Coupling by Gravity Waves Through the Middle and Upper Atmosphere in Antarctica: Are Dominant Stratospheric Gravity Waves the Direct Source of Persistent Gravity Waves in the MLT?

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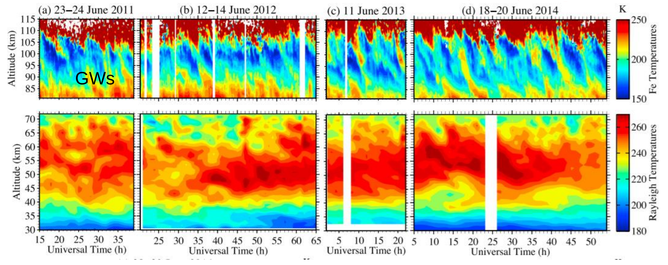
1. Abstract

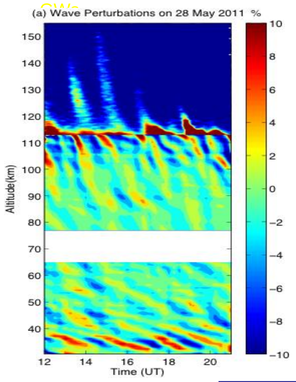
Persistent gravity waves with periods of 3–10 h were discovered in the Mesosphere and Lower Thermosphere (MLT) above McMurdo, Antarctica. Several theories have been proposed for the sources of these waves, e.g., resonant vibration of Ross Ice Shelf and secondary wave generation. Chen et al. [2013] performed a ray-tracing study and pointed possible wave sources to the stratosphere. Furthermore, gravity waves are found to play crucial roles in the formation of thermospheric Fe layers and such waves are traced down to the stratosphere. All these discoveries urge the need to analyze gravity waves in the stratosphere to shed light on the sources of waves in the MLT. We characterized the lognormal distributions of vertical wavelengths, periods, vertical phase speeds, and potential energy densities from atmospheric temperature observations obtained by the Fe Boltzmann lidar. The fractions of gravity waves with downward phase progression increase from summer ~59% to winter ~70%. The monthly mean vertical wavelengths and periods exhibit clear seasonal cycles with vertical wavelength growing from summer ~5.5 km to winter ~8.5 km, and period increasing from summer ~4.5 h to winter ~6 h. Gravity wave potential energy density form a repeated annual pattern with winter maximum and summer minimum. Possible causes of this phenomenon such as critical level filtering, in-situ wave sources, Doppler shift theory are discussed. Statistically significant linear correlations are found between the monthly mean vertical wavelengths/periods and the mean zonal wind velocities. The monthly mean horizontal wavelengths, intrinsic periods, and group velocities are inferred for stratospheric gravity waves. In general, gravity waves propagate along north-south direction with elevation angles ~1.1 deg and horizontal phase speeds ~20 m/s. The horizontal wavelengths of gravity waves in the stratosphere vary from 350 to 450 km, which are much shorter than those of the persistent waves in the MLT (at least 1000 km to over 2000 km). We conclude that the dominant gravity waves in the stratosphere are not the direct source of the persistent gravity waves in the MLT. Secondary wave generation theory provides the explanation for the source of such persistent gravity waves. “Fish-bone” patterns in the temperature perturbations, which are the theoretically predicted patterns from the secondary wave generation theory, are presented from our lidar measurements.

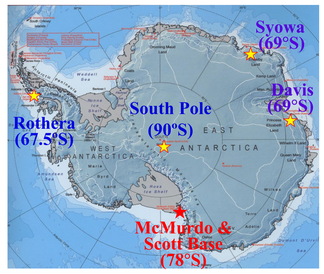
2. Scientific Motivations: What sources can generate such persistent, dominate, large-amplitude gravity waves?

Persistent gravity waves discovered in Antarctica [Chen et al., JGR, 2016]



GWs crucial to thermospheric Fe layer

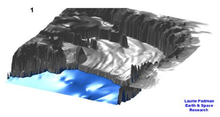




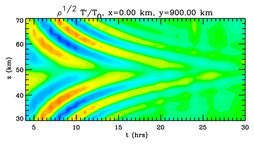
Persistent gravity wave signatures:
- Large amplitude (±20K)
- Dominating temperature variations
- Perpetually exist in the MLT
- Periods 3 to 10 hours
- Vertical wavelength 20 to 30 km

Potential Source?

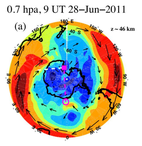
Resonant vibration of Ross ice shelf [*Godin and Zabotin*, 2016]



Secondary Wave Generation [*Vadas and Becker*, private comm.]



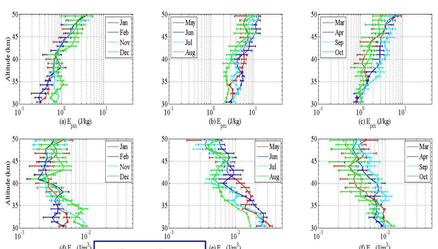
Possible wave suorce in stratosphere [*Chen et al*, 2013]



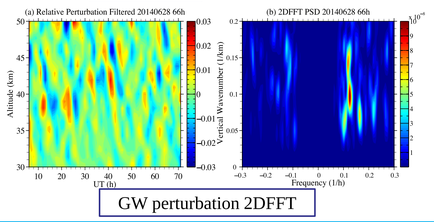
Urge the need to characterized gravity waves in the stratosphere GWs: Coupling between the stratosphere and the MLT

3. Derivation of Gravity Wave Parameters

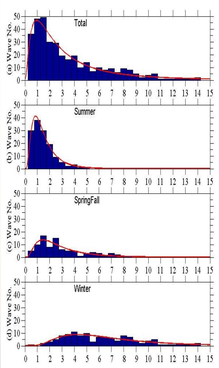
Data Analysis Procedures:
- ➢ Subtract background
- ➢ High pass Butterworth filter in time, altitudinal domain
- ➢ GW perturbations
- ➢ 2DFFT
- ➢ Pick the first three peaks, record wavelengths and periods
- ➢ Gravity wave potential energy density



E_{pm}, E_{pv}

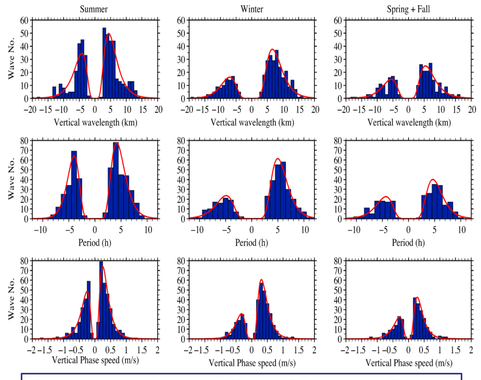


GW perturbation 2DFFT



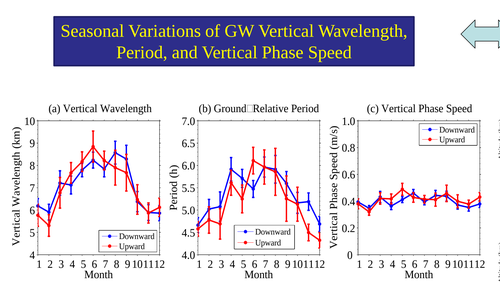
Lognormal Distributions of GWPEDs

4.1. Vertical Wavelength, Period vs Background Wind, Inferred GW Intrinsic Properties



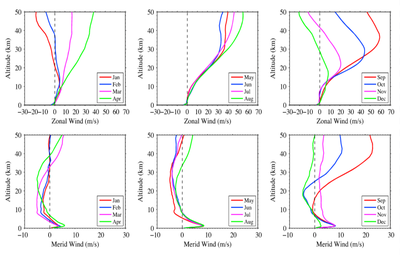
Lognormal distribution of Vertical Wavelengths, Periods, and Vertical Phase Speeds

Seasonal Variations of GW Vertical Wavelength, Period, and Vertical Phase Speed



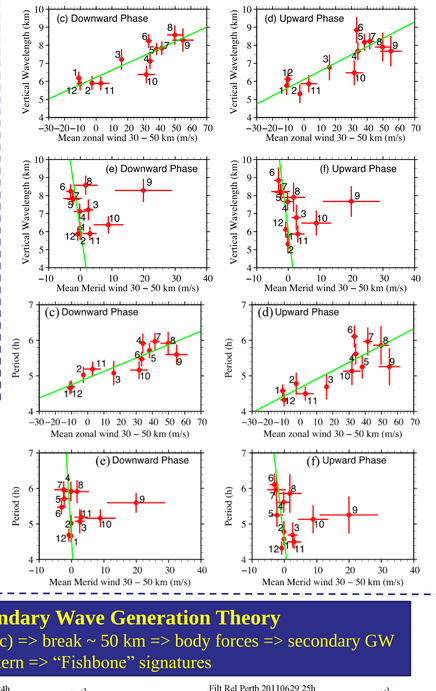
Vertical wavelength: ~5.5 km (summer) to ~8 km (winter)
Ground-relative period: ~4.5 h (summer) to ~5.7 h (winter)
Vertical phase speeds: constant (~0.4 m/s) throughout the year

Background Wind from ECMWF



Monthly mean zonal and meridional wind profiles

Monthly mean vertical wavelengths, periods and monthly mean zonal winds from 30 to 50 km



Gravity wave dispersion relation with f term ignored

$$\hat{\omega} = N\left|\frac{k_h}{m}\right|$$

$$\lambda_z \cong \frac{2\pi}{N}\left(c_h - \bar{u}_h \cos\theta\right)$$

$$S_{I_z} = -\frac{2p\cos q}{N}$$

Doppler shift between $\hat{\omega}$ and ω

$$\hat{\omega} = \omega - \vec{k}\cdot\vec{\bar{u}} \cong \omega - k_h\bar{u}_h\cos\theta = \omega\left(1 - \frac{\bar{u}_h\cos\theta}{c_h}\right)$$

$$\tau = \hat{\tau}\left(1 - \frac{\bar{u}_h\cos\theta}{c_h}\right)$$

$$S_t = -\frac{\hat{t}}{c_h}\cos q = -\frac{2pk_h\cos q}{\hat{w}\times w}$$

[Zhao et al., JGR, 2017]

Assume C_h constant

$$c_h(\bar{u}_h\cos\theta = 0) = \frac{N\cdot\lambda_z(\bar{u}_h\cos\theta = 0)}{2\pi}$$

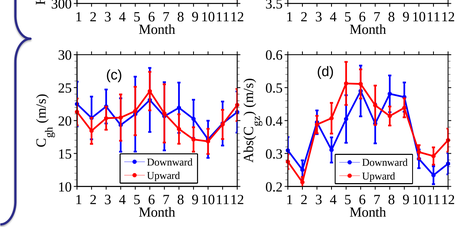
$$l_h \gg \frac{N\times l_z(\bar{u}_h\cos q = 0)\times t}{2p}$$

$$\hat{\tau} \approx \frac{\lambda_z(\bar{u}_h\cos\theta = 0)}{\lambda_z/\tau}$$

$$\cos q = -\frac{S_{I_z}\times N}{2p}$$

$$c_{gh} = \frac{\partial\omega}{\partial k_h} = \frac{k_h\left(N^2 - \hat{\omega}^2\right)}{\hat{\omega}\left(k_h^2 + m^2 + 1/4H^2\right)} + \bar{u}_h\cos\theta$$

$$c_{gz} = \frac{\P w}{\P m} = -\frac{m\left(\hat{w}^2 - f^2\right)}{\hat{w}\left(k_h^2 + m^2 + 1/4H^2\right)} + \bar{w}$$



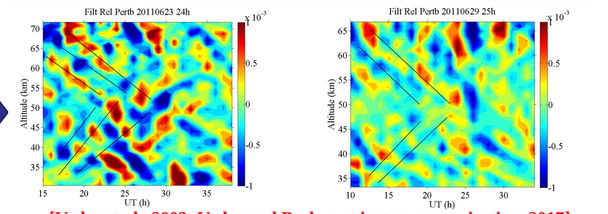
- Propagate along North-South Direction
- Propagation elevation angle ~1.1°
- Horizontal Wavelength different from GWs in MLT (Horiz. WL at least 1000 km to over 2000 km [*Chen et al.*, 2012; 2013])
- **Dominant stratospheric GWs are not the direct source to persistent GWs in the MLT**

	Down	Up
C_h(m/s)	21.2	20.8
cos(θ)	-0.14	-0.16

[Zhao et al., JGR, 2017]

Potential Wave Source ?

Secondary Wave Generation Theory
Primary GW(orography) => break ~ 50 km => body forces => secondary GW
Break-regeneration pattern => “Fishbone” signatures

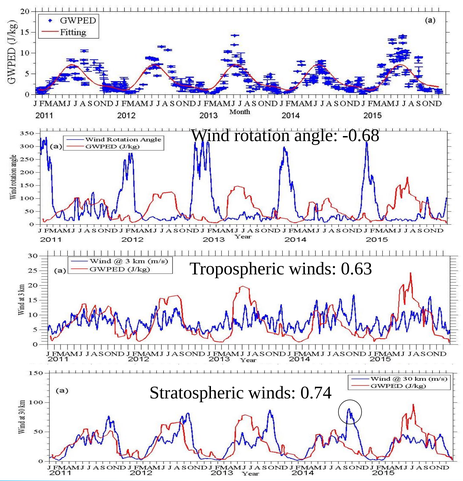


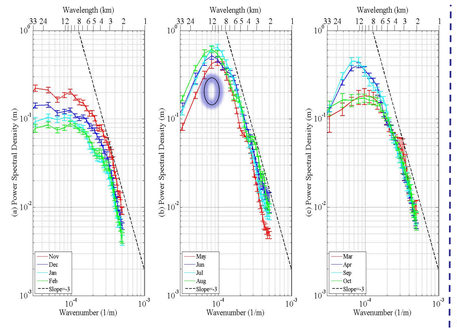
[Vadas et al., 2003; Vadas and Becker, private communication, 2017]

4.2. GWPED vs Wind Rotation Angle, tropospheric wind, stratospheric wind, polar vortex

E_{pm} Summer minima (Feb), winter maxima (Jun)

Single GWPED vary substantially, Quite large year-to-year variability



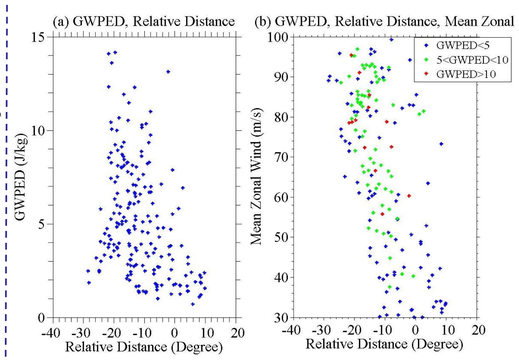


- ➢ Wind Rotation Angle
  Critical layer filtering of orographic GWs
- ➢ Tropospheric winds
  Forcing strength of orographic GWs
- ➢ Stratospheric winds
  Doppler shift theory [Whiteway et al., 1997]
  Less critical layer filtering
  Polar vortex as in-situ source
  More secondary gravity wave generation

Polar Vortex position and strength

Large gravity wave E_{pm} occur:

1) when McMurdo is inside the jet stream core 6 to 24 degrees towards the pole. Unbalanced flow or wind shear induced by the jet stream edge ⇔ Potential gravity wave source?
2) when mean zonal wind is large, i.e., the polar vortex is strong. The westerly jet in the stratosphere is still quite strong even if McMurdo sits on the inner edge of the jet stream core



Open Questions:
1) What cause the lognormal distributions of $\lambda_z, \tau, c_z, E_p$? Why N^2 does not follow lognormal distribution?
2) What answer for the observed abrupt difference in m-spectra from March to April and from September to October?
3) What are the reasons of the observed seasonal variations of λ_z, τ? Why c_z remain almost constant throughout a year?
4) What are the exact sources of persistent gravity waves in MLT above McMurdo?

5. Conclusions

- ➢ Lognormal distributions of $\lambda_z, \tau, c_z, E_{pm}$ of stratospheric gravity waves at McMurdo, Antarctica
- ➢ Fraction of downward phase progression gravity waves increases from summer ~59% to winter ~70%
- ➢ λ_z grow from summer ~5.5 km to winter ~8.5 km, τ increases from summer ~4.5 h to winter ~6 h
- ➢ Linear correlations: monthly mean vertical wavelengths/periods and mean zonal wind velocities
- ➢ Inferred intrinsic periods (4–5.5 h), horizontal wavelengths (~400 km), gravity waves propagate along north south direction with ~1.1° elevation angle and ~20 m/s horizontal phase speed
- ➢ Dominant stratospheric gravity waves are not the direct source of persistent GWs in the MLT
- ➢ Frequency spectra: Slopes from about -1.9 in 30–60 km to -1.45 around 60–65 km. Shallower than those in the MLT
- ➢ Vertical wavenumber spectra: PSD at vertical wavelengths of ~5–20 km decrease from the winter maximum to the summer minimum
- ➢ First multiple years of GWPED seasonal variations with a summer minimum and a winter maximum in Antarctica
- ➢ GWPED seasonal variations have statistically significant correlations with:
  1. Wind Rotation Angle 2. Tropospheric winds 3. Stratospheric winds 4. Polar Vortex position and strength
- ➢ GWPED seasonal variations : Critical level filtering of GWs from lower atmosphere and in-situ generation of primary waves in winter

We acknowledge Brendan Roberts, Zhangjun Wang, Wentao Huang, John Smith, Chester Gardner, Vladimir Papitashvili, Julie Palais, and Richard Dean for their contributions and supports to the McMurdo lidar campaign. We thank the staff of the United States Antarctic Program, Antarctica New Zealand and Scott Base for their generous supports. This project is supported by the NSF OPP grants ANT-0839091 and PLR-1246405.