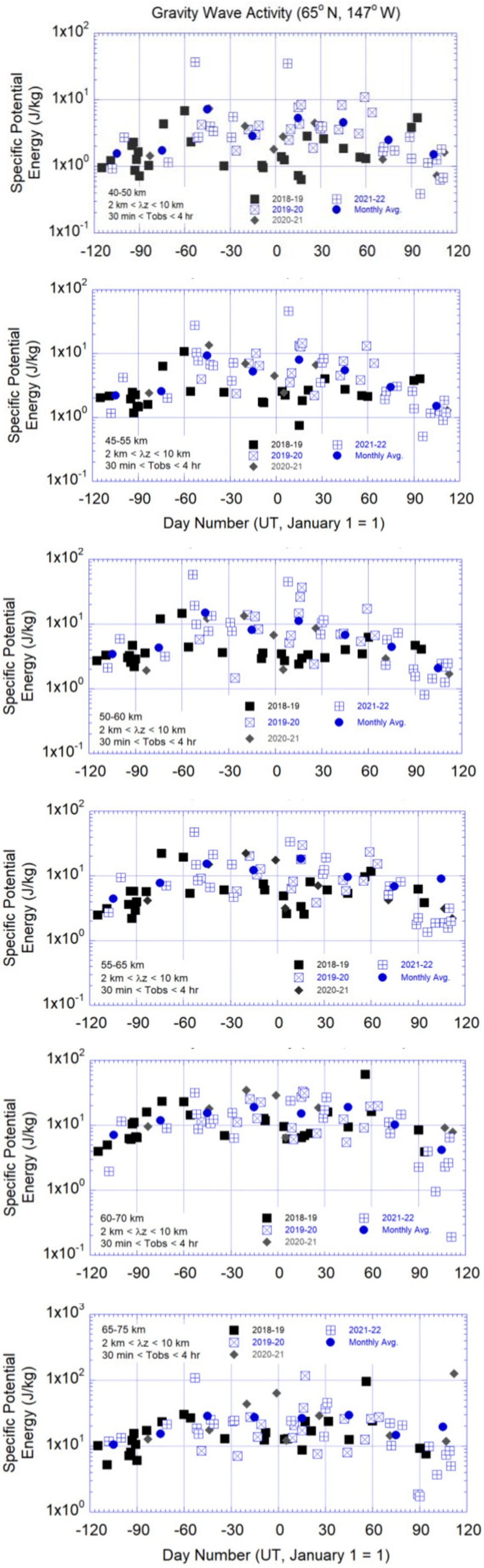

Figure 2. Specific potential energy as a function of day number at different altitudes.

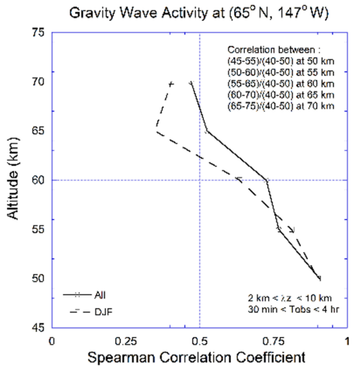

Figure 3. The correlation between the gravity wave activity at 40-50 km and other altitude ranges.

We consider the propagation of gravity waves also in terms of the ratio of the SPE with altitude. 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.

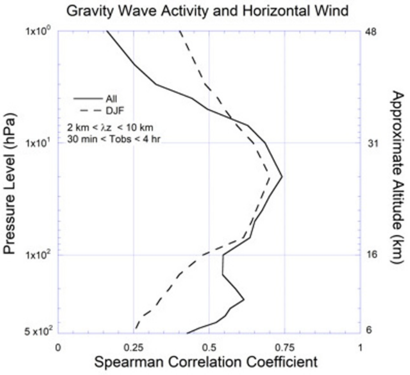

Figure 4. Correlation between the gravity wave SPE and horizontal winds.

Wind can control the propagation of gravity waves through Doppler shifting of the waves. Typically, weaker winds cause the breaking of slower gravity waves. The correlation is calculated between the gravity waves at 40-50 km to the MERRA-2 winds below that altitude. The Spearman correlation coefficient is plotted in figure 4. 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. The correlation in DJF (December, January, and February) suggests similar behavior.

4. Monochromatic Wave Analysis

In this section, we present persistent gravity wave signature in the RDTL over Chatanika, Alaska. 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. To remove tidal waves from the fluctuations we apply a Butterworth filter to the density data that removes all periods longer than 11 h and wavelengths greater than 30 km. 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.

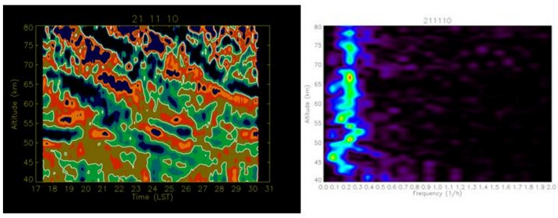

Figure 5. Relative density fluctuation on November 10, 2021 (Left) and the frequency spectrum in altitude.

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 6. 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 7 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.

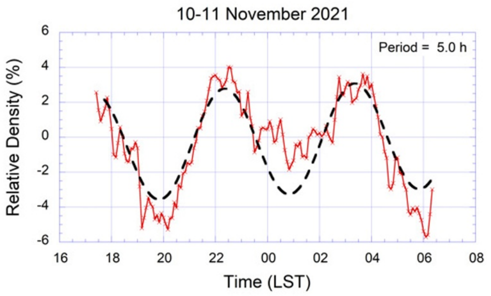

Figure 6. Relative density perturbation with 5.0 h harmonic fit.

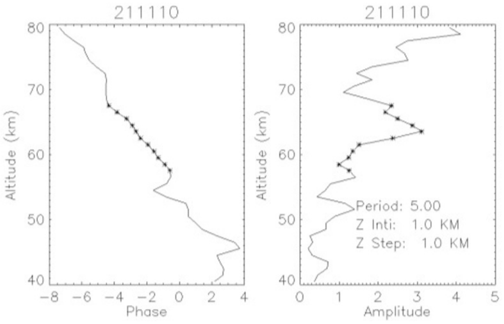

Figure 7. Phase and amplitude of the 5.0-hour wave with altitude.

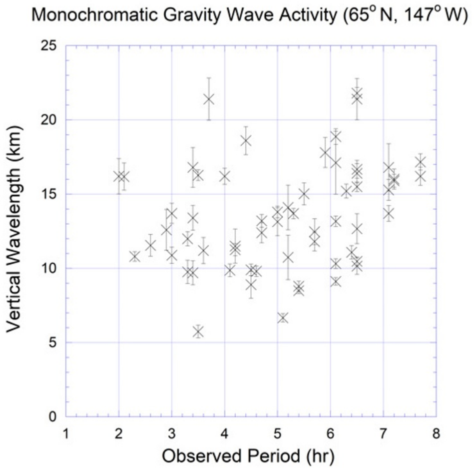

Figure 8. Gravity wave parameters detected by Rayleigh lidar at Chatanika, AK.

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 (Figure 8). All the fits are confirmed with visual inspection of the density fluctuations. These waves have similar periods and wavelengths to waves reported in the mesosphere in Alaska and Antarctica, but somewhat longer periods and vertical wavelengths than the stratospheric waves (30-50 km) reported in Antarctica [4,5,6].

5. Conclusions

We have characterized gravity wave activity in the Arctic stratosphere and mesosphere. We find the gravity wave activity is strongest in mid-winter and early spring. The variability is evident night-to-night but also interannually, associated with large scale SSWs when wave activity is reduced over several months. We find that waves are not propagating freely but are 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.

6. References

[1] D. C. Fritts, M. J. Alexander, “Gravity wave dynamics and effects in the middle atmosphere,” in Reviews of Geophysics, 41, 1003 (2003).

[2] C. T. Triplett, “Role of Wind Filtering and Unbalanced Flow Generation in Middle Atmosphere Gravity Wave Activity at Chatanika Alaska,” in Atmosphere 8, 27 (2017).

[3] J. Jandreau, X. Chu, “Comparison of three methodologies for removal of random-noise-induced biases from second-order statistical parameters of lidar and radar measurements,” in Earth and Space Science, 9, e2021EA002073 (2021).

[4] R. L. Collins, R. W. Smith, “Evidence of damping and overturning of gravity waves in the Arctic mesosphere: Na lidar and OH temperature observations,” in Journal of Atmospheric and Solar-Terrestrial Physics, 66, pp. 867-879 (2004)

[5] J. Zhao, “Lidar observations of stratospheric gravity waves from 2011 to 2015 at McMurdo (77.84°S, 166.69°E), Antarctica: 1. Vertical wavelengths, periods, and frequency and vertical wave number spectra,” in Journal of Geophysical Research Atmospheres, 122, pp. 5041-5062, (2017).

[6] C. Chen, “Lidar observations of persistent gravity waves with periods of 3–10 h in the Antarctic middle and upper atmosphere at McMurdo (77.83°S, 166.67°E),” in Journal of Geophysical Research Space Physics, 121, pp. 1483–1502 (2016).