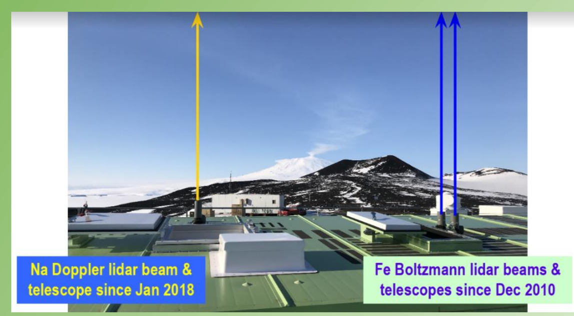
Lidar Investigation of Gravity Waves Potential Energy Density from the Stratosphere to the Thermosphere above McMurdo (77.84 °S, 166.67 °E), Antarctica, and Possible Link to Equatorial QBO



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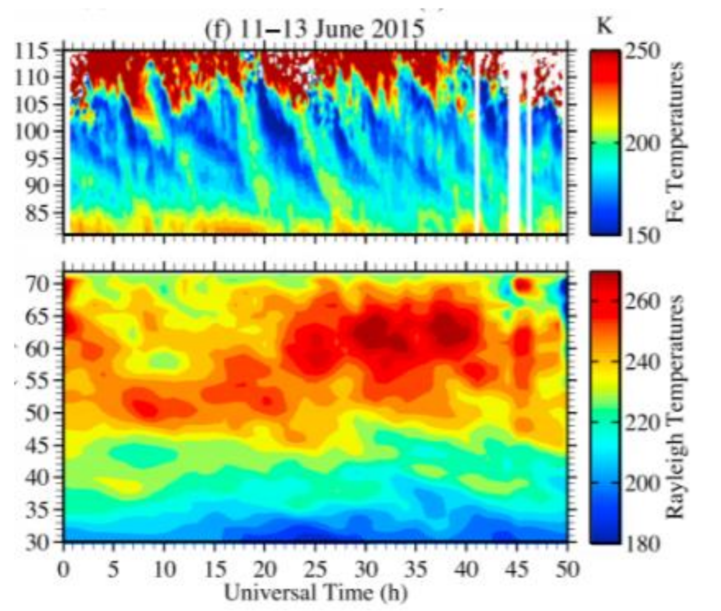
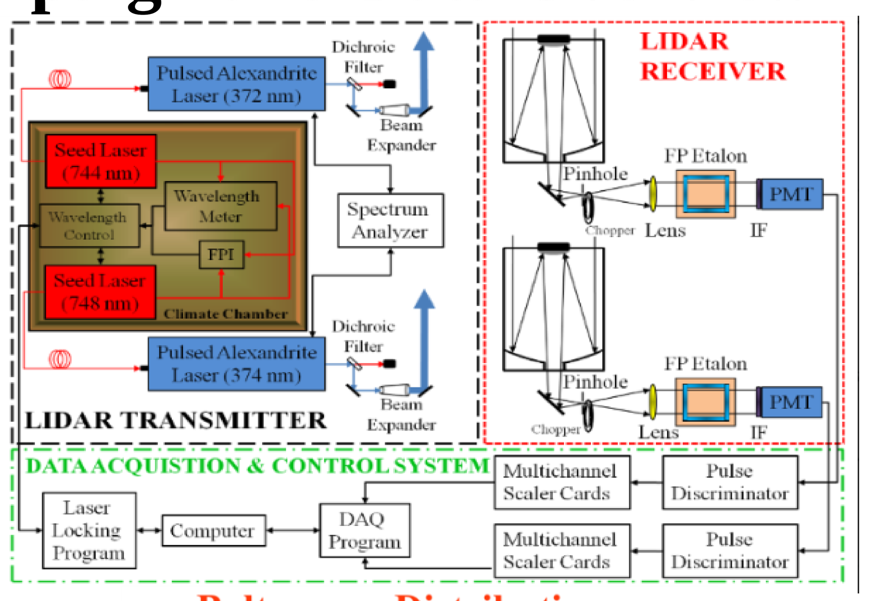
Abstract

It is known that gravity waves play an important role in the middle and upper atmosphere environment since the seminal work by Hines [1960]. Since then, gravity waves have been recognized for their dominant contributions to the residual circulation and thermal structure of the mesosphere and lower thermosphere region. It may even affect global climate change and possibly influence the satellite drag. The vertical evolution of the potential energy mass density is an important indicator of the wave dissipations. This knowledge can help evaluate the gravity wave influences and may help us to demonstrate the generation of the secondary gravity waves. An Fe Boltzmann lidar installed at McMurdo (77.84 °S, 166.67 °E), Antarctica has been observing gravity wave signatures since Dec 2010. Chen et al. [2016] described the discovery of persistent gravity waves in the MLT region that the persistent and large-amplitude waves with 3-10 hours periods and vertical wavelengths ~20-30 km are the dominant waves in MLT region. Following this discovery, Zhao et al. [2017] and Chu et al. [2018] traced the waves to the stratosphere and analyzed the wave features and potential energy density from 30 to 50 km over the five years from 2011 through 2015. In addition, Lu et al. [2015] analyzed three years of winter month data and showed the potential energy density without noise subtractions varying considerably from the stratosphere to the MLT. In this study, the potential energy mass density is calculated using the spectral proportion method to overcome the negative Epm issues at certain dates and altitudes. Comparing the altitude mean Epm in the MLT region, the stratosphere, and the QBO, there are some correlations between them. Since at local minimum of QBO, the altitude mean Epm is the local maximum in the Stratosphere and the local minimum in the MLT region.

1. McMurdo Lidar Campaign and Data Overview





Boltzmann Distribution

$$\frac{P_2(J=3)}{P_1(J=4)} = \frac{\rho_{Fe(374)}}{\rho_{Fe(372)}} = \frac{g_2}{g_1}\exp(-\Delta E/k_B T)$$

A lidar campaign ongoing at McMurdo (77.84°S, 166.67°E), Antarctica has been provided 9 years of high-resolution temperature data from 30 to 115 km. The Fe Boltzmann lidar measures iron (Fe) layers, atmos. density, aerosol layers, and temperatures [Chu et al., 2011; Chen et al., 2016].

Six years of Fe Boltzmann lidar's Fe temperature data from 2011 to 2016 at McMurdo are used to characterize gravity wave potential energy mass density (Epm) in the MLT region 80-110km. The resonance lidar measures the temperature of atmospheric iron with a vertical resolution of 0.5 km and a temporal resolution of 0.25 h. In order to analyze the spectral proportion of gravity waves, the vertical resolution and the temporal resolution is reduced to 0.5 km and 0.5 h. According to the method in Zhao et al. [2017], the observations with duration less than 6 h are ignored, and the observations with durations greater than 12 h are divided into 6-12 h segments.

	Total Time[H]	May[H]	June[H]	July[H]	August[H]
All 2011 2016	1906	475	604	470	357
Used 2011 2016	1311.7	260.2	454.6	388.5	208.4
All 2011	259	61	75	49	74
Used 2011	186.6	39.2	59	43.7	44.2
All 2012	228	58	88	32	50
Used 2012	150.2	45.8	62.8	17.8	23.8
All 2013	317	64	88	91	74
Used 2013	226	31.2	66.3	72.1	56.4
All 2014	397	147	147	78	25
Used 2014	324.7	103.3	136.9	67.9	16.6
All 2015	362	55	115	102	90
Used 2015	265.2	29.3	93.4	85.1	57.4
All 2016	343	90	91	118	44
Used 2016	159	11.4	35.7	101.9	10

Table.1 Statistics on observational Segment from 2011 to 2016 Employed in this study

Over the six years, around 2000 hours of data were collected in Antarctica winter but the data collection was mainly dictated by weather conditions. After data screening and division process as described in Chu et al.[2018], the actual total data used in this study is 1906 hours. All the data segments used in this study are between 6 to 12 hours in duration. Using this method to segment the data enriches sufficient statistical samples while presenting the persistent gravity waves with periods of 3-10 hours in MLT above McMurdo.

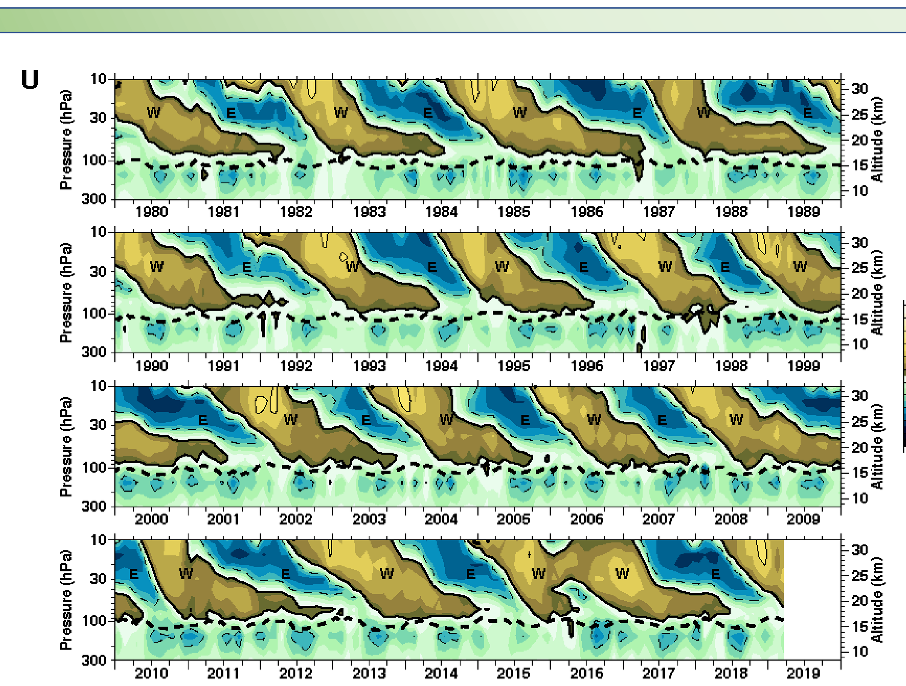


Fig.11 Zonal wind measurements from Singapore

The QBO (Quasi-Biennial Oscillation) is an equatorial phenomenon that dominates the variability of the equatorial stratosphere (~16-50 km) and is easily seen as downward propagating easterly and westerly wind regimes. It has an average period of ~28 months, but its period is variable by more than a year between the shortest and longest QBO periods. However, as shown in Fig.11, after 2007, the period of QBO changes to be 3 years and it corresponds to the interannual changes of Epm in the stratosphere.

2. Data Analysis Procedures

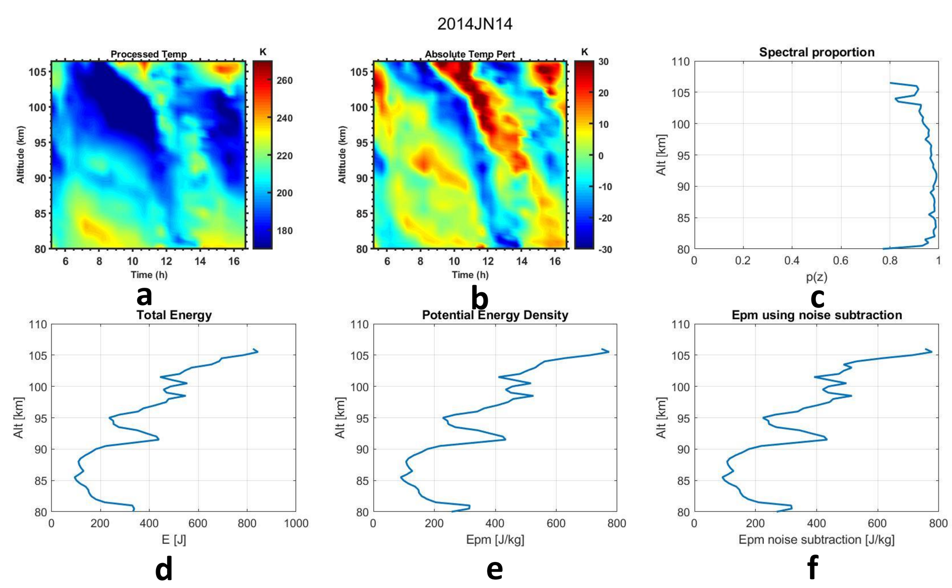


Fig.1 Data Analysis Procedure. (a) is processed temperature with filling gaps. (b) is the absolute temperature perturbations derived from (a). (c) is the gravity wave spectral proportion derived from (b). (d) is the total energy calculated from equation on the right. (e) is the Epm using spectral proportion method and (f) is the Epm using noise subtraction method.

- Procedure to derive temp perturbations following Chen et al. [2016]
  - Subtracting the temporal background $T_0(z)$ to remove the DC term and long-period waves like planetary waves in the frequency spectra.

    $$T'(z,t) = T(z,t) - T_0(z)$$

  - Apply a **sixth-order Butterworth high-pass filter** with a cutoff frequency of $\frac{1}{12}\ h^{-1}$
- Procedure to derive the gravity wave spectral proportion following Chu et al. [2018]
  - Construct **1,000 sets of 2-D temperature map with Gaussian white noise** added to the lidar-measured raw temperature
  - Run each of so constructed 2-D temperature to **obtain the filtered temperature perturbation fields.**
  - Calculate **1-D FFT power spectra** for each time series of the 1000 filtered temperature perturbations at each altitude
  - Take the mean of these 1000 spectra of 1-D FFT to **estimate the spectral noise floor**.
  - Integrate the power spectral density above and below the spectral noise floor to **obtain the wave and noise areas**.
  - Derive the **gravity wave spectral proportion** as

$$p(z) = \frac{Wave\ Area\ in\ PSD}{Wave\ area + Noise\ area\ in\ PSD}$$

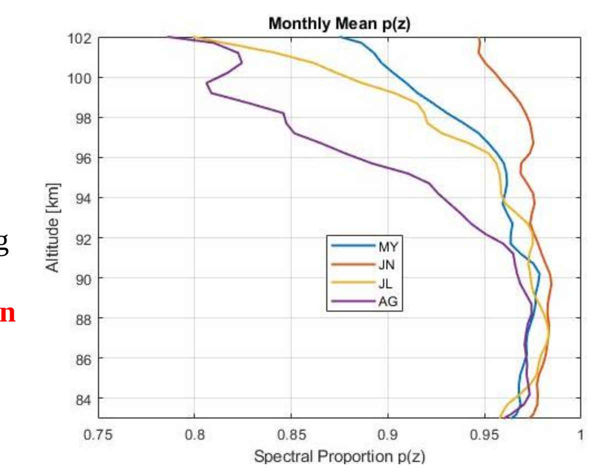


Fig.2 Monthly Mean p(z)

P(z) varies only between 0 and 1 so that the derived Epm will never be negative. Thus it overcomes the issues associated with the noise variance subtraction method.

- Equations for Total energy, Epm using spectral proportion method and Epm using noise subtraction method
  - Equations for total energy

    $$Epm(z) = \frac{1}{2}\frac{g^2}{N^2(z)}\frac{1}{N_p}\sum_{i=1}^{N_p}\left(\frac{T'_{GW}(Z,t)}{T_{bkg}(z)}\right)^2$$

  - Equations of Epm

    $$Epm(z) = \frac{1}{2}\frac{g^2}{\overline{N^2(z)}}\frac{1}{N_p}\sum_{i=1}^{N_p}\left(\frac{T'_{GW}(Z,t)}{T_{bkg}(z)}\right)^2$$

  - The main difference between Epm using spectral proportion method and noise subtraction method is the way to calculate the temperature perturbations induced by gravity waves.
- **T' using spectral proportion**

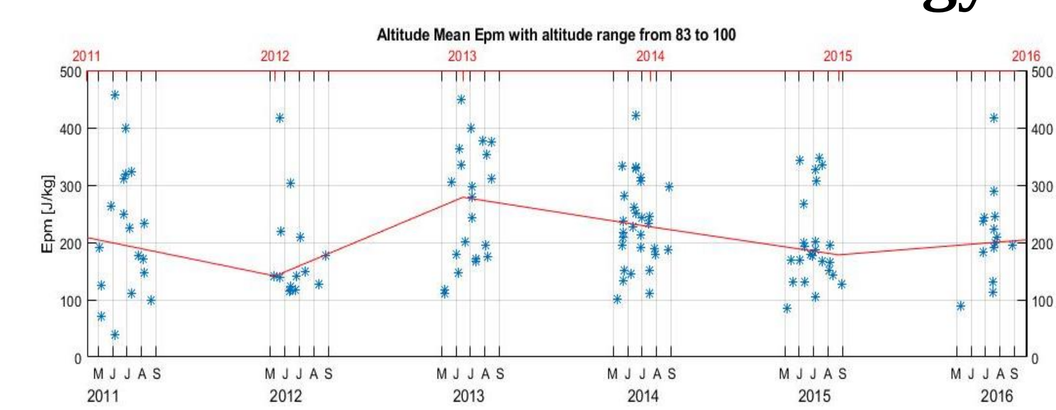
  $$\overline{[T'_{GW}(z,t)]^2} = \overline{[T'(z,t)]^2} * p(z)$$

- **T' using Noise Subtraction method**

  $$\overline{[T'_{GW}(z,t)]^2} = \overline{[T'(z,t)]^2} - \overline{[\boldsymbol{\sigma}_T(z,t)]^2}$$

  $$\overline{[\boldsymbol{\sigma}_T(z,t)]^2} = \frac{1}{N_p}\sum_{i=1}^{N_p}[\delta T(z,t_i)]^2$$

4. Altitude Mean Potential Energy Mass Density



MLT Region (80-102km)

Fig.7 Altitude Mean Epm from 83 to 100km in 2011 to 2016. The blue asterisks denote the actual Epm observation from 83 to 100km and the red line is the median of the altitude mean Epm in each ear.

Stratosphere (30-50km)

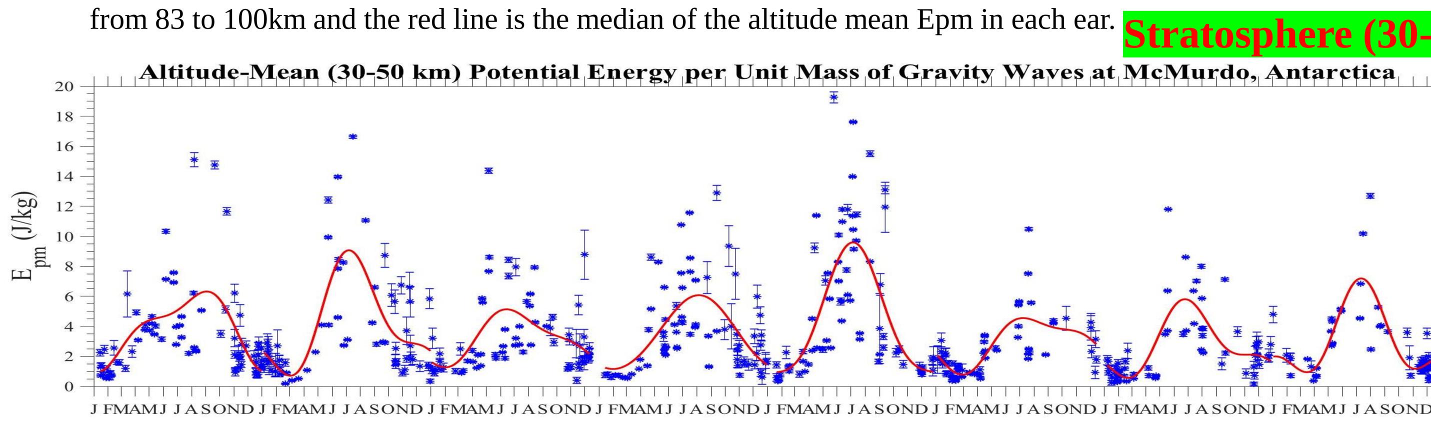


Fig.8 Altitude Mean Epm from 30 to 50km in 2011 to 2018 from Zimu. The blue asterisks denote the actual Epm observation from 83 to 100km and the red lines are overall annual + semiannual fits for 8 years.

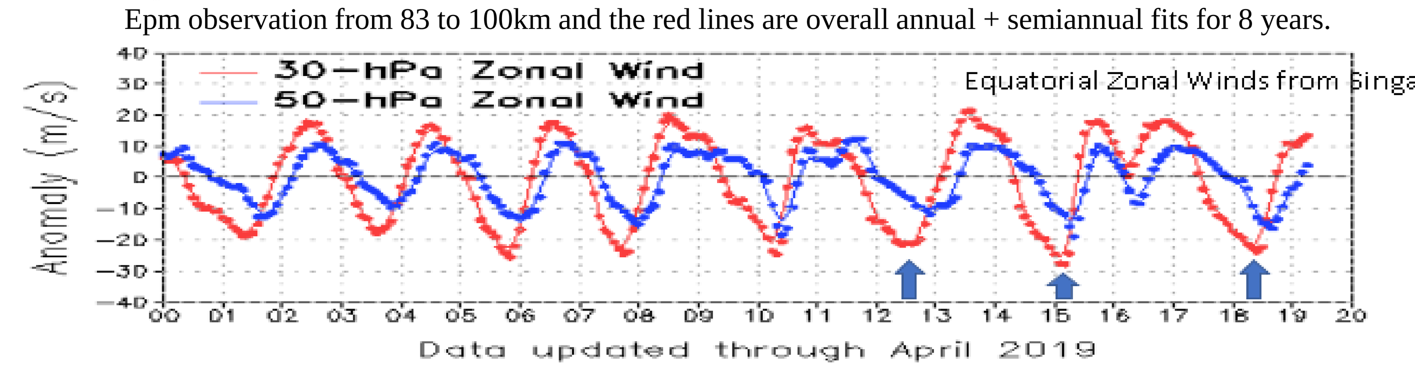


Fig.9 Equatorial Zonal Winds from Singapore

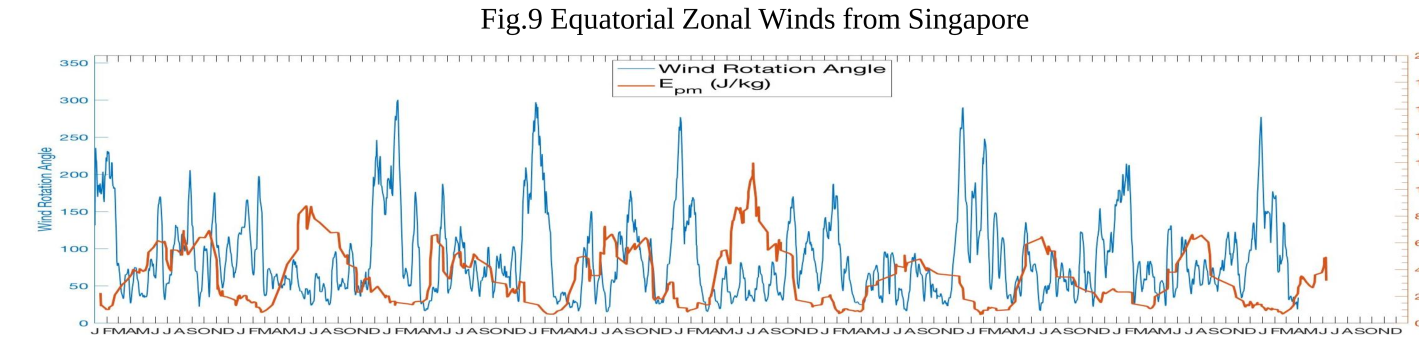


Fig.10 Wind rotation angle from 11-30 km

As shown in Fig.7, the local minimum of the median of altitude mean Epm is in 2012 and 2015. The highest is in 2013 and the lowest is in 2012. In Fig.8, there are relatively two high peaks at 2012 and 2015 and other peaks are all lower than those two. The periods are around three years. In Fig.9, the local minimum of zonal wind is at 2012, 2015 and 2018 which corresponds to the local maximum of the altitude mean Epm in the stratosphere and the local minimum in the MLT region. Fig.10 explains that if the wind rotation angle is too strong, then the wind will kill out the majority of the large amplitude gravity waves in the stratosphere but the gravity waves with small amplitudes and large vertical wavelengths may survive and propagate to the MLT region causing the opposite trends for the altitude mean Epm in stratosphere and MLT. Therefore, there might be a correlation between altitude mean Epm and the equatorial QBO.

3. Monthly Mean Epm Profiles

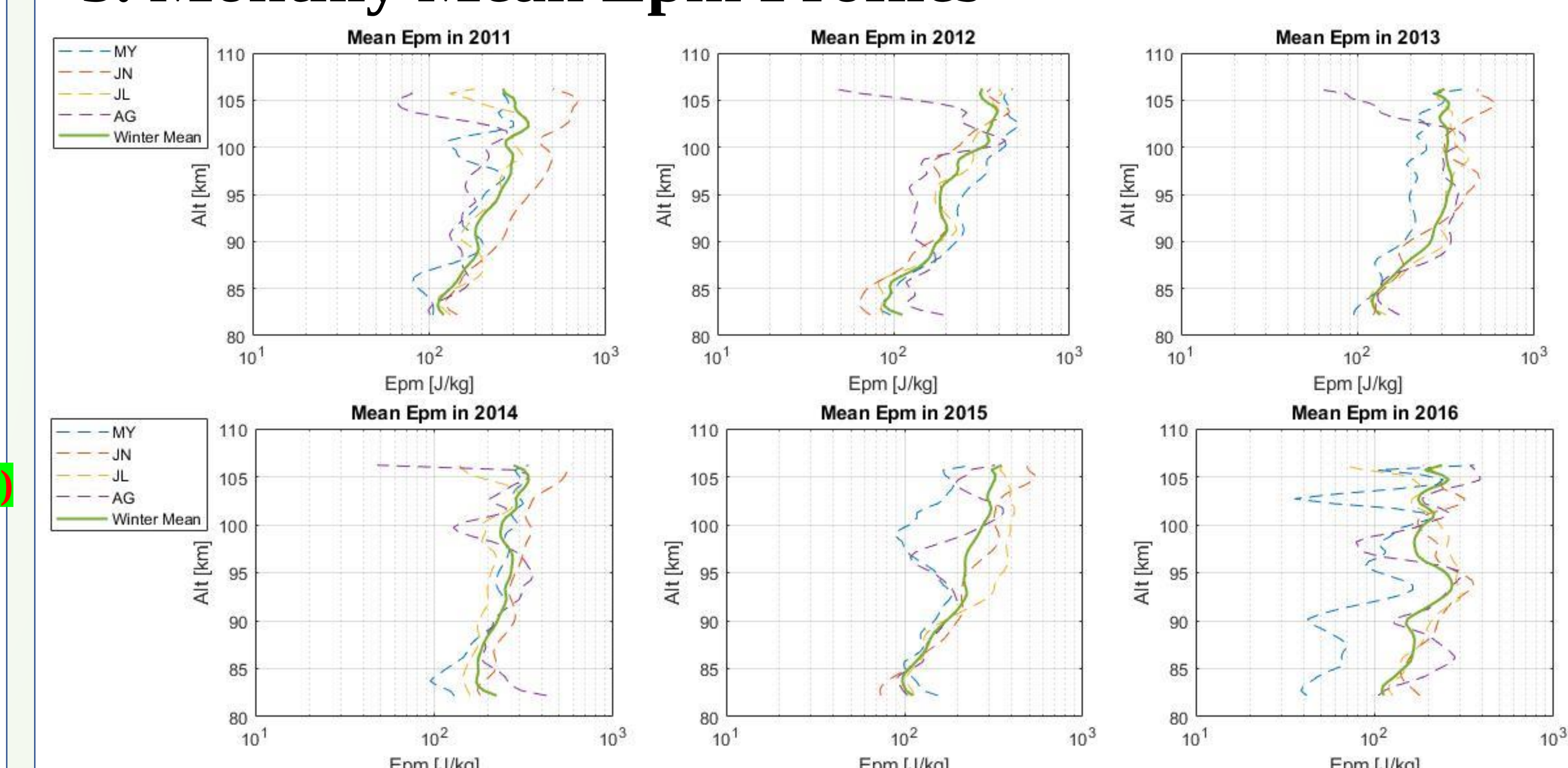


Fig.3 Monthly Mean Epm from 2011 to 2016

In most of the years, Epm profiles in mid-winter in Antarctica like June and July are highest than other months. But in 2012, Epm profile in May is highest because the majority of data is collected in late May which is close to June and the data is even better than some of them in June.

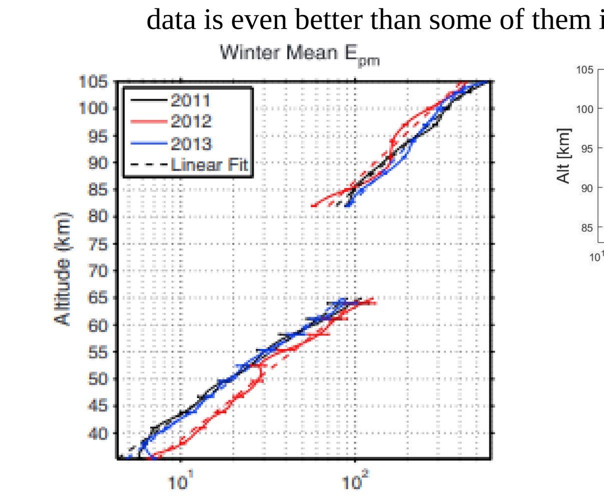


Fig.4 Winter Mean total energy by Lu et al.[2015]

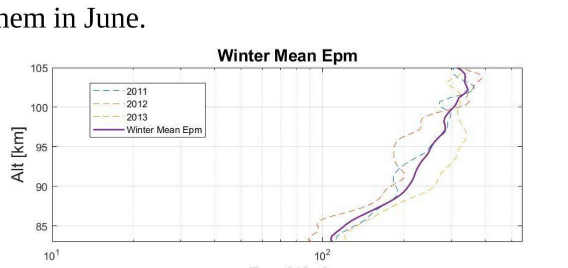


Fig.5 Winter Mean Epm from 2011 to 2013

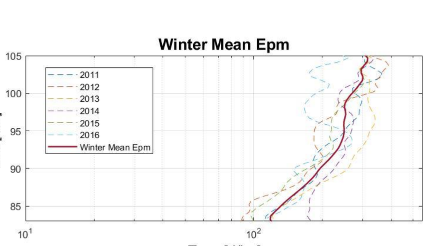


Fig.6 Winter Mean Epm from 2011 to 2016

Fig 4 and 5 are comparable but the winter mean Epm using spectral proportion in Fig.5 is lower than that in Fig.4 because Xian didn't subtract the noise. Fig.6 is the winter mean Epm over 6 years using spectral proportion method is close to Fig.5 but a littler lower because of the three more years of data.

Conclusion and Future Work

Nine years of data in the stratosphere exhibits the interannual change of Epm with a period of about 3 years. The Epm in 2012, 2015 and 2018 in the stratosphere are higher than the other years, but the Epm in 2012 and 2015 in the MLT region are lower than the other years with a period of 3 years. It indicates the signatures of the easterly phase (negative zonal wind) at 30 hPa zonal wind. As shown in Fig.9, the period of the QBO easterly phase zonal wind seems to have expanded from 2 years to 3 years now which corresponds to the interannual change of the Epm. The Epm profiles in the MLT region is higher in June than the other months. The winter mean Epm also increases exponentially from around 100 J/kg to 260-400 J/kg in Fe region (83-105km). This study has also successfully implemented the spectral proportion method to derive the pure gravity wave potential energy density to overcome the negative Epm issues happened in the noise subtraction method.

In the future, the mechanics of the relationship between the QBO and the gravity wave potential energy density still needs to be explored. More years of data is needed to confirm the relationship and the signatures of the QBO.