Evaluating Sources of Gravity Waves in the Upper Atmosphere Using 10 Years of Lidar Observations at McMurdo, Antarctica

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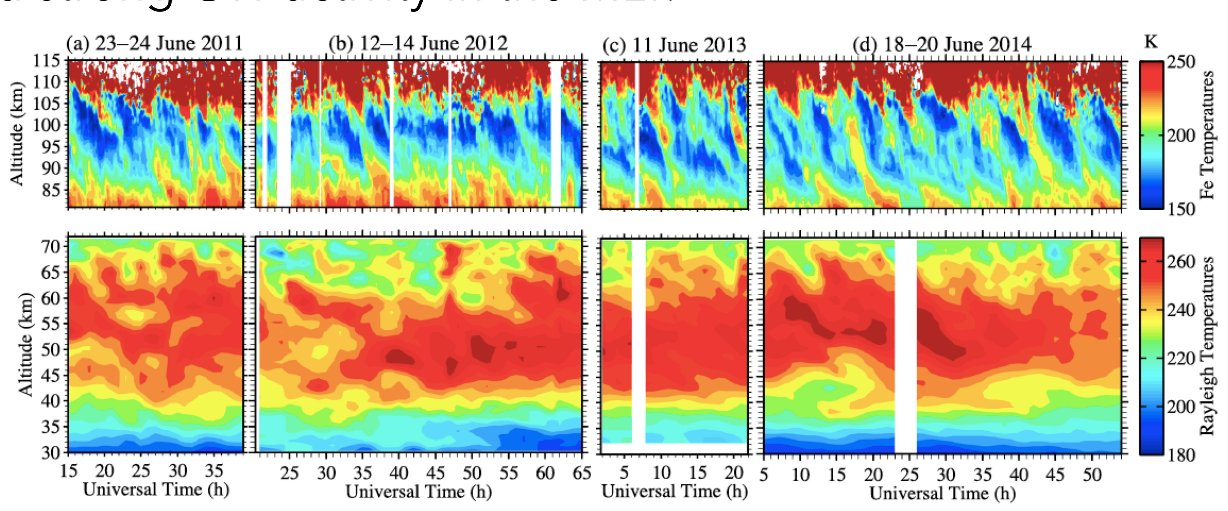
Introduction

Gravity waves (GWs) are important drivers of variability and coupling in the global atmosphere, particularly in the upper atmosphere where breaking GWs significantly influence large-scale circulations. There is a lack of comprehensive, observational studies of GWs in the upper atmosphere due to the lack of instruments that can probe this region with the cadence and resolution needed to resolve the majority of the GW spectrum. The lidar systems deployed at McMurdo Station, Antarctica by the University of Colorado Lidar group are a notable exception. These instruments have been making observations of GWs in the upper atmosphere since 2010 and numerous, high-impact studies on GWs have been produced with the help of this still growing dataset. A key example is the discovery of strong and persistent GW activity in the mesosphere and lower thermosphere (MLT) above McMurdo (Chen et al., 2016). These observations were critical in the development of the multistep vertical coupling mechanism (Vadas et al., 2018) which has dramatically altered our understanding of how GWs transport momentum throughout the atmosphere. Vadas and Becker, 2018 used the Kühlungsborn Mechanistic general Circulation Model (KMCM) to simulate GWs at McMurdo and concluded that the majority of the GWs in the MLT were secondary GWs. However, convincing observational evidence to support this conclusion has yet to be identified. Previous analyses of the properties of GWs at McMurdo have focused on either the Rayleigh region (30 – 70 km) or the MLT (> 80 km) separately, and analyses of GWs in the MLT were limited to the month of June. This work utilizes 10 years of Fe Boltzmann lidar data to characterize GW properties in both regions, from the stratosphere to the thermosphere, for the first time. Comparison of these results with the KMCM results of Vadas and Becker, 2018 show general agreement indicating that secondary wave generation is the likely source of the persistent and strong GW activity in the MLT.

Fe Boltzmann lidar temperature measurements clearly show the strong and persistent GW activity in the MLT



Data & Methodology

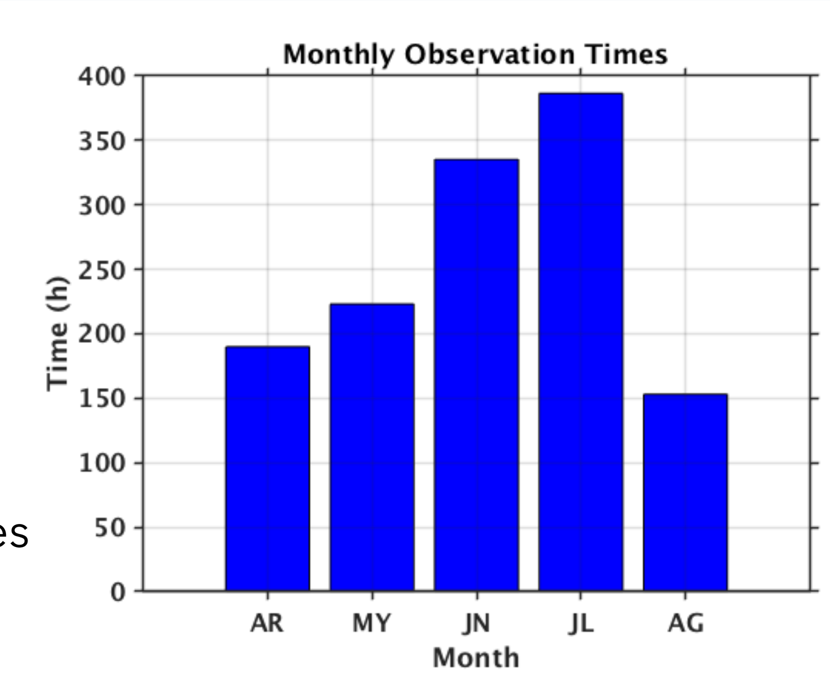
Analysis incorporates **1288 h** of temperature measurements in the Rayleigh region and the MLT from **~ 100 lidar observations** made in the wintertime between 2011 and 2020.

Rayleigh Region:

- Range: 30 – 60 km
- Resolution: 2 h x 1 km
- Filtered to suppress tidal and planetary waves

MLT:

- Range: 81 – 105 km
- Resolution: 0.1 h x 0.1 km



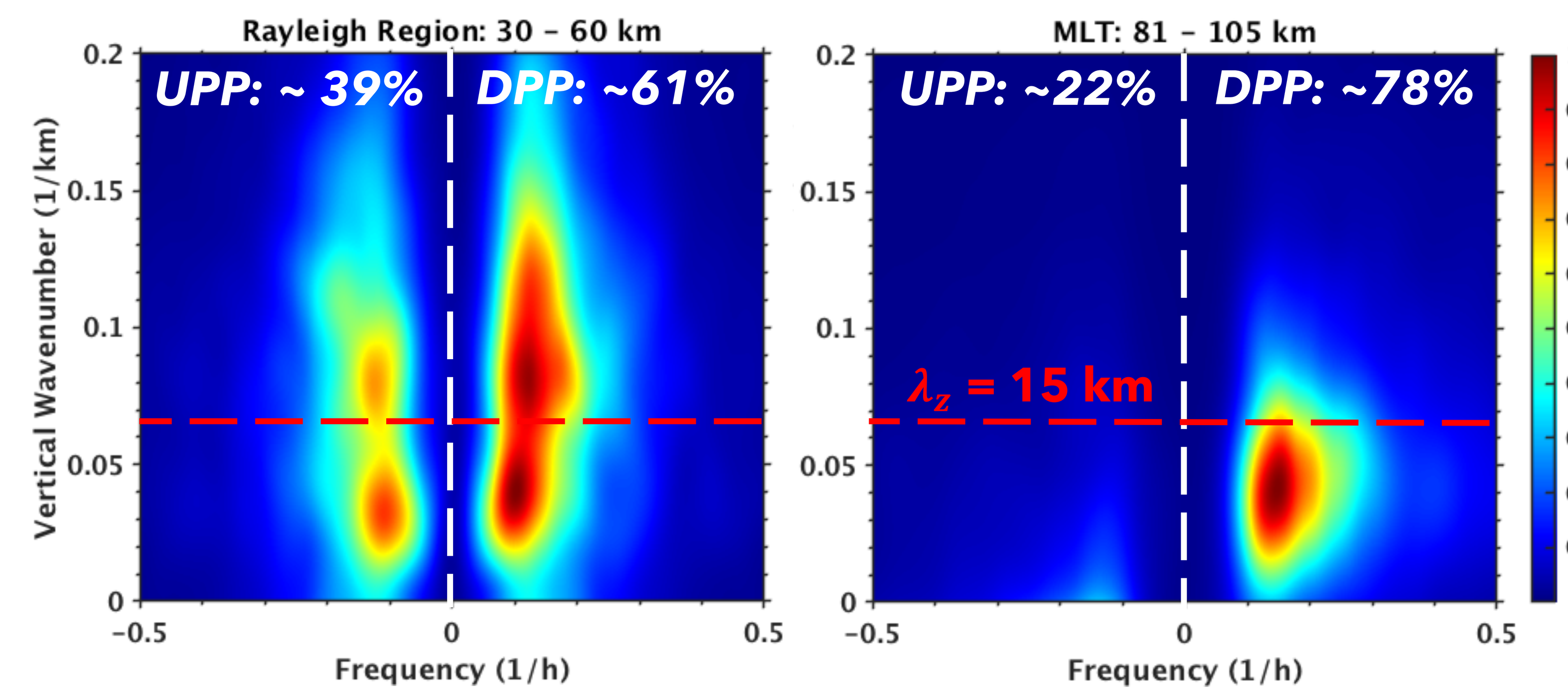
Relative temperature perturbations, scaled by a normalized atmospheric density profile from MSIS, are calculated as:

$$T'_{Rel}(t,z) = \sqrt{\frac{\rho(z)}{\rho(z_0)}} * \frac{T(t,z) - T_{mean}(z)}{T_{mean}(z)}$$

Power spectrums are derived by applying a 2D FFT transform to $T'_{Rel}(t,z)$. The ground-based periods (τ_{GB}), vertical wavelengths (λ_z), and vertical phase speeds (c_z) of GWs are determined from peaks in the power spectrum.

Striking Differences Between the Analysis Regions

- **Downward phase progression (DPP)** suggests upward energy propagation and **upward phase progression (UPP)** suggests downward energy propagation, however this is dependent on the background winds
- Rayleigh region is characterized by a mix of UPP and DPP GWs and there are a significant amount of GWs with λ_z < 15 km
- DPP is dominant in the MLT and the majority of waves have λ_z > 15 km



Normalized mean power spectrums and percentages of the total power occupied by the UPP and DPP sides of the power spectrum

Key Takeaways

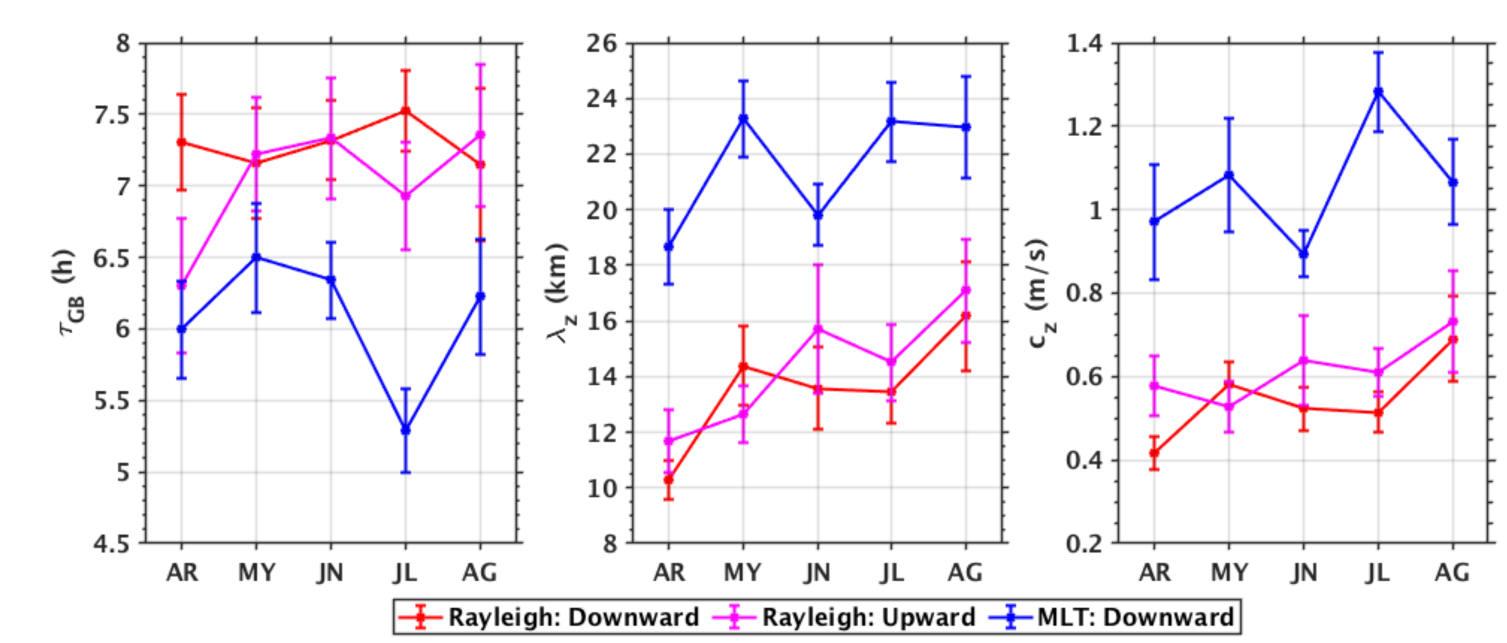
- Between 30 – 60 km UPP (DPP) GWs occupy 39% (61%) of the total spectral power, respectively, on average. Between 81 – 105 km, UPP (DPP) GWs occupy 22% (78%) of the total spectral power, respectively. Little variability is seen in this distribution of power throughout the winter months (not shown). Dominant DPP in the MLT indicates that the majority of waves are generated at lower altitudes, if it is assumed that DPP corresponds to upward energy propagation.
- GWs between 30 – 60 km tend to have longer τ_{GB}, smaller λ_z, and faster c_z than the GWs in the MLT. Secondary waves typically have larger λ_z than the breaking primary waves which generate them.
- **Significant seasonal variation in τ_{GB} is seen in July** with $\overline{\tau_{GB}}$ being ~1 h shorter than that of the other months. Future work will investigate this variability in detail.

Wave Selection Criteria & Mean Properties

GW properties are determined by identifying peaks in the power spectrums of individual lidar runs. This analysis focuses on waves with τ_{GB} = 3 – 10 h and λ_z = 5 – 40 km. Only waves with these properties and powers that exceed that of a noise spectrum derived from the temperature measurement errors are deemed as qualified for the analysis. Out of the qualified waves, **only the peaks with the highest power on the UPP and DPP sides of the spectrum are taken from each observation** resulting in ~100 sample points for each category in each region.

Mean wave properties and standard errors calculated from the strongest DPP and UPP signal in each power spectrum

<table>
<tr><th></th><th>Rayleigh
(DPP | UPP)</th><th>MLT
(DPP | UPP)</th></tr>
<tr><td>$\overline{\tau_{GB}} \pm \sigma$
(h)</td><td>7.3 ± 0.2
7.0 ± 0.2</td><td>6.0 ± 0.2
5.9 ± 0.2</td></tr>
<tr><td>$\overline{\lambda_z} \pm \sigma$
(km)</td><td>13.4 ± 0.6
14.2 ± 0.7</td><td>21.6 ± 0.7
20.5 ± 0.9</td></tr>
<tr><td>$\overline{c_z} \pm \sigma$
(m/s)</td><td>0.54 ± 0.03
0.61 ± 0.04</td><td>1.08 ± 0.05
1.05 ± 0.06</td></tr>
<tr><td>$\overline{P_{Peak}}$
(Arbitrary)</td><td>0.041
0.026</td><td>2.6
0.3</td></tr>
</table>



Monthly mean wave properties. Properties of UPP waves in the MLT are not shown here because the spectral powers corresponding to these signals are an order of magnitude less than the DPP signals on average.

Conclusions

This work presents the first comprehensive analysis of GW properties between the stratosphere and thermosphere at McMurdo Station, Antarctica. Previous studies have hypothesized that the persistent and strong GWs in the MLT are secondary waves generated by primary waves breaking in the lower atmosphere. These results provide further evidence to support this claim as the differing properties of GWs between 30 – 60 km and 81 – 105 km are consistent with expectations based on the theory of multistep vertical coupling. Furthermore, these results compare well with KMCM simulations of a MW event that produced secondary waves in the MLT during which:

- 47% (53%) of the total spectral power was occupied by UPP (DPP) GWs between 30 – 60 km and 29% (71%) of the total spectral power was occupied by UPP (DPP) GWs between 60 – 100 km
- GWs had τ_{GB}~ 7 – 11 h and τ_{GB}~ 3 – 11 h between 30 – 60 km and 60 – 100 km, respectively

Further analysis is needed to conclusively say whether the persistent GWs are secondary waves. However, if this hypothesis can be proven from an observational standpoint it would have far reaching impacts for the atmospheric dynamics field. Future work will focus on analyzing the variability of GW properties between the stratosphere and thermosphere, as well as lower in the atmosphere with McMurdo radiosonde data, in order to identify any trends that could be linked to secondary wave generation or other wave sources that may be at play.

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