Lidar observations of vertical wavelengths, potential energy densities, and frequency spectra of stratospheric gravity waves from 2011 to 2015 at McMurdo (77.8º S, 166.7º E), Antarctica

Jian Zhao[1], Xinzhao Chu[1], Cao Chen[1], Xian Lu[1], Weichun Fong[1], Zhibin Yu[1], Adrian McDonald[2], Andreas Dörnbrack[3]

[1]CIRES & Aerospace, University of Colorado Boulder, USA, [2]University of Canterbury, New Zealand, [3]DLR, Institut für Physik der Atmosphäre, Germany

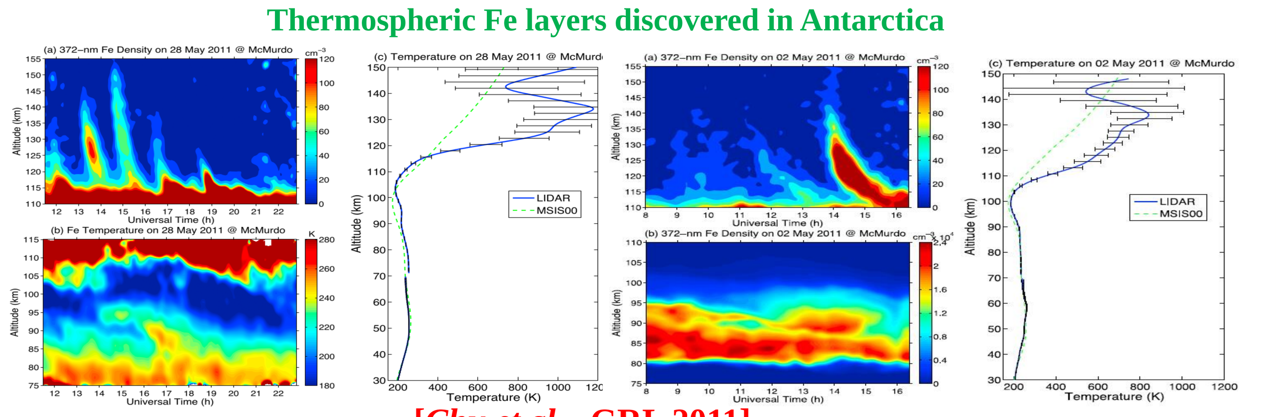
1. Abstract

Five years of atmospheric temperature data have been accumulated since University of Colorado Boulder lidar group deployed an Fe Boltzmann lidar at McMurdo Station, Antarctica. Vertical wavelengths, periods, phase speeds, as well as potential energy densities of gravity waves among stratosphere (from 30 km to 50 km) over the past five years (from 2011 to 2015) are investigated in details. Typical values for gravity wave vertical wavelength and period are ~7.5 km and ~5.5 h, respectively. Monthly variations of vertical wavelength as well as period show a clear seasonal trend with higher values in winter and lower values in summer. Gravity wave potential energy densities (GWPEDs) obtained through temperature perturbations vary significantly from observation to observation, however, they do follow a seasonal trend with a winter maximum and a summer minimum. Efforts were made in order to reveal the mechanisms behind the uncovered signatures of stratospheric gravity waves in this work. Background winds from European Centre for Medium-Range Weather Forecasts (ECMWF) model are analyzed carefully for this specific purpose. The analysis proves that the seasonal change of the background wind from ECWMF considerably supports these variations of gravity wave signatures.

2. Scientific Motivations

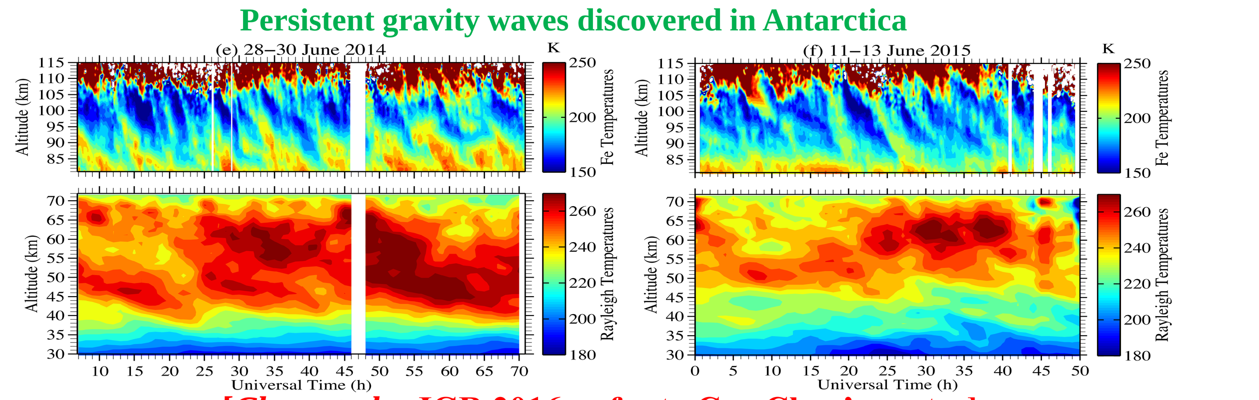
❑ Lidar observations from McMurdo, Antarctica

Thermospheric Fe layers discovered in Antarctica



Case I, May 28, 2011 [Chu et al., GRL 2011] Case II, May 2, 2011

Persistent gravity waves discovered in Antarctica



[Chen et al., JGR 2016, refer to Cao Chen's poster]

- Gravity waves play essential roles in atmospheric dynamics and chemistry
- Gravity waves are crucial to the formation of thermospheric Fe Layers
- 3-10 hours persistent gravity waves in MLT region, downward phase progression
- How are the gravity waves look like in the stratosphere at McMurdo?
- Does gravity waves in the stratosphere have any relations with those in the MLT?

3. Data Analysis

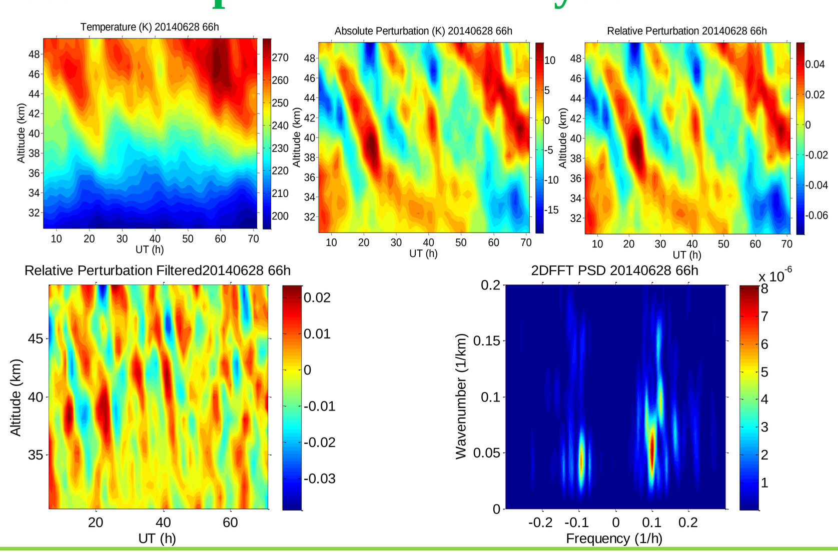
3.1 Statistics on Lidar Observations

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2011	82	85	36	40	59	72	54	67	14	38	148	160	855
2012	108	95	19	26	53	72	21	26	49	98	96	49	712
2013	90	19	49	99	45	71	83	63	47	53	91	81	791
2014	23	41	54	30	126	97	79	34	31	82	50	130	777
2015	61	51	57	52	66	121	104	42	67	48	14	81	764
Total	364	291	215	247	349	433	341	232	208	319	399	501	3899

3.2 Data Analysis Procedures

- Subtract the temporal mean
- Subtract the altitudinal mean
- Absolute perturbation $T'(z,t)$: Apply a high pass filter in time domain at each latitude Filter out waves with periods longer than 11 hours using a sixth order butter-worth filter in frequency domain through 1 Dimensional Fast Fourier Transform and 1 Dimensional Inverse Fast Fourier Transform
- Relative perturbation $T_{Rel}(z,t)$: Absolute perturbation divided by background
- 2 Dimensional Fast Fourier Transform (2DFFT) using relative perturbation $T_{Rel}(z,t)$
- Pick the first three peaks, record wavelengths and periods
- Perform a statistical study on wave characteristics
- Calculate GWPEDs with corresponding errors using relative perturbation $T_{Rel}(z,t)$

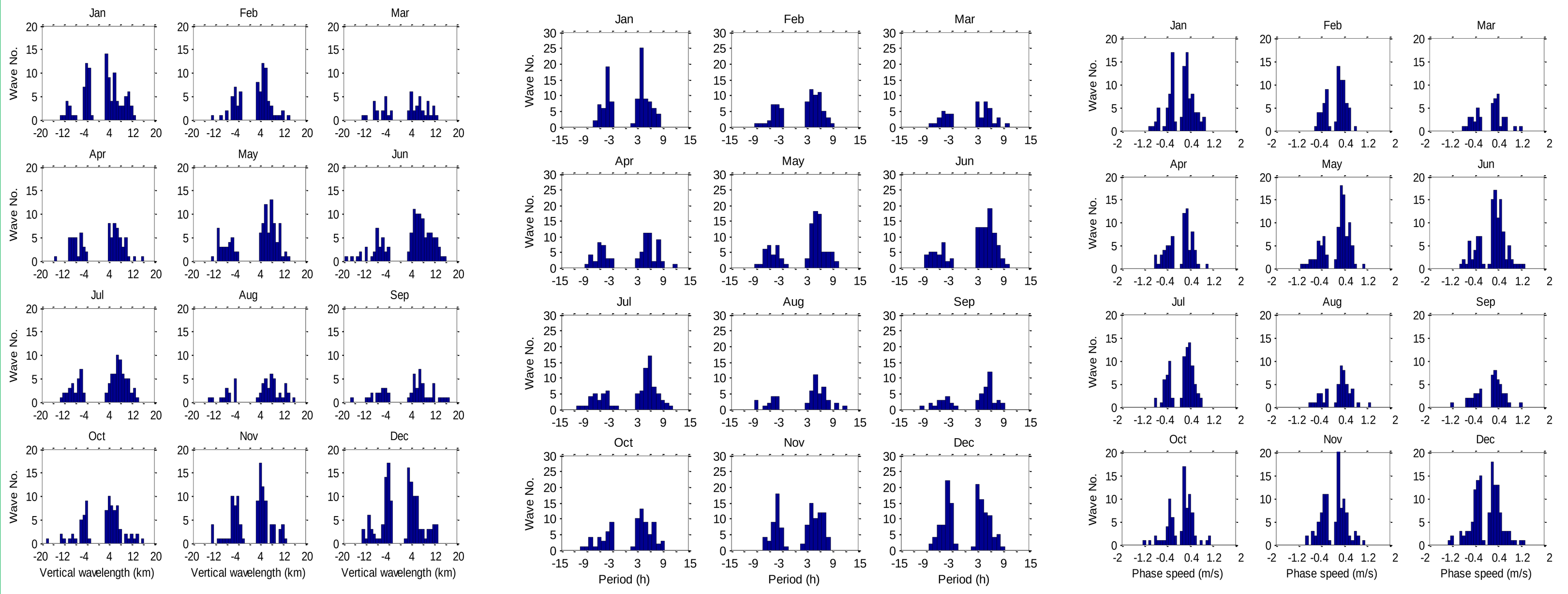
3.3 Example on Data Analysis Procedures

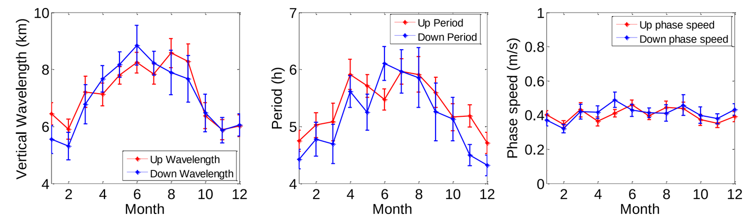


An example of data processing procedures:

- Data resolution 2 hour by 1 km unless stated otherwise
- Observation on 28-30 June 2014
- Wave structures are obvious
- Gravity waves are revealed after high pass filtering
- Gravity wave information can be extracted and recorded from 2DFFT PSD plot
- Relative perturbations are also used to calculate GWPEDs

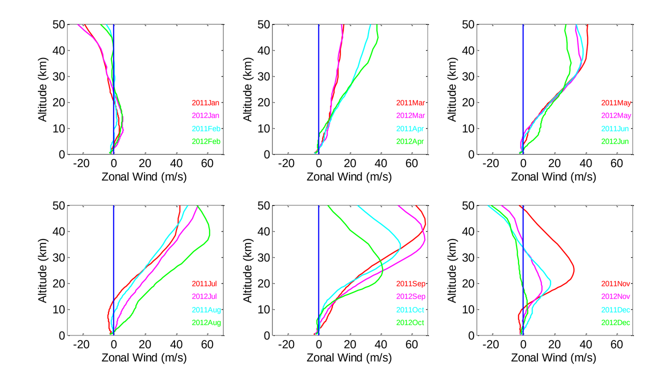
4.1. Vertical Wavelength, Period, Phase Speed



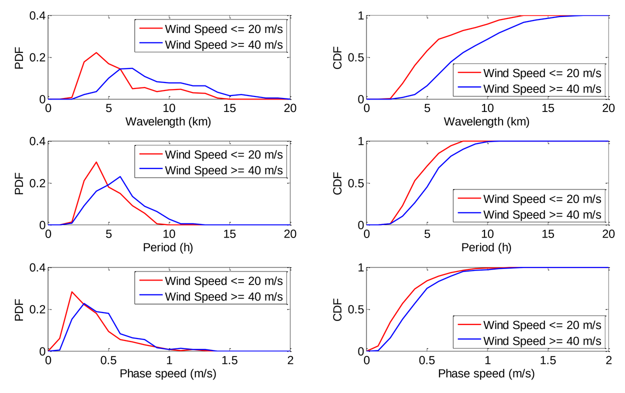


Statistical study
Monthly averaged vertical wavelength: ~ 7.5 km,
Monthly averaged period: ~ 5.5h
Monthly averaged phase speed: ~0.4 m/s
Monthly change in vertical wavelengths is prominent

Monthly mean zonal wind from ECWMF at McMurdo



Background wind ⬆, vertical wavelength ⬆



Vertical wavelength seasonal change — *Whiteway et al., [1997]* — Background wind seasonal change

- Much of the wave spectrum will have small phase speeds (Source: flow over the rough terrain)
- Vertical wavelength ∝ the difference between phase velocity and background wind speed
- A substantial portion of the waves will have vertical wavelengths that are proportional to background wind speed
- wind speed is largest in the westerly jet in winter, gravity waves are Doppler shifted to longer vertical wavelengths

$$\lambda_z = \frac{2\pi}{m} \cong \frac{2\pi}{N}\frac{\omega}{k} = \frac{2\pi}{N}(c - U\cos\theta)$$

c: Wave's horizontal phase speed
U: Background wind speed
θ: Angle between the wind and wave propagation direction
N: Buoyancy frequency

Spring, fall, and winter, waves in stratosphere are likely to propagate against background wind

Intrinsic frequency $\widehat{\omega} = \omega + k\bar{u}$. ω: observed frequency. $k = \frac{2\pi}{\lambda_h}$: zonal wavenumber. λ_h: zonal wavelength. $\bar{u}$: zonal mean wind

The change of $\widehat{\omega}$ from Fall to Winter

$$\Delta\widehat{\omega} = \widehat{\omega}_{Winter} - \widehat{\omega}_{Fall} = \frac{2\pi}{T_{Winter}} - \frac{2\pi}{T_{Fall}} + \frac{2\pi}{\lambda_h}(\bar{u}_{Winter} - \bar{u}_{Fall})$$

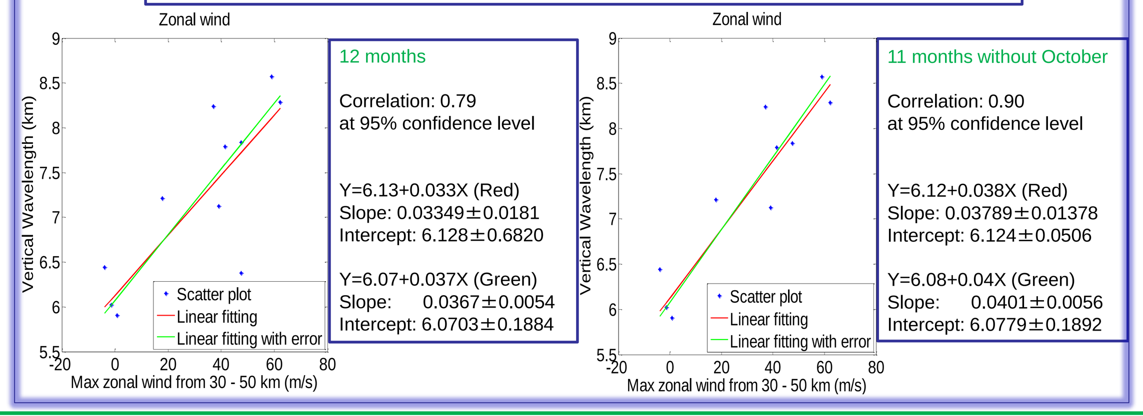
Dispersion relation: $\widehat{\omega} = N\left|\frac{k}{m}\right|$

$$\Delta\widehat{\omega} = \frac{2\pi}{T_{Winter}} - \frac{2\pi}{T_{Fall}} + \frac{2\pi}{\lambda_h}(\bar{u}_{Winter} - \bar{u}_{Fall}) = N\frac{\lambda_z^{Winter} - \lambda_z^{Fall}}{\lambda_h}$$

T_{Fall} = 4.75 h, T_{Winter} = 5.75 h, $\bar{u}_{Fall}$ = 15 m/s, $\bar{u}_{Winter}$ = 40 m/s, N=$\sqrt{5} \times 10^{-2}$ (1/s), and λ_h = 1000 km

$$\Delta\lambda = \lambda_z^{Winter} - \lambda_z^{Fall} = \left(\frac{2\pi\lambda_h}{T_{Winter}} - \frac{2\pi\lambda_h}{T_{Fall}} + 2\pi(\bar{u}_{Winter} - \bar{u}_{Fall})\right)\frac{1}{N} = 4.16\ km$$

Correlation between monthly mean vertical wavelengths and monthly zonal wind maximums from 30 to 50 km



4.2 Gravity Wave Potential Energy Density

Gravity wave potential energy density: $E_p(z) = \frac{1}{2}\frac{g^2}{N(z,t)^2}\overline{\left(\frac{T'_{GW}(z,t)}{T_0(z)}\right)^2}$

N(z, t), buoyancy frequency: $N(z,t)^2 = \frac{g}{T_0(z,t)}\left(\frac{\partial T_0(z,t)}{\partial z} + \frac{g}{C_p}\right)$

$T'_{GW}(z,t)$, gravity wave perturbations: $\overline{[T'_{GW}(z,t)]^2} = \overline{[T'(z,t)]^2} - \overline{[\sigma_T(z,t)]^2}$

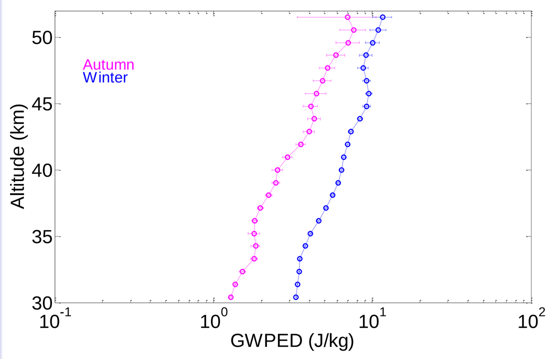
$\overline{[\sigma_T(z,t)]^2}$, noise variance: $\overline{[\sigma_T(z,t)]^2} = N_p^{-1}\sum_{i=1}^{N_p}[\delta T(z,t_i)/T_0(z)]^2$

$\delta E_p(z)$, uncertainty in GWPEDs: $\delta E_p(z) = \frac{1}{2}\frac{g^2}{N(z,t)^2}\left(\frac{\sigma_T(z,t)}{T_0(z)}\right)^2\frac{1}{\sqrt{N_p}}$

$g = 9.7 (m/s^2)$:	Gravitational acceleration
$T_0(z)$:	Monthly mean temperature background
z and t:	Altitude and time, respectively
$C_p = 1004 (J/K/kg)$:	Specific heat at constant pressure
$T'(z,t)$:	Relative perturbation
$\delta T(z,t_i)$:	Uncertainty in temperature profile
N_p:	Number of perturbation profiles

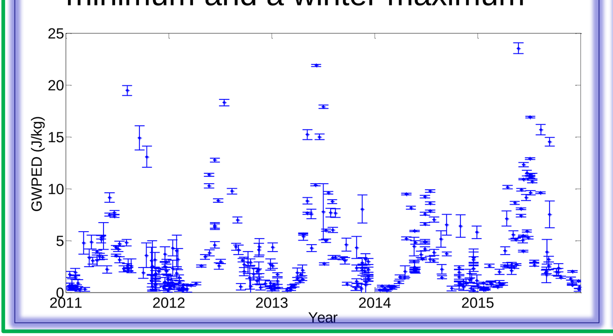
GWPEDs VS. Altitudes

Exponential increase versus altitude

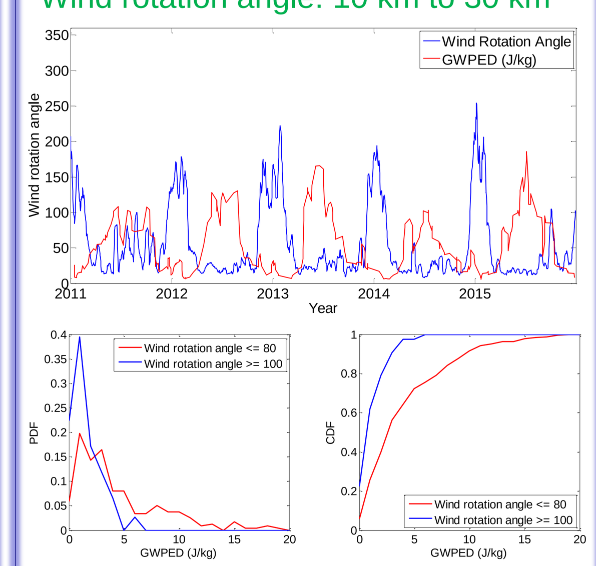


Altitudinal mean from 30 to 50 km

Seasonal trend with a summer minimum and a winter maximum

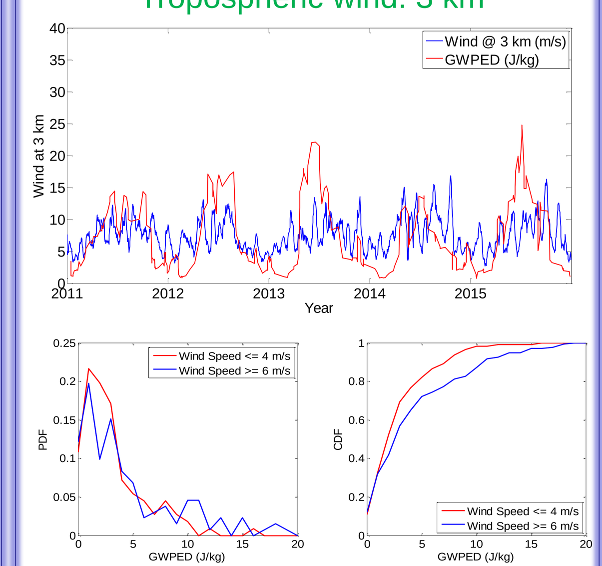


Wind rotation angle: 10 km to 30 km



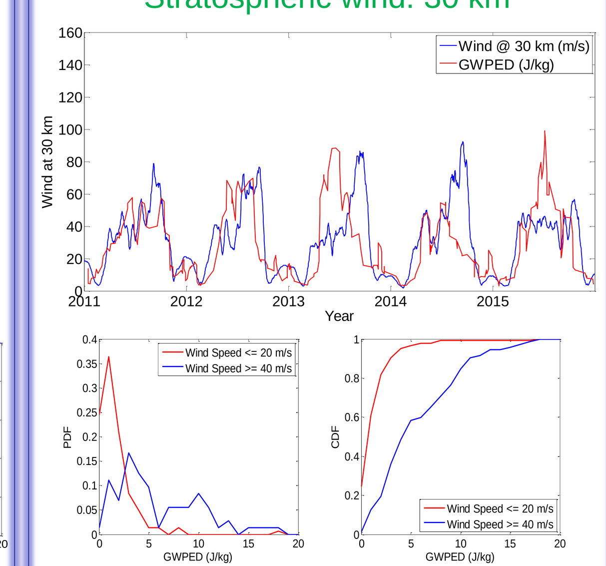
- Wind rotation angle increases, GWPEDs decrease
- Critical layer filtering of upward propagating gravity waves [*Yamashita et al., 2009*]
- Monthly mean correlation: -0.68 at 95% confidence level

Tropospheric wind: 3 km



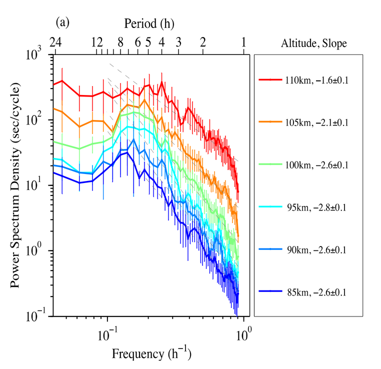
- Tropospheric winds increase, GWPEDs weakly increase
- Tropospheric winds ⟺ Forcing strength of orographic waves
- A week correlation was also found in north polar region *Yoshiki and Sato* [2000]
- Monthly mean correlation : 0.63 at 95% confidence level

Stratospheric wind: 30 km

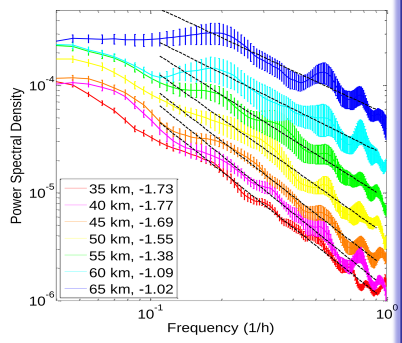


- Stratospheric winds increase, GWPEDs obviously increase
- Elevated levels of gravity wave activities ⟺ Enhancement in the long vertical wavelength portion of the gravity wave spectrum [*Whiteway et al., 1997*]
- Monthly mean correlation : 0.74 at 95% confidence level

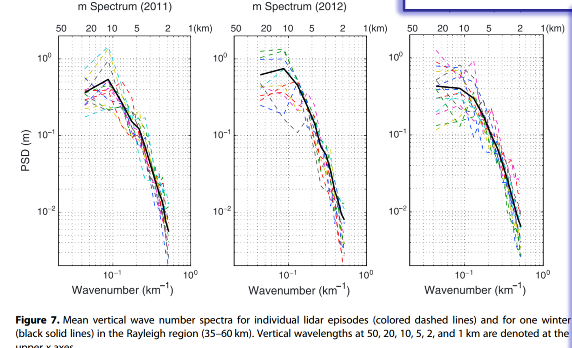
4.3 Gravity Wave Frequency Spectra



[Chen et al., JGR 2016]



- June data from 2011 to 2015 with resolution 0.5 hour by 1 km
- Frequency spectra at different altitudes
- Slopes: 1.6-1.8 from 30 km to 50 km, close to ~1.7 [*Hostetler and Gardner, 1994*]
- Slopes shallower around 60 km: Gravity waves with higher frequencies are less susceptible to dissipation than those with lower frequencies, presuming waves have similar vertical wavelengths [*Vadas, 2005, 2007*]
- Slopes among 30-50 km do not change as much as they do around 60 km, a potential wave source exists among 30 - 50 km?
- Slopes in stratosphere are much smaller than those in MLT region (-2.6 to -1.6 from 85 to 110 km at McMurdo [*Chen et al., 2016*]). What's happening between 65-85 km? Wave sources?



[Lu et al., JGR 2015]

- Vertical wavenumber spectrum was studies by *Lu et al.* [2015]
- Exhibit power law forms for vertical wavelengths λ_z< ~10 km
- Mean spectral slopes (2–10 km) are about -2.55± 0.36 and -2.26 ± 0.38 in the Rayleigh and Fe regions
- Large variations in the power spectral densities are seen for λ_z > 10 km in 35–60 km

5. Conclusions

- A major finding: Mean vertical wavelengths from 30-50 km exhibit seasonal variations with maximum values in late winter and early spring at McMurdo, and their correlation with maximum stratospheric zonal winds is statistically significant.
- This finding can be explained by: The formation of polar vortex in winter ➡ Stronger stratospheric winds from 30 to 50 km ➡ Most of gravity waves that can reach stratosphere from lower altitudes are propagating against background wind ➡ Vertical wavelengths increases with increasing stratospheric winds due to gravity wave dispersion relation.
- GWPEDs seasonal trend with a summer minimum and a winter maximum is revealed through this statistical study.
- This seasonal variations have statistically significant correlations with: 1. Wind rotation angle – Critical layer filtering 2. Tropospheric winds – Forcing strength of orographic waves 3. Stratospheric winds – Enhancement in the long vertical wavelength portion of the gravity wave spectrum
- First investigation of frequency spectra in the upper stratosphere at Antarctica to search for more or new wave sources. The changes of frequency spectra slopes could possibly indicate the existence of wave sources. Wave source could potentially exist nearby the regions where these slopes remain relative constant, which is around 40 km in this study.

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