

# Long-term Lidar Observations of the Gravity Wave Activity near the Mesopause at Arecibo

Xianchang Yue<sup>1,2</sup>, Jonathan S. Friedman<sup>4</sup>, Qihou Zhou<sup>5</sup>, Xiongbin Wu<sup>1,2</sup>, Jens Lautenbach<sup>3</sup>

<sup>1</sup>School of Electronic Information, Wuhan University, Wuhan, 430072, China

<sup>2</sup>Collaborative Innovation Center of Geospatial Technology, 129 Luoyu Road, Wuhan, 430072, China

<sup>3</sup>Arecibo Observatory – University of Central Florida, Arecibo, Puerto Rico.

<sup>4</sup>Puerto Rico Photonics Institute, School of Science and Technology, Universidad Metropolitana, Cupey, Puerto Rico.

<sup>5</sup>Electrical and Computer Engineering Department, Miami University, Oxford, Ohio, USA

*Correspondence to:* Xianchang Yue (yuexc@whu.edu.cn)

**Abstract.** 11-years long K Doppler lidar observations of temperature profiles in the mesosphere and lower thermosphere (MLT) between 85 and 100 km, conducted at the Arecibo Observatory, Puerto Rico ( $18.35^{\circ}\text{N}$ ,  $66.75^{\circ}\text{W}$ ), are used to estimate seasonal variations of the mean temperature, the squared Brunt-Väisälä frequency,  $N^2$ , and the gravity wave potential energy in a composite year. The following unique features are obtained: 1.) The mean temperature structure shows similar characteristics as a prior report based on a smaller dataset; 2.) ~~The profiles of  $N^2$  usually reach the maxima at or just below the temperature inversion layer when that layer is present.~~ The first complete range-resolved climatology of potential energy ~~derived from~~ temperature ~~fluctuations~~-data in the tropical MLT exhibits an altitude dependent combination of annual oscillation (AO) and semiannual oscillation (SAO). Between 88 to 96 km altitude, the amplitudes of AO and SAO are comparable, and their phases are almost the same and quite close to day of year (DOY) 100. Below 88 km, the SAO amplitude is significantly larger than AO and the AO phase shifts to DOY 200 and after. At 97 to 98 km altitude, the amplitudes of AO and SAO reach their minima, and both phases shift significantly. Above that, the AO amplitude becomes greater. The annual mean potential energy profile reaches the minimum at 91 to 92 km altitude. The altitude-dependent SAO of the potential energy is found to be highly correlated with the satellite observed mean zonal winds reported in the literature.

## 1 Introduction

Gravity waves (GWs) are believed to be the primary force driving the large-scale circulation and coupling of different atmospheric layers due to their momentum and energy deposition when breaking or dissipating (Fritts and Alexander, 2003; Lindzen, 1981; Smith, 2012). Gravity waves ~~usually often~~ originate from copious tropospheric sources and propagate upward. Their amplitudes grow rapidly with altitude under the condition of atmospheric density decreasing and begin to break or dissipate in the MLT where gravity wave influences have been shown to be strong by various observations (e.g., Baumgarten et al. 2018; 2017; 2015; Cai et al., 2014; Gardner and Liu, 2010; Li et al., 2010; Lu et al., 2009; Yuan et al., 2016). Gravity waves are therefore an essential component in current General Circulation Models (GCMs) [e.g., Liu and

Meriwether, 2004; Picone et al., 2002]. Associated modeling studies have shown that including the effects of GWs is a key to simulate realistic quasi-biennial and semiannual oscillations and other phenomena in the stratosphere and mesosphere [e.g., Dunkerton, 1997; Huang et al. 2010; Xu et al., 2006].

The upward propagations of GWs are often influenced by the background wind fields (e.g., Yigit and Medvedev, 2017). The 5 altitude ranges, where GWs interact with the background wind dissipating and depositing energy and momentum is of high interest to researchers. This happens mainly in the middle atmosphere near or between stratopause and mesopause. Above 35 km altitude, the semiannual oscillation (SAO) shows a predominance in the annual variability of the zonal winds (e.g., Garcia et al., 1997; Hirota, 1980). The SAO phase of zonal winds shifts approximately 180° with the altitude increasing from stratosphere to mesosphere. The stratospheric SAO leads to a seasonal variation of filtering of the upward propagating waves,

10 which results in a specific seasonal variation of GW activity in the mesosphere~~The GWs penetrated to the mesosphere are filtered by the stratospheric SAO leading to specific seasonal variations of GW activity in the mesosphere.~~

The mean zonal winds in mesosphere and lower thermosphere (MLT) have been measured by both ground-based radar (e.g., Garcia et al., 1997; Lieberman et al., 1993) and satellites such as the High-Resolution Doppler Imager (HRDI), Wind Imaging Interferometer (WINDII) and the Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research

15 Satellite (UARS) or the Doppler Interferometer (TIDI) on board the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (e.g., Smith, 2012). They show different features of the zonal winds in the mesopause range above and below about 80 km from tropical region to middle latitude regions. Garcia et al. (1997) and Smith (2012) showed that, for example, the westerly wind prevailed in the range 80-95 km both in January and July in the HRDI equatorial zonal wind but it reversed below or above this range, while it dominated in the range extending downwards to the stratopause in

20 January or upwards to 110 km or higher in July at higher latitude in the north hemisphere. The monthly mean HRDI equatorial zonal wind in tropical MLT showed that, the easterly winds were prevailing in equinoxes seasons near 80 km altitude. They then decreased with altitude from 80 km above and turned to increase above ~ 92.5 km, while the westerly winds prevailed in the range 80-94 km in solstice seasons, they then turn to be easterly. the reversal is at about 95 km (Smith, 2012). Therefore, the zonal winds are low or zero around 91-92 km altitude in tropical region. The zero-wind lines

25 will enhance damping or dissipating of zonal propagating gravity wave with low to moderate phase speed.

Temperature is a crucial parameter indicating the state of the atmosphere. To measure the temperature in the MLT region, satellite and lidar techniques are have been developed in recent decades. Satellite measurements have the advantage of resolving large spatial scale wave structures, but the short-term variability in dynamical features gets lost. While for the lidar measurements, they provide a vertical profile of temperature with a suitable temporal and vertical resolution at a particular 30 location. Lidar data can well resolve gravity waves with short and medium periods and their temporal development. The perturbation or standard deviation from zonal mean temperature is often used as a wave activity indicator in the atmosphere. For instance, Offermann et al. (2006) use the temperature measured from CRISTA (CRYogenic Infrared Spectrometers and Telescopes for the Atmosphere) and from SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) to investigate the global wave activity from upper stratosphere to lower thermosphere. They showed quite different wave

behaviors below and above their defined ‘wave-turbopause’ close to but lower than the mesopause. Below the turbopause, the propagation of the wave is significantly dissipated, while above that, the propagation of the wave is almost free.

The damping of GW activity has also been presented by lidar temperature measurements at mid-latitude sites (Mzé et al., 2014; Rauthe et al., 2008). Both Mzé et al. (2014) and Rauthe et al. (2008) showed that the GW activities presented an

5 annual variation with maximum in winter and minimum in summer, they damped significantly at the upper mesosphere altitudes above ~ 70 km in all seasons, while the damping below ~ 70 km is not so ~~eminently evident~~. Mzé et al. (2014) ~~almost observed a nearly undamped the conservation propagation of GW-potential energy in summer in the low mesosphere. Meanwhile, Rauthe et al. (2008) also reported the weakest damping occurring in the summer seasons. Since the effects of GW in the numerical climate and weather prediction models are usually represented simply by parameterization (Kim et al., 2003), there are still large discrepancies between model and measurement results (Geller et al., 2013). Therefore, These results suggest more attention should be paid to the GW parameterization about these kind of -observations of~~in the upper mesosphere and mesopause region to improve the ~~GW-parameterization-in-the atmospheric model results~~.

10 Seasonal variations of GW activities based on lidar temperature measurements have been investigated at ~~a few~~ low latitude sites (Chane-Ming et al., 2000; Li et al., 2010; Sivakumar et al., 2006). These ~~researches-studies~~ used Rayleigh lidar data and focused mainly on the upper stratosphere and lower mesosphere in an altitude region from 30 to 80 km. They showed the 15 SAO dominated the seasonal variability of GW activities with maxima in both winter and summer and minima near the equinox. Li et al. (2010) related this to the dominated SAO in the mean zonal wind in the tropical stratosphere and lower mesosphere. Considering the ~~different transition forming~~ of the mean zonal wind ~~in the range above~~—80–95 km in the tropical region ~~noted above~~, the seasonal variability of GW activity in the tropical upper mesosphere is expected to be 20 different from either the lower altitudes or the mid- and high-latitude regions.

To our knowledge, the seasonal variability of GW activity retrieved from mesospheric lidar temperature data with high temporal and vertical resolution have never been reported from a tropical location.

Such measurements of atmospheric temperature have been conducted with the K Doppler lidar located at the Arecibo Observatory ( $18.35^{\circ}\text{N}$ ,  $66.75^{\circ}\text{W}$ ), Puerto Rico (Friedman and Chu, 2007; Yue et al., 2013, 2016, ~~2017~~). Since December 25 2003, the Arecibo Observatory K Doppler lidar has operated routinely, producing high-quality temperature data. In this report, we estimate the mean temperature, the squared Brunt-Väisälä frequency,  $N^2$ , and the gravity wave potential energy and their annual variability from the temperature dataset. ~~The vertical structures of SAO and AO in these parameters and their relationships are exhibits.~~ We find an altitude-to-altitude close relationship between the annual variability of the potential energy in this report and that of the mean zonal winds in the literature. Their implications to the role of gravity 30 wave in the MLT are discussed.

## 2 Observations

The Arecibo K Doppler lidar probes the potassium D1 line to deduce the potassium density and neutral air temperature simultaneously by employing the three-frequency technique (e.g., Friedman and Chu, 2007; Friedman et al., 2003). The temperature was obtained at 0.45/0.9 km vertical and 10/30 minutes temporal resolution, respectively (Friedman and Chu, 2007; Yue et al., 2017), and we unify them into profiles with resolutions of 0.9 km and 30 minutes in vertical and temporal dimensions, respectively. This data processing excludes the perturbations relevant to gravity waves with vertical wavelengths and observed periods less than 1.8 km and 1 hour, respectively. Their exclusion may bias the deduced gravity wave associated potential energy estimations towards mid- and low-frequency gravity waves. The root mean square (RMS) temperature errors is about 2 to 3 K at the peak of the K density layer and increase to about 10 K at the edge of the layer around 85 and 100 km (Friedman and Chu, 2007; Yue et al., 2017).

Measurements are made only at night in two periods, one from December 2003 to January 2010, the other from November 2015 to April 2017. Data were available for every calendar month. Across the 11 years of the data collection period, 198 observing nights with a total of 1451 hours of data were available at the time of preparing this report. The number of observation nights/hours varies from 4 nights/27 hours in October, to 32 nights/253 hours in January. On average there are 16.5 nights or 121 hours of observation each month. The statistics for the used temperature observations are plotted in Fig. 1 and the numbers of observational nights and durations are summarized for each month in Table 1. When the data are binned into weekly intervals, they cover 45 weeks of a year. On average there are 3.8 nights or 32.2 hours of observation each week. The gaps are at weeks 7, 18, 19, 25, 26, 39 and 42. The distribution of the data is quite evenly during the year. This allows us to fit the gravity wave activity annual variability through weekly means of temperature.

## 20 3 Calculating Methods

~~The gravity wave energy includes kinetic and potential energy. The ratio of kinetic to potential energy can be taken as a constant according to the linear theory of the gravity wave (e.g., Ratnam et al., 2004; Tsuda et al., 2000); therefore, it is possible to estimate gravity wave energy from temperature observations only. The potential energy density  $E_p$  can be estimated from temperature observations and then is chosen as a measure of GW activity, and  $E_p$  is defined as (see, e.g., Vincent et al., 1997)~~

$$25 E_p = \frac{1}{2} \left( \frac{g}{N} \right)^2 \left( \frac{T''}{T} \right)^2 \left( \frac{T'}{T} \right)^2, \quad (1)$$

where

$$N^2 = \frac{g}{T} \left( \frac{dT}{dz} + \frac{g}{c_p} \right), \quad (2)$$

Here  $g$  equals to  $9.5 \text{ ms}^{-2}$ , is the gravitational acceleration in MLT;  $N$  is the Brunt-Väisälä frequency calculated according to Eq. (2);  $\bar{T}$  is the mean temperature averaging over altitude;  $T'$  is the temperature perturbation; and  $C_p$  is the constant-pressure heat capacity, equals to  $1004 \text{ JK}^{-1}\text{kg}^{-1}$ . In Eq. (1), the calculation of  $E_p$  depends on the estimations of  $N$ ,  $\bar{T}$  and  $T'$ .

The procedure adopted by Gardner and Liu (2007) is closely followed here for the estimation of  $T'$ . For each night of observation, data points with photon noise errors larger than 10 K in temperature are discarded first. The linear trend in time is then subtracted from temperature profiles at each altitude to compute the temperature perturbations, perturbations exceeding three standard deviations from the nightly mean are discarded. Finally, the vertical mean is subtracted from each temperature perturbation profile.

The unified 0.9 km and 0.5 h resolution temperature profiles and the extracted temperature perturbation profiles on each observational night in the same week are binned to the same vertical and temporal grids to construct their composite mean night for each week of a year. The weekly composite night data of  $\bar{T}$  is shown in Fig. 2. Temperature Inversion Layers (TIL) can be found in almost every month.

The weekly composite night data of  $\bar{T}$  and  $T'$  are first spatially and then temporally smoothed using Hamming windows with full widths at half maximum (FWHM) of 2.7 km and 3 hours, respectively. After that, the weekly composite nights of  $N^2$  and the consequential  $E_p$  at 0.9 km and 0.5 h resolutions are estimated through Eq. (2) and (1), respectively. For each parameter, the weekly composite nights are then averaged to derive the weekly mean profiles which are fitted to a harmonic fit model including the annual mean plus 12-month (annual) oscillation and 6-month (semiannual) oscillation. The equation of the model is as following:

$$\Psi(z, t) = \Psi_0(z) + A_{12}(z)\cos\left[\frac{2\pi}{365/7}(t - \varphi_{12}(z))\right] + A_6(z)\cos\left[\frac{4\pi}{365/7}(t - \varphi_6(z))\right] \quad (3)$$

where  $\Psi(z, t)$  is the value of a weekly mean parameter at altitude  $z$  and week  $t$ , expressed in week of the year (1-52).  $\Psi_0(z)$  is the annual mean,  $A_n(z)$  and  $\varphi_n(z)$  ( $n = 6, 12$ ) are the amplitude and phase of the -month oscillation, respectively.

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#### 4 Results and Discussion

In the following the results of the analysis is shown and discussed with respect to the seasonal variation of the mean temperature (4.1), Square of the Brunt-Väisälä frequency (4.2) and seasonal variation of the gravity wave activity (4.3). Therefore, we plot the fitted seasonal variations of  $\bar{T}$ ,  $N^2$ , and  $E_p$  in Fig. 32a, 34a, and 54a (top left panels), respectively, at 0.9 km vertical and one-week temporal intervals. The amplitudes and phases of the 12-month and 6-month oscillations of the regression model are plotted in Fig. 23c, 34c and 54c (bottom top left right panels) and 23d, 34d and 45d (bottom right panels), respectively. The annual mean profiles of  $N^2$  and  $E_p$  are also plotted in Fig. 34c and 45c. In the raw data,

temperature error due to photon noise is usually less than 5 K in the altitude range 87-97 km because the K density in this range is usually rather larger (e.g., Yue et al., 2017). To show the seasonal variation of each parameter more clearly, the data between 87 and 97 km are averaged in altitude and then fitted to the same seasonal model consisting of the annual mean, AO and SAO. Note that it is in a risk of smoothing the temporal variations for those parameters, such as  $N^2$ , which is strongly varying in term of altitude in this range. The averaged results and the fitted curves are plotted in Fig. 23b, 34b and 45b (bottom left top right panels). The statistical parameters for this fit are summarized in Table 2.

5

#### 4.1 Seasonal Variation of the Mean Temperature

Figure 23a shows that the Arecibo climatology is warmer in late-autumn-early-winter and colder in summer throughout all altitudes. An inversion layer TIL is present most of the time. The altitude of the local maximum of the temperature inversion layer TIL occurs at ~95 km from February to May and descends to ~ 91 km in early June, after which it maintains this altitude until September.

10 The mesopause is above 96 km except in the period from the second half of September to November where it is situated at ~ 96 km. The amplitudes of the AO are obviously larger than that of the SAO as shown in Fig. 23c. The phases (defined as the time of the maximum perturbation) of both AO and SAO are independent of height and located near DOY 110 and 330, respectively. Figure 43b shows that the mean temperature is warmest between October and November and coldest in July.

15 An insignificantA secondary peak/trough occurs in April/February.

Notice that the warmest temperature occurs around October with shortest observation times which reduce the confidence level of the harmonic fit. However, the observation times in both September and November are longer than 100 hours in more than 10 nights, they help to keep the confidence level of the harmonic fit. Moreover, the temperature structure shown 20 in Fig. 3a agrees well with the temporal variations of the equatorial zonal mean temperature in the range 85-100 km observed by SABER (Xu et al., 2007). The amplitudes and phases of both SAO and AO observed by SABER at 20° N latitude had been shown by Xu et al., 2007 in their middle panels of Figure 10. Comparisons show that the lidar observed phases of both SAO and AO shown in Fig. 3d agree with those obtained by SABER in the same altitude range. The SAO amplitude shown in Fig. 3c agree quite well with that observed by SABER in both magnitude and vertical structure. The 25 lidar AO amplitude show similar vertical structure with that of SABER, but the magnitude of lidar AO amplitude is at least 1 K larger than that observed by SABER. The agreement between lidar and SABER observations gives us more confidence to use the lidar observed temperature data studying the GW activities in latter sections.

Except for the smaller amplitude of SAO oscillation in this study, the phase of SAO, the amplitude and phase of AO seasonal variation of the mean temperature is consistent with a previous study by Friedman and Chu (2007) (see their Fig. 30 6 to 7), who used data collected between December 2003 and September 2006. Comparing Fig. 3a here to the Fig. 6 in Friedman and Chu (2007), there are some different features in these two climatology results. For example, the temperatures are a bit warmer in the winter months of December and January, but they are obviously colder in the range 90-100 km in March and April in this study. The differences are caused by three reasons. The first and the key point is the quality control

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to calculate the temperature perturbation in this study. The second reason is the much more extensive data set from year 2003 to 2017 covering a whole solar period here. The last reason is the harmonic fit model is in term of week here, while it was in term of month in Friedan and Chu (2007).

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#### 4.2 Square of the Brunt-Väisälä frequency

5 The square of the Brunt-Väisälä frequency  $N^2$  is a good indicator to characterize the atmospheric static stability. Gardner and Liu (2007) indicated that the resulting  $N^2$  were usually overestimated in this way due to the eliminations of gravity waves when the weekly mean temperature profiles were derived by employing data averaging. However, they pointed out that the lower-value regions of  $N^2$  represented well the lower stability of the atmosphere, i.e., the greater wave dissipations. Figure 3a-4a shows that the atmosphere is statically stable on average throughout the height range from 85 to 100 km. The 10 region of greater average stability lay just at and below the temperature inversion layers (shown in Fig. 2a3a) just above the mesopause where the mean temperatures increase with increasing altitude.

The fitted curve of  $\overline{N^2}$  (average of  $N^2$  between 87 and 97 km height) as shown in Fig. 3b-4b clearly exhibits seasonal variations. The maximum occurs in July and the minimum between October and November, while a secondary maximum occurs between January and February and a secondary minimum in May. It is worth to note that  $\overline{N^2}$  is larger than  $3.5 \times 10^{-4}$  15  $s^{-2}$  in all months, which indicate that the atmosphere is highly stable in this region over Arecibo.

Figure 3e-4c shows that the annual mean  $N^2$  is larger than  $4.0 \times 10^{-4} s^{-2}$  at all altitude. The amplitudes of the 12-month and the 6-month oscillations are comparable throughout most of the altitude range of interest, but their phases fluctuate randomly with altitude as shown in Fig. 3d4d. The 6-month phase is near DOY 100 (-82) at the bottom and shifts to DOY 80 at the top. Meanwhile, the 12-month phase oscillates in a wide range between DOY 0 (near the bottom) and 290 (-75 in the 20 96 to 98 km range).

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The mean temperature and  $N^2$  profiles exhibit strong seasonal variations. The seasonal variation of the mean temperature and  $N^2$  profiles are used to determine the seasonal variation of gravity wave activity in this region.

#### 4.3 Seasonal Variation of the Gravity Wave Activity

Gravity wave activity is directly manifested by the wave energy. Figure 4a-5a shows the contour plots of the harmonic fitted 25 gravity potential energy climatology from lidar observation.  $E_p$  is colored in a logarithmic scale (log10). It can be seen that, below 97 km altitude,  $E_p$  the potential energy always reaches the maximum in equinox seasons below 97 km altitude, and mostly near spring equinox. More interesting, in equinox seasons the potential energy decreases with altitude from the bottom to ~ 91 km and then shifts to increase with altitude in the range from 91 to 95 km. However, the potential energy is quite smaller and almost constant in the altitude range at 85- to 95 km altitude during solstices. The energies are low near 91 30 km throughout all the year. Above 91 km and below an obvious semiannual oscillation is visible at all altitudes in Fig. 3a5a. The oscillations of potential energy become very weak around 97 km.

Figure 4e-5c shows that the annual mean profile of potential energy reaches its minimum around 91 to 92 km altitude. It increases toward both the top and bottom edge. The amplitudes of both the 12-month and the 6-month oscillations are comparable and significant in a height range from about 88 to 95 km. The amplitude of 6-month oscillation is larger below

5 about 88 km but smaller above 95 km. Both amplitudes reach their minima near 97 to 98 km altitude. The phase of 6-month oscillation is almost independent of altitude. It is quite close to DOY 100 except that it is close to DOY 10 in the 97 to 98 altitude range. The 12-month oscillation has almost the same phase as the 6-month oscillation from 88 to 96 km altitude. Its phase shifts to the end of the year near the top edge where it is the dominant seasonal variation.

As the seasonal variations of  $E_p$  all show semi-annual oscillation dominated features with the approximated phases in the

10 altitude range 87-97 km, the mean  $E_p$  in the range 87-97 km and the corresponding harmonic fit shown in Fig. 5b represent the behaviour of  $E_p$  well. The harmonic fit curve of  $E_p$  shows a combination of annual and semi-annual oscillations with the maximum of  $404 \text{ J.kg}^{-1}$  near vernal equinox and the minimum of  $264 \text{ J.kg}^{-1}$  in the end of November. The maximum is a factor of 1.5 larger than the minimum.

#### 4.4 Discussion

15 The TIL in the upper mesosphere over Arecibo had been reported both in raw data of temperature and composite monthly mean night temperature (Yue, et al., 2016; Friedman and Chu, 2007). The formation mechanism for TIL had been reviewed by Meriwether and Gerrard (2004). One primary mechanism for the upper mesosphere TIL is that upward propagating GWs reach a critical level via interaction with the background flow and/or tides. The GW potential energy accumulates with the wave compressed in reaching to the critical level. Xu et al. (2009) analysed satellite observations and showed that the DW1

20 tide interacted with GW leading to the damping of both DW1 tide and GW, the larger the amplitude of DW1, the larger the damping. Consequently, the occurrence of TIL and the increase of the GW  $E_p$  are expected at and just below the locations where DW1 amplitude is large. Climatology of WACCM Simulations showed that, at  $20^\circ$  N, both the zonal and meridional components of DW1 tide amplitudes are large in height range 80-100 km around vernal equinox and in altitude range 90-100 km in summer months from June to August (e.g. Fig. 10 in Smith, 2012). These areas with large DW1 tide amplitude in that

25 Fig. 10 match perfectly with the TILs in Fig. 3a and the locations with larger GW  $E_p$  in Fig. 5a here. This suggests that the GW activity is filtered out by the upper mesospheric diurnal tides through critical level effects.

We point out a semi-annual cycle of GW  $E_p$  with maximum in spring and minimum in summer and a second maximum in autumn and a second minimum in winter in the altitude range 87-97 km. The maximum of the GW  $E_p$  alters to autumn below 87 km and above 97 km altitude. These results agree with the observations at other low-latitude station. Gavrilov et al.

30 (2003) studied the GW seasonal variations by using Medium-Frequency (MF) radar observation over Hawaii ( $22^\circ$  N,  $160^\circ$  W). They found a semiannual variation of GW with the maximum intensity at the equinoxes above 83 km, the mean zonal wind had also a mainly semiannual variation in this altitude range. The seasonal variations of GW activities at low-latitude

stations are different to those obtained from lidar observations at other latitude stations in the upper mesosphere (Mzé et al., 2014; Rauthe et al., 2006, 2008). Rauthes et al. (2008) provided the seasonal variations of GW  $E_p$  at a 54° N latitude station by using a 6-years of lidar temperature observations from 1 to 105 km. They showed an annual-dominated variation of GW  $E_p$  with the maximum in winter and the minimum in summer in the mesopause region. Mzé et al. (2014) reported a semi-

5 annual variation of GW  $E_p$  with maxima in winter and in summer and minima during the equinoxes in the upper mesosphere (~75.5 km) by using Rayleigh lidar observations from 1996 to 2012 at a mid-latitude station (~44° N). They showed that the maximum of  $E_p$  was about 144 J. kg<sup>-1</sup> on average at 75.5 km in August while the minimum of  $E_p$  is about a factor of 2.5 smaller than the maximum. The factor of ratio between the maximum and the minimum is obviously larger than that of 1.5 in the altitude range 87-97 km at Arecibo.

10 For freely propagating GWs, the potential energy per unit mass (J. kg<sup>-1</sup>) should increase exponentially with altitude for the conservation of energy. Fig. 5a shows that the potential energy decreases firstly and then turn to increases gradually with altitude below ~ 95 km in all seasons. Above ~ 95 km, the GW potential energy enhanced significantly with altitude. This feature is clearly shown by the annual mean potential energy profile in Fig. 5c. The solid curve varies slightly below ~ 95 km but turns to increase exponentially with altitude above. This behavior of mean potential energy is much similar to that

15 retrieved from satellite temperature data (Offermann et al., 2006, see their Figures 10 and 11). The altitude of ~ 95 km is in the vicinity of their ‘wave-turbopause’ altitude range, and close to the mesopause over this site [Friedman and Chu, 2007; Yue et al., 2017]. This result indicates that the GW damps significantly dissipating or depositing energy below about the mesopause (or the wave-turbopause defined by Offermann et al. 2006), but it propagates upward almost freely after penetrating to the thermosphere.

20 To learn in depth the dissipation of GW in the mesopause region at Arecibo, we multiplied the harmonic fitted  $E_p$  with the air density taken from the CIRA-86 reference atmosphere [Fleming et al., 1990], and average every 13 weekly profiles centering at each equinox or solstice. The resulted 4 profiles of the potential energy per unit volume (in J. m<sup>-3</sup>) are plotted in Fig. 6. If GWs propagate upward without energy dissipation, the lines of energy per unit volume would be vertical. Therefore, the four left-sloping lines in Fig. 6 indicate that the damps of GW potential energy occur below ~95 km in all

25 seasons. The damp of GW potential energy in the mesosphere had been reported by lidar observations at other latitude stations (e. g. Mzé et al., 2014; Rauthe et al., 2008). Both observations of Mzé et al. (2014) and Rauthe et al. (2008) indicate dissipation of GW  $E_p$  throughout the mesosphere in all seasons.

It is noticed that the green line almost keeps vertical above 94 km which indicate that the GW potential energies are almost conserved in this altitude range in winter. The slopes of the other three lines turn to be positive above ~97 km. The transition

30 of potential energy per volume from decrease to increase with altitude also occurred in the study of lidar observed GW activity at the 54° N latitude station (Rauthe et al. 2008) but with the transition altitude being above ~93 km.

The cause of the observed seasonal variations of GW activities in the mesosphere was discussed by several authors. One that is often concerned is the influence of critical level filtering of GW by the background wind (Lindzen, 1981, Yue et al., 2005).

The semiannual variation of GW intensity and mean zonal winds reported by Gavrilov et al. (2003) had been attributed to the dependence of GW generation and propagation on background wind and temperature by numerical simulations. In a mid-latitude station Juliusruh ( $55^{\circ}$  N,  $13^{\circ}$  E), Hoffmann et al. (2010) reported a semiannual variations of GW activity in the upper mesosphere and lower thermosphere with maxima in winter and summer and minima during equinoxes by using MF radar measured winds. This seasonal dependence is assumed to be mainly due to the filtering of GW by the background wind in the stratosphere and lower mesosphere. It is not always the case. Rauthe et al. (2008) did not find a direct correlation between the strength of the GW activity and the background wind direction and/or wind speed taken from European Centre for Medium-Range Weather Forecasts analysis.

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Here we also want to check the relation between our observed GW activity and the wind direction and/or wind speed. In retrospect to the Some scientific literature reported studies about seasonal variation in-of SAO mean zonal wind studies in the mesopause region in low-latitude region (see e.g., Fig. 3 in Garcia et al. 1997; Fig. 3 in Smith 2012). -This provides us the opportunity to compare our GW  $E_p$  climatology shown in Fig. 5a with the mean zonal winds climatology shown in the upper panel of the Fig.3 in Smith (2012) season to season and altitude to altitude. Here we focus on the altitude range 85-100 km. Firstly, the mean zonal winds have a dominated semiannual oscillation with westerly winds prevailing in solstice seasons and easterly winds prevailing in equinoxes seasons, meanwhile, our GW  $E_p$  has a semiannual oscillation with minima in winter and summer and with maxima during equinoxes. Secondly, the easterly winds are much larger in the altitude range 85-95 km around vernal equinox than around autumn equinox, which corresponds to the fact that the magnitude of GW  $E_p$  in spring is significantly greater than that in autumn. This is also verified by the fitted curve in Fig. 5b. The maximum of  $E_p$  at vernal equinox with a value of  $404 \text{ J.kg}^{-1}$  is a factor of 1.3 larger than the second maximum of  $319 \text{ J.kg}^{-1}$  at autumn equinox. Thirdly, the largest westerly winds near 90 km in June matches perfectly with the minimum  $E_p$  at almost the same altitude range and in almost the same period. Fourthly, the zero wind line near and above 95 km altitude throughout a whole year is accordance to the almost equal  $E_p$  near 97 km in all seasons. Fifthly, the transition of mean zonal winds to easterly above 96 km throughout the whole year corresponds well with the overall increase of  $E_p$  in the same altitude range. These five features provide strong evidence to a definite relationship between the mean zonal wind direction and wind speed and the GW  $E_p$ . This relationship agrees perfectly with the connection of wind and GW in the middle atmosphere demonstrated by Lindzen (1981).

The important result that the damping of GW  $E_p$  is observed in the mesopause region at all season cannot be explained reasonably by the effect of filtering by background wind. Considering that the amplitudes of upward propagating GWs usually become large enough, saturation and breaking of GW will lead to the dissipation of energy.

30 the features of gravity wave potential energy characterized above can be easily connected to the seasonal cycle of zonal winds measured by HRDI (see e.g., Fig. 3 in Garcia et al. 1997; Fig. 3 in Smith 2012). In equinox seasons, the decrease and then increase of gravity wave potential energy relates closely to the fact that the prevailing easterly winds decreases with altitude below  $-91 \text{ km}$  and then shifts to increase with altitudes above and reaches a maximum just below  $100 \text{ km}$  altitude.

The stronger potential energy in spring equinox season compared to autumn equinox season agrees well with larger easterly winds in spring than in autumn. In solstice seasons, the constantly low potential energy below about 92 km is in accordance with the always prevailing westerly winds in this region. In these seasons, the HRDI westerly winds constantly decrease with altitude from below and turn to westerly winds above ~91 km. The increase of potential energy above 91 km in summer and winter is corresponding to the slow development of easterly winds. Near the 91 to 92 km altitude range, where the annual mean profile of potential energy reaches the minimum, the HRDI winds reach zero or near zero in all seasons. At 97 to 98 km altitude range, where the magnitudes of AO and SAO in potential energy reach the minima, the HRDI winds also oscillate slightly throughout the year. These close relationships between the gravity wave potential energy estimated here and the HRDI zonal winds reported in the literature suggest the effect of filter by the mean winds. The propagations of gravity waves are favored at easterly winds and they are enhanced to damp or dissipate when the easterly winds become weaker; the gravity wave is filtered out when the westerly winds are prevailing. It is also suggested that the temperature perturbations can be excited locally, the strength of the perturbations is in good scale with the magnitude of zonal winds. For freely propagating GWs, the potential energy per unit mass ( $J \cdot kg^{-1}$ ) should increase exponentially with altitude for the conservation of energy. Fig 4a shows that the potential energy decreases firstly and then turns to increases gradually with altitude below ~95 km in all seasons. Above ~95 km, the GW potential energy enhanced significantly with altitude. This feature is clearly shown by the annual mean potential energy profile in Fig. 4c. The solid curve varies slightly below ~95 km but turns to increase exponentially with altitude above. This behavior of mean potential energy is much similar to that retrieved from satellite temperature data (Offermann et al., 2006, see their Figures 10 and 11). The altitude of ~95 km is in the vicinity of their ‘wave turbopause’ altitude range, and close to the mesopause over this site [Friedman and Chu, 2007; Yue et al., 2017]. This result indicates that the GW damps significantly dissipating or depositing energy below about the mesopause (or the wave turbopause defined by Offermann et al. 2016), but it propagates upward almost freely after penetrating to the thermosphere.

SAO is the main feature for the seasonal variability of the GW activity in the tropical upper mesosphere. The maxima occur in both spring and autumn and the minima near solstice. However, the SAO in the GW activity in the tropical lower mesosphere reaches the maxima in both summer and winter and the minima near equinox [e.g., Li et al., 2010]. The transforming of GW activity phase from solstice to equinox with altitude from lower to upper mesosphere coincides well with the seasonal transforming of mean zonal wind phase in this region. This suggests that the filter of mean wind fields damps the GWs on one hand, and the deposited energy and momentum by the dissipated GWs impacts on the background mean wind fields on the other hand.

## 30 5 Summary and Conclusion

A seasonal analysis of gravity wave activity in the tropical mesopause region is present using 11 years long nocturnal temperature measurements by the K Doppler lidar over the Arecibo Observatory. The mean temperature  $\bar{T}$ , the square of the

Brunt-Väisälä frequency  $N^2$  and the potential energy of perturbation associated with gravity waves  $E_p$  are estimated with high accuracy and resolution from the temperature data. All these parameters exhibit obvious AO and SAO harmonics, the phases of AO and SAO ~~are random~~<sup>vary</sup> with altitude for  $\bar{T}$  and  $N^2$ , but are independent of altitude and close to DOY 100 at most altitudes for  $E_p$ . The annual mean profile of potential energy reaches the minimum at 91 to 92 km altitude range. The

5 amplitudes of AO and SAO for potential energy reach the minima at 97 to 98 km altitude.

The seasonal variations and vertical structures of  $E_p$  relate closely to ~~bot that of~~ the HRDI zonal winds ~~and that of the DW1 tide amplitude at 20° N~~ reported in the literature. These relationships ~~agree well with the effect of spectral filter due to lower atmosphere winds and the critical level encountering of GW accounting for the formation mechanism of upper mesosphere TIL imply that the gravity wave activities are determined by the filtered-out and dissipating effects of background winds for one aspect and by the local excitation due to the background winds for the other aspect.~~ The gravity-wave-filter-out effects in solstice seasons and the stronger damp or dissipation of the gravity wave in spring equinox than in autumn equinox means that there is almost no energy or momentum of gravity wave deposited in summer and winter, but there are more energy or momentum deposited in spring and autumn with the largest deposition in autumn. ~~This sequitur also helps to understand the seasonal variations of the mean profiles of atmospheric temperature in MLT over Arecibo.~~

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*Competing interests.* The authors declare that they have no conflict of interest.

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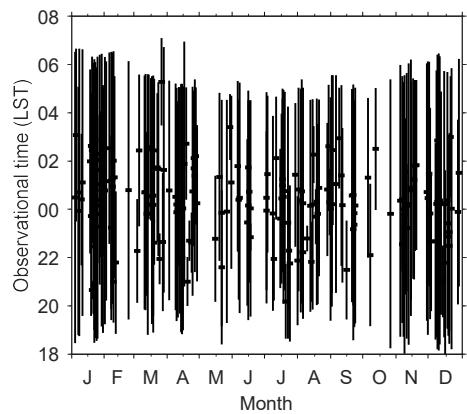
**Table 1.** Arecibo K lidar temperature data used in this study (Days/Hours) by month.

	Total	2004	2005	2006	2007	2008	2009	2010	2015	2016	2017
month	D/H <sup>a</sup>	D/H	D/H	D/H	D/H	D/H	D/H	D/H	D/H	D/H	D/H
<b>Jan.</b>	21/253	4/27		4/44	2/14	6/34		4/35		7/62	5/43
<b>Feb.</b>	7/101		5/33						4/38	3/31	
<b>Mar.</b>	20/135	2/9	10/74		4/30	1/4	3/19				
<b>Apr.</b>	21/149	1/5	14/103	3/16		1/8	2/12			1/8	
<b>May</b>	6/45	2/12	2/18	2/10							
<b>Jun.</b>	8/62	3/21	2/16			1/1			3/25		
<b>Jul.</b>	18/112	6/41	1/8	1/9		5/26	5/30				
<b>Aug.</b>	16/112	7/46	4/27	2/11	1/6	2/10			2/14		
<b>Sep.</b>	12/107		6/41	4/36		1/8			3/24		
<b>Oct.</b>	4/27	1/5	3/23								
<b>Nov.</b>	11/152	1/2	5/46	4/31		1/9		4/34	3/33		
<b>Dec.</b>	16/196	1/5	4/30	2/19		6/42	3/27 <sup>b</sup>	3/36	5/39		
<b>Total</b>	<b>198/1451</b>	<b>28/171</b>	<b>56/417</b>	<b>22/163</b>	<b>7/50</b>	<b>16/88</b>	<b>18/113</b>	<b>7/62<sup>c</sup></b>	<b>7/70</b>	<b>27/235</b>	<b>9/82</b>

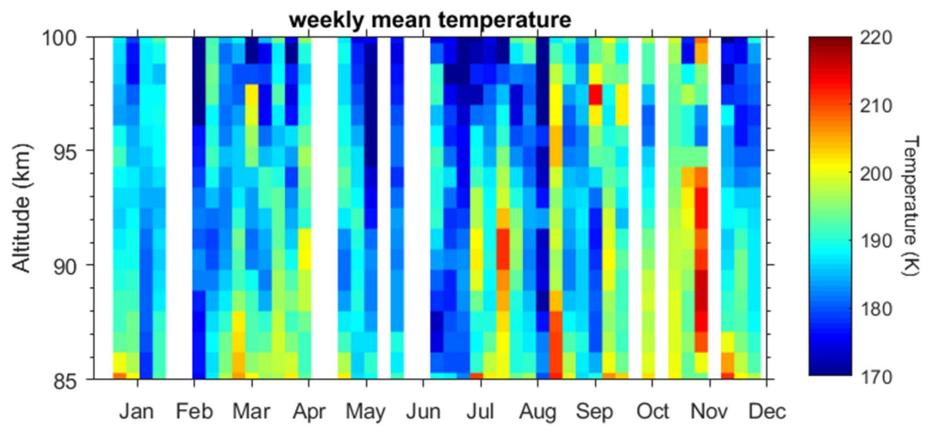
<sup>a</sup>D/H stands for Days/Hours; <sup>b</sup> Observed in 2003; <sup>c</sup> Including the observations in 2003.

**Table 2. Parameters of mean temperature, temperature variance, squared Brunt-Väisälä frequency and potential energy averaged between 87 and 97 km.**

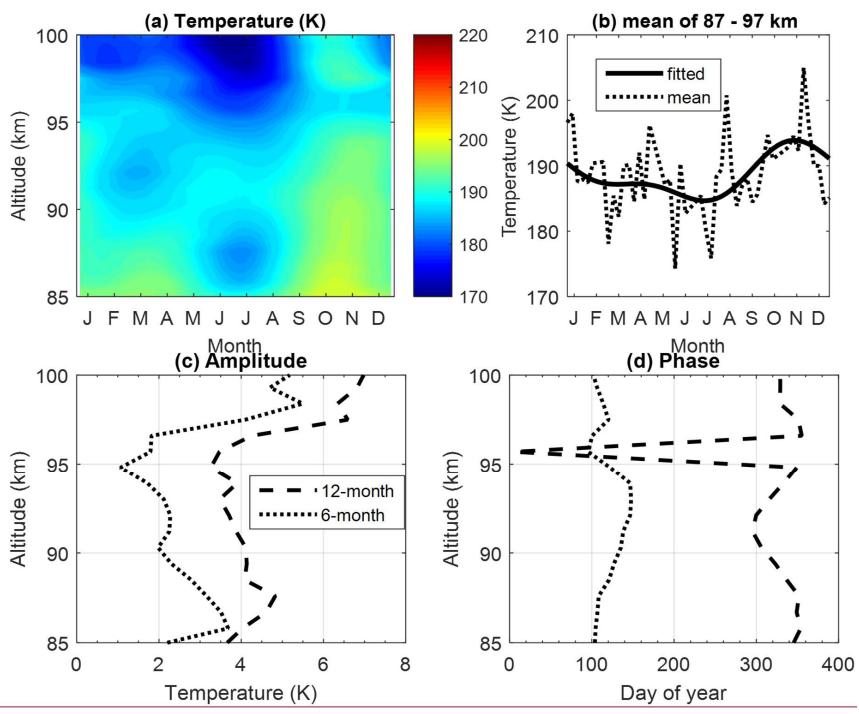
	Annual		Amplitude		Phase (days)		RMS
	Mean	12-month	6-month	12-month	6-month	Residual	
<b>Mean temperature (K)</b>	188.7	3.6	1.8	-34	-57	5.5	
$\overline{N^2}$ ( $10^{-4}\text{s}^{-2}$ )	4.37	0.09	0.12	160	22	0.37	
<b>Potential Energy (<math>\text{Jkg}^{-1}</math>)</b>	351.8	55.9	42.1	119	-89	141.6	



**Figure 1:** Local time coverage of the used temperature data observed by the K-Doppler lidar at Arecibo from December 2003 to January 2010, and from November 2015 to April 2017.



5 **Figure 2:** (a) Seasonal variations of night time temperature plotted versus altitude and month, (b) seasonal variation of mean temperature between 87 and 97 km, (c) 12-month (dashed) and 6-month (dotted) amplitudes and (d) 12-month (solid) and 6-month (dotted) phases.



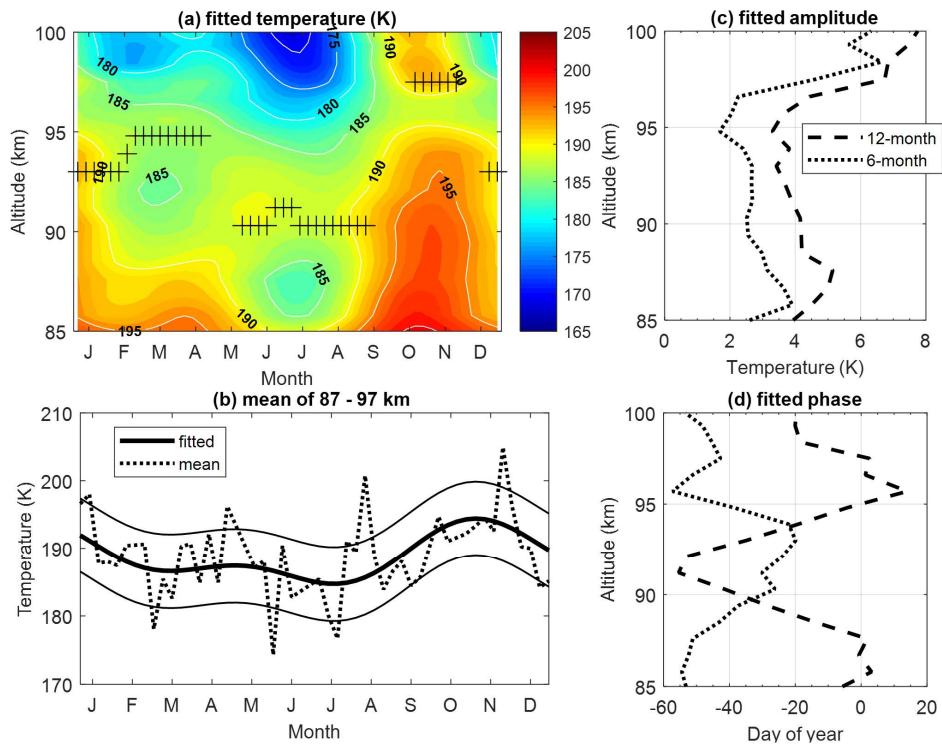
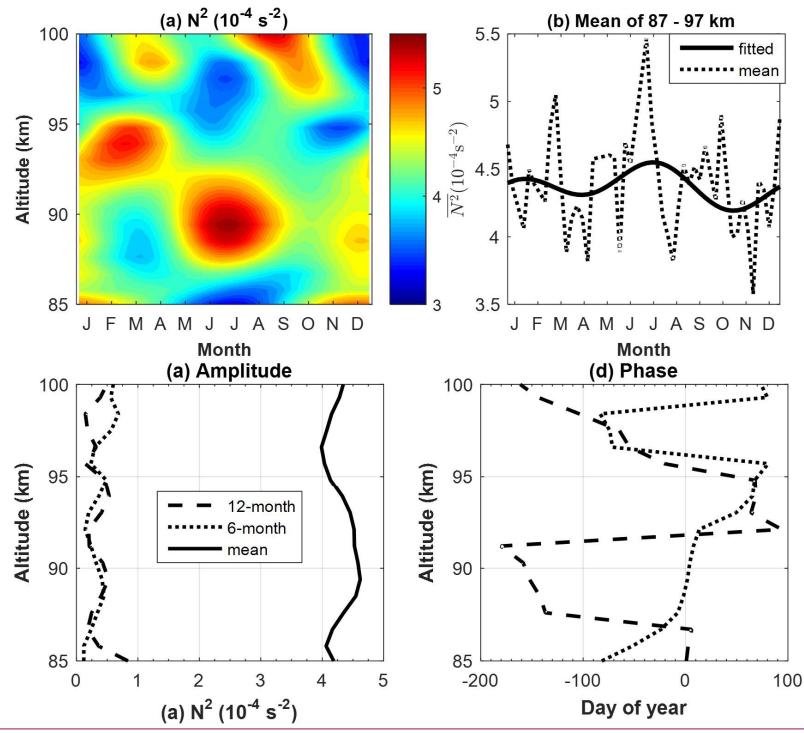
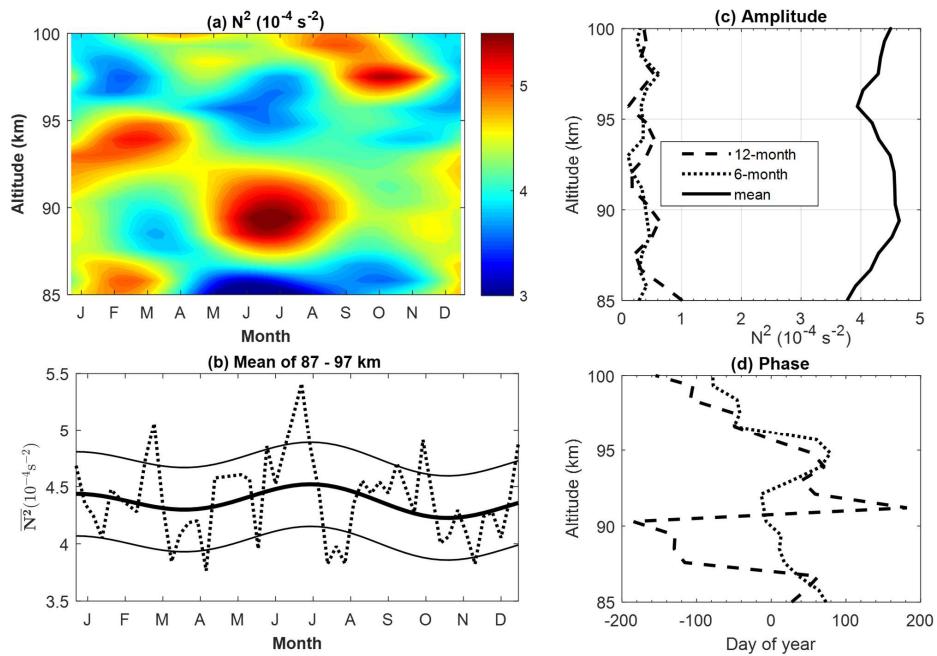
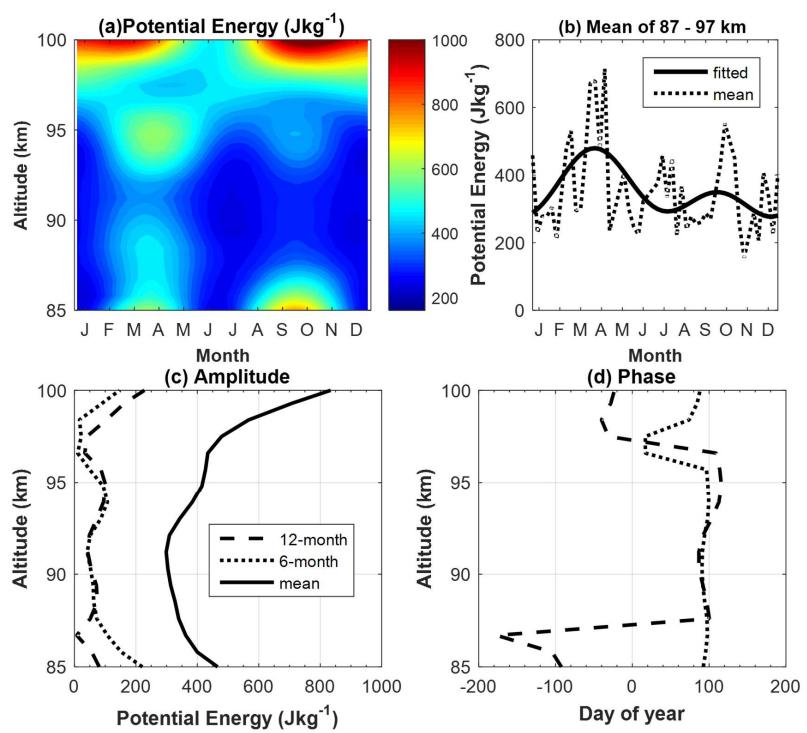


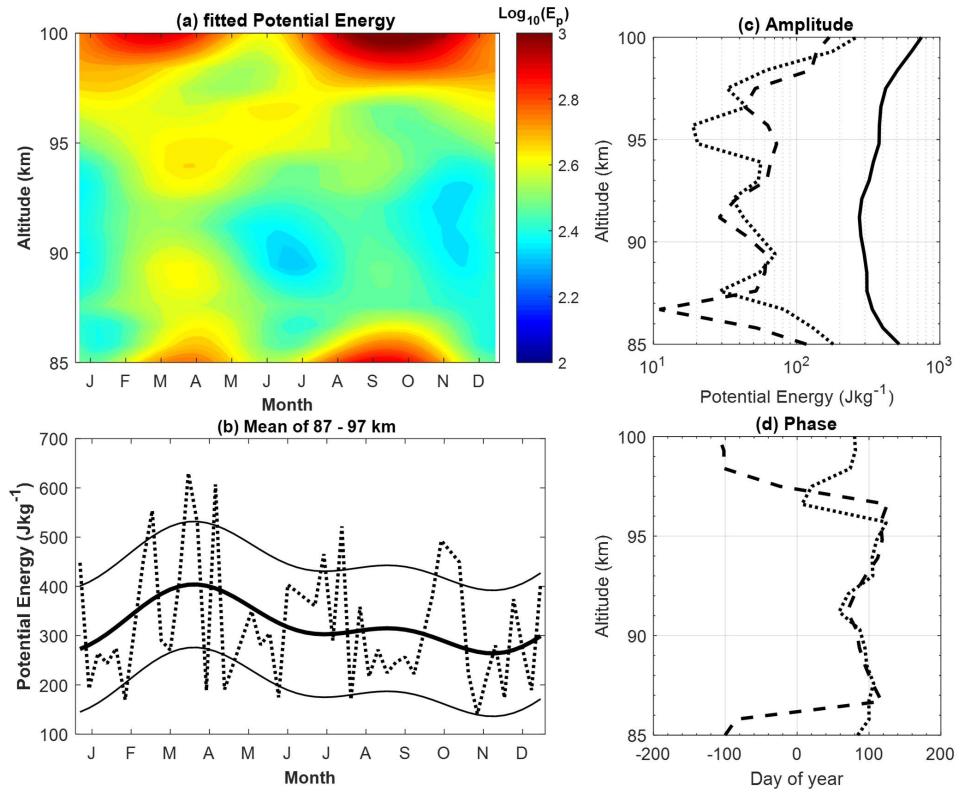
Figure 23: (a) Seasonal variations of night time temperature plotted versus altitude and month, the crosses represent the altitude of temperature inversion layer, (b) seasonal variation of mean temperature between 87 and 97 km, (c) 12-month (dashed) and 6-month (dotted) amplitudes and (d) 12-month (solid) and 6-month (dotted) phases.





**Figure 34:** (a) Seasonal variations of squared Brunt-Väisälä frequency  $N^2$  plotted versus altitude and month. (b) seasonal variation of mean  $N^2$  between 87 and 97 km, (c) annual mean profile (solid) and 12-month (dashed) and 6-month (dotted) amplitudes and (d) 12-month (dashed) and 6-month (dotted) phases.





**Figure 45:** (a) Seasonal variations of squared potential energies plotted versus altitude and month, (b) seasonal variation of mean potential energy between 87 and 97 km, (c) annual mean profile (solid) and 12-month (dashed) and 6-month (dotted) amplitudes and (d) 12-month (dashed) and 6-month (dotted) phases.

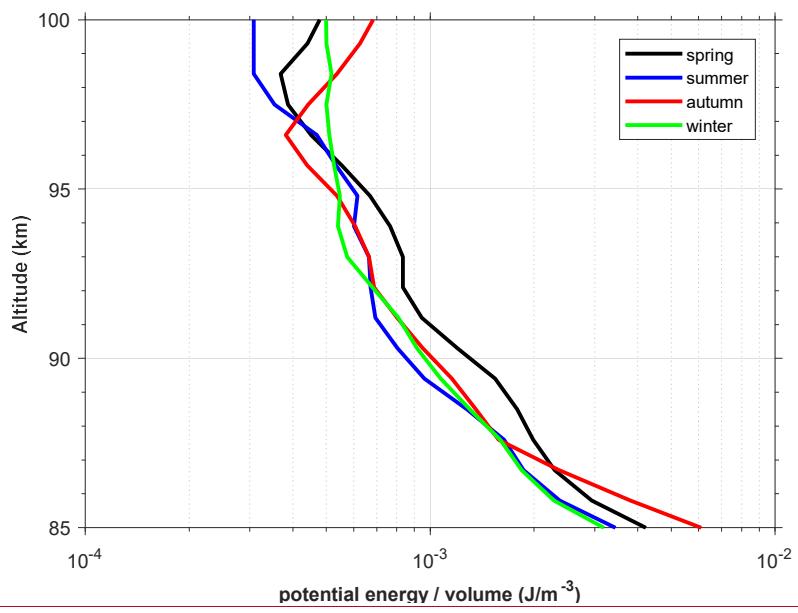


Figure 6: Vertical profiles of the potential energy per unit volume (in  $\text{J.m}^{-3}$ ) averaged over spring (13 weeks centred at vernal equinox, black line), summer (13 weeks centred at summer solstice, blue line), autumn (13 weeks centred at autumn equinox, red line), winter (13 weeks centred at winter solstice, green line).