Vertical Coupling of Traveling Planetary Waves from the Stratosphere to the Lower Thermosphere in Antarctica

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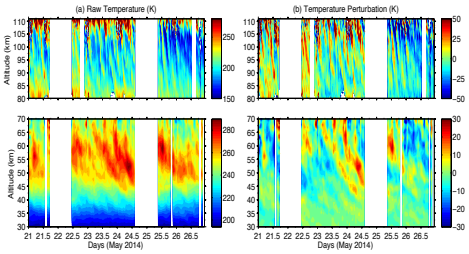
Abstract It is well known that the eastward propagating planetary waves (PWs) persistent and strong in the winter Antarctic in the stratosphere are generated by the instability of the polar night jet. But it is less studied that whether and how they reach in the mesosphere and lower thermosphere (MLT). The lidar-measured temperatures at McMurdo, Antarctica (77.8°S) have shown the planetary wave (PW) signatures from 30 to 110km, and the dominant components are 4-day E1, 5-day E1, 2.5-Day E2 and 1.7-day E3. The SD-WACCM captures the global structure of these eastward traveling PWs and are therefore used for the diagnosis of the wave-induced EP fluxes. In addition to the stratospheric source region (~40 km), another positive EP flux divergence is found in the mesosphere and coincides with shear instability. A linear quasi-geostrophic (QG) model well simulates the wave generation in the stratosphere due to instability and the main wave patterns. The model shows that although the PWs dissipate due to the critical level filtering near 80 km, they can survive through the filtering and penetrate upward. The mean backgrounds in the QG model also have instabilities in both the stratosphere and MLT, implying that the local instability in the MLT may be the reason for the waves to survive and re-amplify after the critical level filtering. The relative contribution from the in-situ generation or amplification due to the instability versus the direct vertical wave propagation needs further investigations.

1. Observations

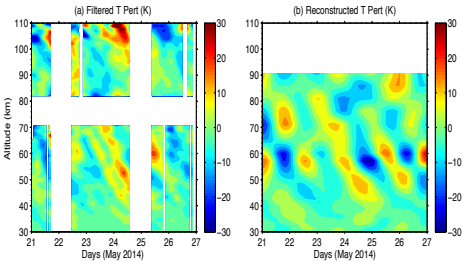
1.1 Six-Day Continuous Observation of Temperature at McMurdo

Temperature (left) and Perturbations (right) at McMurdo



Filtered T Perturbation at McMurdo

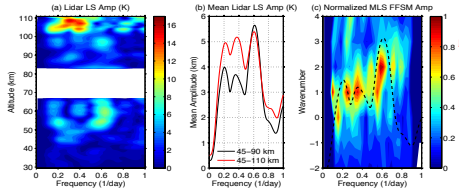
MLS Reconstruction Using Major PW Components



- The PW signatures with periods of several days are prominent.
- After the strong inertia-gravity waves (IGWs) are filtered out, PWs become more obvious in both the stratosphere and MLT region.
- Reconstruction using the major PWs retrieved from MLS temperatures reasonably capture the local T variability.
- Such planetary waves tend to become stronger above 100 km, which is not covered by satellite data.

1.2 Wave Spectra and Global Distribution

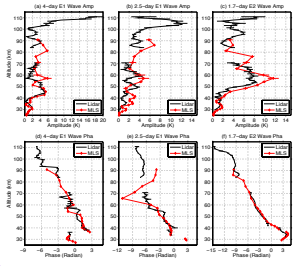
LS Spectra at McMurdo **MLS Spectra**



(Left) Lomb-Scargle (LS) amplitude spectra in lidar temperature (Middle) Vertically averaged LS amplitude spectra in the range of 45–90 km (black line) and 45–110 km (red line) from lidar. (Right) Vertically averaged FFSM amplitude spectra in the range of 45–90 km for a latitude of 77.5° S from MLS.

- The dominant waves from MLS are 4-day E1, 5-day E1, 2.5-Day E2 and 1.7-day E3.
- These planetary waves are highly confined to winter high latitudes and McMurdo is an ideal location to observe them.
- Global structure is similar to the eastward propagating waves with periods of 1.25-5 days in *Lu et al.* [2013], implying that they are generated by barotropic/baroclinic instability of polar vortex.

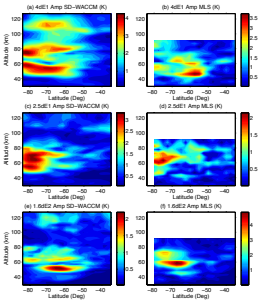
1.3 Wave Amplitudes and Phases at McMurdo



- For both 5- and 2.5-day waves, amplitudes reach minima at ~55 km and increase again.
- In the MLT region, the magnitudes increase with altitude.
- Source region is likely near 40 km. Above it, the wave phases show upward propagating characteristics.

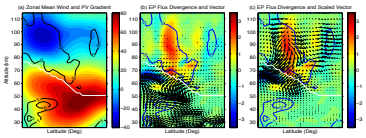
2. SD-WACCM Simulation

2.1 Global Structure



- SD-WACCM simulates the global structure of the amplitudes of the eastward propagating planetary waves.
- 1.6-day is underestimated likely due to the insufficient resolution.
- There are non-negligible wave responses above 100 km.

2.2 EP Flux and Instability



(Left) Zonal mean zonal wind and meridional gradient of the potential vorticity. (b) and (c) are EP fluxes and scaled EP Fluxes.

- The strong positive EP flux divergence induced by PWs exists in the stratosphere, where the PWs are generated by the instability of the polar night jet.
- Another strong unstable region caused by the mesospheric wind shear is found above 70 km, where the positive flux divergence is also found.

3. Quasi-Geostrophic Model Simulating PW Generation and Coupling

3.1 Basic Equation

We start from the vorticity equation of the QG model [*Hartmann*, 1979]:

$$\left(\frac{\partial}{\partial t}+\frac{\bar{u}}{a\cos\phi}\right)\left[\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\Phi'}{\partial\phi}\right)+\frac{1}{\sin^2\phi\cos^2\phi}\frac{\partial^2\Phi'}{\partial\lambda^2}+(2\Omega a)^2\frac{1}{\rho}\frac{\partial}{\partial z}\left(\frac{\rho}{N^2}\frac{\partial\Phi'}{\partial z}\right)\right]+$$

$$\frac{1}{\cos\phi\sin^2\phi}\frac{\partial\bar{q}}{\partial\phi}\frac{\partial\Phi'}{\partial\lambda}=-(2\Omega a)^2\frac{1}{\rho}\frac{\partial}{\partial z}\left(\frac{a\rho}{N^2}\frac{\partial\Phi'}{\partial z}\right)$$

$$\Phi'=\psi(\phi,z,t)\exp(z/2H+im\lambda)$$

is geopotential having a wave form along longitude.

$$\frac{\partial\bar{q}}{\partial\phi}=2\Omega\cos\phi-\frac{\partial}{\partial\phi}\left[\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\bar{u}\cos\phi}{a}\right)\right]-(2\Omega\sin\phi)^2\frac{a}{\rho}\frac{\partial}{\partial z}\left(\frac{\rho}{N^2}\frac{\partial\bar{u}}{\partial z}\right)$$

is vorticity gradient.

3.2 Finite-Difference Scheme

We use time-centered semi-implicit scheme in the time domain and in the spatial domain, the second derivatives which involve five grid points are:

$$\frac{\partial^2\psi}{\partial\phi^2}=\frac{\psi_{i,j+1}-2\psi_{i,j}+\psi_{i,j-1}}{\Delta\phi^2},\ \frac{\partial^2\psi}{\partial z^2}=\frac{\psi_{i+1,j}-2\psi_{i,j}+\psi_{i-1,j}}{\Delta z^2}$$

$$\frac{\partial\psi}{\partial\phi}=\frac{\psi_{i,j+1}-\psi_{i,j-1}}{2\Delta\phi},\ \frac{\partial\psi}{\partial z}=\frac{\psi_{i+1,j}-\psi_{i-1,j}}{2\Delta z}$$

we use the matrix method to solve the equation at the l +1 step:

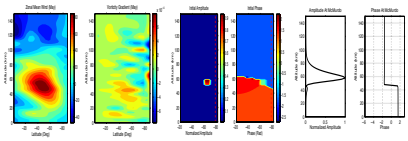
$$A\left(\psi_{1,1}^{l+1},\psi_{2,1}^{l+1},\ldots,\psi_{n,1}^{l+1},\psi_{1,j}^{l+1},\psi_{2,j}^{l+1},\ldots,\psi_{n,j}^{l+1},\psi_{1,m}^{l+1},\psi_{2,m}^{l+1},\ldots,\psi_{n,m}^{l+1}\right)'=$$

$$\left(Y_{1,1}^{l+1},Y_{2,1}^{l+1},\ldots,Y_{n,1}^{l+1},Y_{1,j}^{l+1},Y_{2,j}^{l+1},\ldots,Y_{n,j}^{l+1},Y_{1,m}^{l+1},Y_{2,m}^{l+1},\ldots,Y_{n,m}^{l+1}\right)$$

The coefficient matrix has a dimension of (n×m, n×m), and the Y matrix has a dimention of (n×m, 1) which is related to the geopotential at both l and l-1 steps. The time step is 1.5 h, the latitude and vertical resolution are 5 degree and 2 km, respectively.

3.3 Background and Initial Condition

The mean zonal wind is obtained from the HWM07 model, which shows a strong eastward jet at -50° around 50 km. Initial condition is given as a small perturbation.

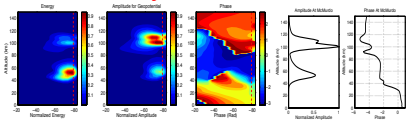


- The negative potential vorticity gradient highlights the unstable regions, which are prevalent in both the stratosphere and MLT region at high latitudes.
- Phase speed of the PWs is ~20 m/s, corresponding to an altitude of ~90 km.
- The initial disturbance has to be placed in the region with instability in order to generate PWs.

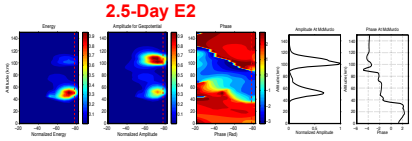
3.4. Model Results

Global Structure **Wave at McMurdo**

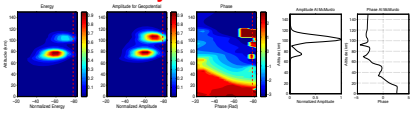
4-Day E1



2.5-Day E2



1.3-Day E3



- The model **Does** capture: 1) excited Periods and Wavenumber; 2) overall global structure; 3) local maximum around 50 km and local minimum near 90 km; 4) reasonable phases.
- The model **Doesn't** capture: 1) exact amplitudes and vertical wavelengths;
- Rayleigh friction and GW parameterization are needed to be incorporated in order to better simulate MLT region.

4. Conclusions and Discussion

- Six-day nearly continuous temperature observations at McMurdo, Antarctica enable us to observe the planetary waves with dominant periods of 5-, 2.5- and 1.7 days. Utilizing the MLS temperatures, it is found that the major wave components are likely 4-day E1, 5-day E1, 2.5-Day E2 and 1.7-day E3.
- Such PWs can penetrate to the MLT region with non-negligible amplitudes and cause temperature perturbation of ±25 K. They often suffer dissipations around 60 and 90 km, before they continue upward. According to the QG model simulation, amplitude decreases around 90 km are likely associated with the critical level filtering where zonal mean winds become weak eastward and approach the phase speed of the PWs.
- The SD-WACCM well simulates the global structure of the waves. It highlights two major unstable regions which also coincides with the positive EP flux divergences induced by the PWs. It implies that the PWs found in the MLT region may be amplified or generated in-situ by the local instability caused by the mesospheric wind shears.
- The discrepancy of the vertical wavelength between simulation and observation may imply that the GW effects especially those from the strong inertia-GWs on PWs should be considered in the QG model.
- The future work needs to consider both dissipation effects in the MLT region and the in-situ generation of PWs. The relative contribution of the in-situ generation/amplification, GW effects, and vertical propagating will be studied.

References:

*Lu, X. et al (2013), Eastward propagating planetary waves with periods of 1–5 days in the winter Antarctic stratosphere as revealed by MERRA and lidar, JGR, **118**, 9565–9578.*

*Hartmann, D., (1979), Baroclinic Instability of Realistic Zonal-Mean States to Planetary Waves1. J. Atmos. Sci., **36**, 2336–2349.*

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