Response to the Referee #1

Comments from referees:

Interactive comment on "Long-term Lidar Observations of the Gravity Wave Activity near the Mesopause at Arecibo" by Xianchang Yue et al.

5 Anonymous Referee #1 Received and published: 30 August 2018

Author's response: Thank you for your constructive and kind comments.

Comments from referees:

General comments: This paper shows the extended climatology of temperature and potential energy density above Arecibo using lidar data. My main comment about the paper is that the work on gravity wave activity is not a major part of the paper

10 despite it's title. I would like to see included at least one comparison with other gw lidar studies in the mesopause region (regardless of latitude) to see how their results compare in terms of seasonal variation or magnitude of gw activity observed. Perhaps also an expansion of the GW section by also looking at the year to year variation of GW PE if the authors feel it is appropriate and are not planning on doing this for a future paper.

Author's response: Thank reviewer #1 for this constructive comment. We have done comparisons to the gravity wave potential energy observations in the mesopause region at other stations. These comparisons are added in the discussion section of the revised version. The contexts are as following:

Author's changes in manuscript: *"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-*

- 20 latitude station. Gavrilov et al. (2003) studied the GW seasonal variations by using Medium-Frequency (MF) radar observation over Hawaii (22°N, 160°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
- 25 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-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⁻¹ 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."

Comments from referees:

5 Specific comments:

Page 3, line 1 – What do you mean by the conservation of GW potential energy? This needs a clearer explanation.

Author's response: Thank you for pointing out this improper sentence, the corresponding sentence has been rephrased by "Mzé et al. (2014) observed a nearly undamped propagation of GW in summer in the low mesosphere".

Comments from referees:

10 Page 3, lines 2-3 – you need to include more detail into why these studies show that more attention should be paid to the mesosphere in terms of gw parameterizations. What do your results in this paper offer that will help improve these parameterizations?

Author's response: Thank you for this comment, this sentence has been revised as:

Author's changes in manuscript: "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, more attention should be paid to the GW parameterization about these kind of observations in the upper mesosphere and mesopause region to improve the model results."

Comments from referees:

Page3, line 9 – "transforming" is not the right word here, I think you mean changes. Also, what is the change in the mean 20 zonal wind above 80 km in the tropical region? This needs to be explained.

Author's response: "transition" is a proper word to replace "transforming". The changes in the mean zonal wind near mesopause in the tropical region has been introduced in the 3rd paragraph of the introduction section.

Comments from referees:

Page 4 – line 1 – Can you please include a reason as to why there is a 5 year gap in the dataset. Is the data from two different K lidars? Was the one lidar broken?

Author's response: In the time from 2011 to 2015 the lidar building was upgraded with an extension for the telescopes which were in a hut until this time.

Comments from referees:

Page4, equations 1 and 2 – why have you used the EP equations for temperature from Vincent et al and not used the one that 5 Mze et al (2014) use in their lidar studies?

Author's response: The difference between equation (1) in this manuscript and the equation (8) in Mze et al (2014) is that $\left(\frac{T'}{\bar{T}}\right)^2$ in this (1) is replaced by atmosphere variance in that (8). The temperature inversion by an K Doppler lidar near the mesopause region uses the resonance scatter signal of K atoms, while the atmosphere variance estimation by a Rayleigh lidar from 30 to 80 km uses the Rayleigh scatter signal of atmosphere molecules which is taken as part of the background noise of

10 K Doppler lidar.

Comments from referees:

Page 4, line 21 - please include a brief description of the procedure for calculating T' rather than just pointing at a reference.

Author's response: The brief description added is as the following:

Author's changes in manuscript: "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."

Comments from referees:

Page 4, line 25 – Doesn't applying this Hamming window alter again the minimum period and wavelength gravity waves
that you will be able to detect? This will make the values you state at the start of section 2 invalid. Please address this in the text.

Author's response: Thank you for this question. We made a mistake in the writing. We have not applied this Hamming window on the temperature perturbation T'. "*The weekly composite night data of* \overline{T} *and* T' *are*" have been updated to "*The weekly composite night data of* \overline{T} *is*" after we checked the data processing MATLAB procedure.

Page 4, lines 27-29 – what model is referred to here? I suspect it's the harmonic fit used in the Friedman and Chu paper you reference but it's not clear at all. More detail on what exactly is being done here and why is needed in the text.

Author's response: Yes, it is just a harmonic fit, we have added the following texts and equation in the revised manuscript:

5 Author's changes in manuscript:

"The equation of the model is as following:

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

10 Comments from referees:

Page 5, line 19 – why is the secondary peak insignificant? Surely it is just not as large, why does that make it statistically insignificant?

Author's response: We have used an improper word here. 'An insignificant secondary' has been updated to "A secondary" in the revised version.

15 Comments from referees:

Page 5, line 21 – I have compared Figs 6 and 7 in the Friedman and Chu paper (F&C) with your Figure 2 and yes the annual variation is similar but there are also large differences that need to be explained. In your Fig 2a the vertical temperature structure is different to that shown in F&C, with you showing warmer temperatures around March and October/November that are more extensive that those in the F&C paper. Also the semi-annual phase and amplitudes they show are quite

- 20 different to yours in Fig 2c&d (which is expected as the SAO you show is different). The question needs to be asked as to why your climatology (which includes the data used in the F&C paper) is showing such differences. Are you using the exact same method as F&C? If not, when you perform your analysis on the same section of data as used in F&C do the results agree? Are there one or two years which have this warmer vertical structure and that is influencing the results in your paper? You need to explain why you are seeing a different structure to other results which use part of the same dataset.
- 25 Author's response: Thank you for pointing out the difference between these two works. The differences are caused by three reasons.

Author's changes in manuscript: "The first and the key point is the lack of adding the smoothed residual temperature back to T(z,t) estimated by using (3) 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)."

5 Comments from referees:

Page 6, line 25 - you need to show an example of the seasonal cycle of the zonal winds to which you refer to in the paper

Author's response: Thank you for this suggestion. We have added:

Author's changes in manuscript: "(see e.g., Fig. 3 in Garcia et al. 1997; Fig. 3 in Smith 2012), the monthly mean HRDI equatorial zonal wind showed that, the easterly winds were prevailing in equinoxes seasons near 80 km altitude. They then

10 decreased with altitude from 80 km above and turned to increase above ~ 92 km, while the westerly winds prevailed in 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 92 km altitude in tropical region. The zero-wind lines will enhance damping or dissipating of zonal propagating gravity wave with low to moderate phase speed' in the discussion.

Comments from referees:

15 Figure 2a – can you plot the MIL you refer to on the text on the figure

Author's response: The altitude of MILs has been plotted by black crosses in the revised Fig.3a.

Comments from referees:

Figure 4a – it might be easier to compare with other sites/lidar gw studies if you plot the lognormal of the GW PE.

Author's response: The GW PE is plotted in log-normal in the revised Fig. 5a.

20 Comments from referees:

Technical corrections:

Abstract – the phrase "potential energy of the temperature fluctuations" is not correct. You are using the temperature fluctuations to determine the potential energy density of the gravity wave field, i.e. the gravity wave activity levels. Please change so that it is correct.

Author's response: Thank you for pointing out this error. Phrase 'potential energy of the temperature fluctuation' has been changed to 'potential energy derived from the temperature data' in the revision

Comments from referees:

Page 2, line 21 - change "are" to "have been"

5 Author's response: It is changed in the revised version.

Comments from referees:

Page 2, line 34 – eminent is not the right word to use here, do you mean evident?

Author's response: "evident" is proper here, and 'eminent' is replaced with 'evident'.

Comments from referees:

10 Page 2, line 34 – again I don't think you mean to use "almost", "also" would make more sense.

Author's response: Thank you for this comment, we have rewritten this sentence as "Mzé et al. (2014) observed a nearly undamped propagation of GW in summer in the low mesosphere."

Comments from referees:

Page 3, line 5 - "These researches" should be replaced with something like: "The studies"

15 Author's response: It is replaced.

Comments from referees:

Page 3, line 18-19 – The sentence "the vertical structures of SAO and AO in these parameters and their relationships are exhibits" does not make sense, please rephrase.

Author's response: since this sentence is not necessary, we omitted it in the revised version.

20 Comments from referees:

Page 4, equations 1 and 2 – The overbar on the temperature indicates averaging over altitude, please include this in your description of the variables.

Author's response: It is included according to this suggestion.

Page 4, line 22 – replace 0.5h with 30 minutes (or replace 30 minutes with 0.5h in the other instance in the paper). Try to be consistent with how you refer a time interval.

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Author's response: "0.5h" has been replaced with 30 minutes here.

Response to the comments from Referee #2.

Interactive comment on "Long-term Lidar Observations of the Gravity Wave Activity near the Mesopause at Arecibo" by Xianchang Yue et al.

5 Anonymous Referee #2 Received and published: 14 September 2018

Comments from referees:

Xianchang Yue et al. report about temperature soundings obtained with a potassium resonance lidar at Arecibo (18°N). Overall, 1451 h of data are obtained between December 2003 and April 2017, with good data coverage especially in the first three years. From this data set the seasonal variations of temperatures and their variability are derived, with emphasis mainly

10 on the AO and SAO. There are only few temperature data sets available from the tropical mesopause region, and these data are a worthwhile contribution. The paper is well written and the Figures are of good quality. Unfortunately the whole reasoning is partly incomplete and digs not very deep into the data. Examples are given below. Overall, I recommend revision and extension of the manuscript.

Author's response: Thank you for your hard work for review and for your evaluation of the manuscript. We will try to make it more valuable through revision.

Comments from referees:

General comments:

The authors describe in the Discussion a relation between the wind field as published by Garcia et al. (1997) and Smith (2012) and the observed variation of GWPED. While there is indeed a pronounced altitudinal and temporal correlation, the

20 paper lacks a description of the mechanism that relates the GW activity and zonal wind velocity. All statements are true, but remain vague and unspecific. The interpretation seems to imply pure zonal propagation of the waves, but the lidar data contain waves of all directions. Is the westerly wind between 60 and 70 km taken into account that may filter a lot of the eastward propagating GW?

Author's response:

- 25 Thank this reviewer for this valuable comment. I've made significant revision and extension in discussing the relation between the wind field and the observed variation of GWPED. These discussions are presented in section 5.3 of the revised version and will be listed in the following paragraph. There is indeed a pronounced altitudinal and temporal correlation between them. This promotes us to a statement that "*This suggests that the seasonal variation of GW activity should be determined mainly by the local wind field through the influence of critical level filtering of GW by the background wind*" in
- 30 the conclusion section. The revised discussions in section 5.3 are as following:

Author's changes in manuscript: "Here we also want to check the relation between our observed GW activity and the wind direction and/or wind speed. Some scientific literatures reported studies about seasonal variation of mean zonal wind in the tropical mesopause region (see e.g., Fig. 3 in Garcia et al. 1997; Fig. 3 in Smith 2012). The monthly mean HRDI equatorial zonal wind showed that, the easterly winds were prevailing in equinoxes seasons near 80 km altitude. They then decreased

- 5 with altitude from 80 km above and turned to increase above ~ 92 km, while the westerly winds prevailed in in the range 80-94 km in solstice seasons, they then turn to be easterly. the reversal is at about 95 km (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
- 10 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 correlation is also verified by the fitted curve in Fig. 5b. The maximum of E_p at vernal equinox with a value of 404 J.kg⁻¹ is a factor of 1.3 larger than the second maximum of 319
- 15 $J.kg^{-1}$ 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 and at almost the same time. Fourthly, the zero-wind line near 96 km altitude throughout a whole year is accordance to the almost equal E_p at almost the same altitude in all seasons. Fifthly, the transition of mean zonal winds to easterly winds 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 an indeed pronounced correlation between the local mean
- 20 zonal wind field and the lidar observed GW E_p. This correlation agrees perfectly with the connection of wind and GW in the middle atmosphere demonstrated by Lindzen (1981). Correlation between GW potential energy and local winds has been suggested by Wright et al. (2016) in their multi-instrument GW measurements over Tierra del Fuego (54°S, 68°W), which was devoted to the Doppler shifting of waves into the observational filters of the instruments by these winds."

Comments from referees:

- 25 The authors do not show any kind of raw data, i.e. mean temperature profiles of a single night or even examples for temperature variability (T'). The lowest level figures are fitted AO and SAO, and it remains open, how representative they are. The authors state that these are the most important variations, but the large variability of the mean values in 2b/3b/4b and the "random phases" (l. 8/1 on page 8) seem to contradict. Therefore I recommend to provide also examples for T and T', as well as unfitted seasonal variations of all relevant quantities.
- 30 Author's response: The unfitted composited weekly mean temperature profiles are shown in Fig. 2 in the revised manuscript. As the inclusion of the other quantities would change the structure of the paper significantly, we would like to provide the pictures of these quantities and the picture of processing temperature perturbation as supplements.

The calculation of T' should be described in much more detail. This is the most crucial point for the interpretation, and a reference to Gardner and Liu 2007 is not sufficient. What are the main points in the retrieval? How does incomplete

5 sampling influence the results? How are tides removed from the fluctuations? How is the increasing uncertainty at the layer edges acknowledged?

Author's response: The procedure to calculate temperature perturbation is described in detail in the revised manuscript according to this commend. It is as the following:

Author's changes in manuscript: "It includes 4 steps. Step 1: for each night of observation, data points with photon noise

- 10 errors larger than 30 K in temperature are discarded. The value of 30 K is set based on the fact that the root mean square errors (RMSE) due to photon noise often reach to about 40-50 K near the edges (~80 km on the bottom and ~105 km on the top) of the temperature profile. Step 2: the linear trend in time at each altitude in the temperature profile is then subtracted to eliminate the potential biases associated with GWs with periods longer than about twice the observation period. Step 3: Perturbations exceeding three standard deviations from the nightly mean are discarded from the resulted temperature
- 15 perturbation series at each altitude to remove occasional outliers. Step 4: the vertical mean is subtracted from each temperature perturbation profile to eliminate the influences of the waves with vertical wave length longer than about twice the profile height range (~ 25 km). The resulted temperature perturbation profiles usually cover the height range 80-105 km. Therefore, the weekly composite nights of temperature, N² and the consequential E_p usually cover the height range 80-105 km. To avoid the uncertainty of the analysis, we focus on the height range 85-100 km where the RMSE of each
- 20 instantaneous observed temperature usually less than 10 K."

Comments from referees:

Specific comments:

l. 1/14-15: I think it is not a unique feature that N^2 maximizes below/at an inversion. This is just the result of the temperature increase with altitude (dT/dz is large and positive).

25 Author's response: thank you for your comment, I learn it. This point has been deleted.

Comments from referees:

1. 1/26: I suggest to replace "usually" by "often" as there are also stratospheric sources, secondary waves etc.
 Author's response: "usually" has been replaced by 'often'.

I. 2/9 there is a logical break. I suggest writing "The stratospheric SAO leads to a seasonal variation of filtering of the upward propagating waves, which results in a specific seasonal variation of GW activity in the mesosphere." **Author's response**: thank you for this correction, and we have replaced this sentence with your suggestion.

5 Comments from referees:

1. 2/34-3/1: Sounds odd. Suggestion "Mze (...) observed a nearly undamped propagation of GW ...". **Author's response**: Thank you for this suggestion, and this sentence has been updated accordingly.

Comments from referees:

1. 3/10: What is meant by "transforming of the mean zonal wind"?

10 Author's response: "transforming" should be "transition", means that the direction of the mean zonal wind changes.

Comments from referees:

1. 3/26 and 1. 3/31: The reference to Yue at al. 2017 is not appropriate here, because the cited paper mainly deals with K density data.

Author's response: This reference has been deleted at these two places.

15 Comments from referees:

4/4: The worst data coverage is (by chance?) right in the month of largest wave activity. This should be discussed shortly.
 Author's response: We give a discussion in the section of "Seasonal Variation of the Mean Temperature" by comparing the lidar data to the SABER observed mean zonal temperature reported by Xu et al. (2007). The discussion is as following:
 Author's changes in manuscript: "Notice that the warmest temperature occurs around October with shortest observation

- 20 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 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
- 25 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 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".

1. 4/11-13: No. The ratio of kinetic and potential energy is a function of the intrinsic period of the wave (and the Coriolis parameter). From temperature soundings only the potential energy can be calculated, but not the total energy, because the intrinsic period is generally unknown.

5 Author's response: Thank you for your opinion, these sentences have been omitted in the revised version.

Comments from referees:

1. 5/8: Please motivate the choice of this altitude interval. Especially N^2 is strongly varying in this range, and the phases of T and N^2 precess.

Author's response: The temperature error due to photon noise is usually less than 5 K in the raw data located in this altitude interval 87-97 km because of the rather larger K density. But it is in a risk of diminishing the feature of seasonal variation for a strongly varying parameter in term of altitude such as N^2. We demonstrate the motivation and discuss the risk around this sentence in the revised manuscript. In the end paragraph of section 4.3 we add the following words to describe the motivation of calculating the mean of the potential energy in this altitude interval:

Author's changes in manuscript: "As the seasonal variations of E_p show semi-annual oscillation dominated features with 15 the approximated phases in the altitude range 87-97 km, the mean E_p in the range 87-97 km and the corresponding harmonic fit shown in Fig. 5b represents the behaviour of E_p well".

Comments from referees:

1. 5/13: Is the inversion also visible in the raw data or is it a result of the fit? If it is real, it should be discussed in more detail because it may strongly affect the propagation of GW. If it is not discussed here, some reference should be made.

20 Author's response: Yes, the inversion is visible in the raw data shown in Fig. 2 of the revised version. We have discussed the temperature inversion layer and its effects on the propagation of GW in section 5.1 and 5.2, respectively. Details is as following:

Author's changes in manuscript:

"5.1 Mesospheric Temperature Inversion Layer

- 25 We have noticed that obvious TILs occur at ~96 km in spring, at ~ 91 km in summer and early autumn, and at ~94 km in winter. The TILs in the upper mesosphere over Arecibo had been reported both in case study and/or study of climatology by using subset of the data used in this study (Yue, et al., 2016; Friedman and Chu, 2007). The formation mechanism for TIL in the mesopause region 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.
- 30 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 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 decrease 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 ° 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).

5 These areas with large DW1 tide amplitude in their Fig. 10 match perfectly with the TILs in Fig. 3a. 5.2 Damp of GW Potential Energy

For freely propagating GWs, the potential energy per unit mass $(J.kg^{-1})$ 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 ~ 97 km in all seasons. Above ~ 97 km, the GW potential energy enhanced significantly with altitude. This

- 10 feature is clearly shown by the annual mean potential energy profile in Fig. 5c. The solid curve decreases below ~ 92 km and turn to increases above. The increase become significant above 97 km altitude. This behaviour 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 ~ 97 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 deposing
- 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.
 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 (period of a season) centring at each equinox or solstice. The resulted profiles of the potential energy per unit volume

- 20 (in $J.m^{-3}$) in four seasons are plotted in Fig. 6. If GWs propagate upward without energy dissipation, the lines of energy per unit volume would be vertical. Therefore, the overall left-sloping lines in Fig. 6 indicate that the damps of GW potential energy occur below ~97 km in all 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.
- 25 The damp of $GW E_p$ in the mesopause region is assumed to be caused by the interaction between DW1 tide and GW (Xu et al. 2009), the larger the amplitude of tide, the larger the energy damp. The climatology of the DW1 tide amplitude at 20°N was shown in Fig. 10 of Smith (2012), which showed the DW1 tidal amplitudes in winter were significantly smaller than the other three seasons, this matches with the smallest damp of $GW E_p$ in winter as shown in Fig. 6 here. The damp of $GW E_p$ indicates the deposition of GW energy and momentum into the background atmosphere, which would lead to the increase of
- 30 background temperature and/or even the occurrence of TIL. This drives us to investigate the relationship between the damp of $GW E_p$ and the temperature structure in depth. We are excited to find that each profile of the GW potential energy per unit volume ((in J.m⁻³) as shown in Fig. 6 shows a rapider damp of energy at and below the TIL altitude of the corresponding season and turns to a much slower damp and/or even conservation of energy above. For examples, the

behaviours of the green curve (profile for winter) around 94 km altitude (the altitude of TILs in winter), the blue curve (profile for summer) around 91 km altitude (the altitude of TILs in summer). The black curve (profile for spring) around 96 km altitude (the altitude of TILs in spring). These close connections of the mesospheric TILs with the damp of GW potential energy provide strong support to the mechanism that the upper mesosphere TIL formed due to the interaction of GW with the

- 5 upper mesospheric wind/diurnal tides through critical level effects. We notice that in the altitude range 85-95 km, where the GW potential energy damps significantly in all seasons, the background temperature decreases in an oscillational way from ~ 195 K to ~185 K. The corresponding mean temperature decreasing rate is of ~ 1 K/km which is extremely smaller than the lapse rate of ~ 9.5 K/km in this altitude region. Above 97 km, the GW potential energy per unit volume either conserves with altitude in summer and winter or turn to increase with
- 10 altitude in spring as shown in Fig.6. Correspondingly, the background temperatures in Fig. 3a decrease sharper in seasons spring, summer and winter. It is worth to note that in autumn the GW potential energy per unit volume turn to increase at ~ 96 km altitude where the mesopause occurs as shown in Fig. 3a. These results are very valuable in helping to improve the parameterisation of GW in the mesopause region in global circulation models. "

Comments from referees:

15 1. 5/15: It remains open from this Figure, whether the mesopause could also be above 100 km in Sep-Dec.Author's response: Yes, it does.

Comments from referees:

5/20 and Fig. 2: It would be helpful to have contour lines to assess the similarity between the data sets.
 Author's response: The contour lines are overplotted in Fig.3a of the revised version.

20 Comments from referees:

1. 5/28: This is essentially expected if N² is calculated from the mean temperature data set. See above. **Author's response**: Yes, it is not a finding but only an effect.

Comments from referees:

6/1-2: Please explain why it is worth to note this. My impression is that any kind of instability would be eliminated by
 building the temperature composite and applying an AO/SAO fit. Is the mesopause region more stable above Arecibo than somewhere else? If so, please explain and provide a reference.

Author's response: It is not worthy to note, consequently, this sentence is omitted.

1. 6/4-5: Consider plotting the phase of the SAO shifted by 180 d between 96 and 99 km (-80 will be +100). It may look nicer. Is the variability of the AO phase really unexpected (being the derivative of another property)? How does the variable phase affect the conclusions of the paper?

5 Author's response: this figure and the related Fig. 4c have been updated to make the shift of phase look nicer and the description has been updated as the following:

Author's changes in manuscript: "we allow negative amplitudes to make the phase oscillation of the two components look in order as shown in Fig. 4d. There are several turning points at altitudes \sim 87 km, \sim 92km, \sim 94 km, \sim 96 km in the profiles of AO and SAO phases. The last three of these altitudes correspond to the altitudes of TILs. This agrees with the fact that the TILs locate at different altitude and N² becomes large just below TIL (increased dynamical stability)."

Comments from referees:

10

1. 6/8/9: Do I understand correctly that the fitted T and N² are used as the mean value to calculate T'? This would be a significant difference to Gardner&Liu. Furthermore, using the fitted time series will affect the seasonal variation of the derived GW activity. Please clarify.

15 **Author's response**: No, the nightly mean temperature is used to calculate T'. I just wanted to write a sentence connecting the preceding and the following, unfortunately, it is not correctly written. This sentence is omitted.

Comments from referees:

1. 7/9-10: I actually do not understand this sentence. Temperature enhancement from dissipating GW? Secondary waves? How relates a strength in temperature variation to a wind velocity?

20 Author's response: I mean that the smaller of the zonal mean zonal wind amplitude, the smaller the GW amplitude. But I can't discuss it further, it is omitted.

Comments from referees:

1. 7/13: How much of the increase above 97 km is due to the increasing uncertainty at the edge of the K layer or by a (potential) deviation of the fit data from the original data?

25 Author's response: the quantitative analysis is not given now.

Comments from referees:

1. 8/1: I do not agree that the phases of T and N² are "random", even if they are less constant with altitude. A random phase would imply that AO/SAO are not relevant oscillations in this altitude range.

Author's response: the conclusion we drawn is subjective, the "are random" is updated to "vary" in this sentence.

1. 8/5-6: Please be more specific: Which processes do you expect that relate the GW activity to the seasonal wind variation in your data and what evidence you have?

Author's response: Thank you for this constructive comment which leads to the thorough rephrase of the discussion section and the conclusion section.

Comments from referees:

5

1. 8/9-10: This statement is rather vague. Please be more precise.

Author's response: We have rephrase this paragraph which is as the following:

Author's changes in manuscript: "The seasonal variations of GW potential energy are dominated by the combination of annual and semiannual oscillations at most altitudes. The maxima occur in spring and autumn and the minima occur during solstices. The observed GW potential energy is compared to the wind field as published by Garcia et al. (1997) and Smith (2002), There is indeed a pronounced altitudinal and temporal correlation between them. This suggests that the seasonal variation of GW activity should be determined mainly by the local wind field through the influence of critical level filtering of GW by the background wind."

15 Comments from referees:

Figure 2-4: Please provide error bars for fit amplitudes and phases.

Author's response: Figures 2-4 (figures 3-5 in the revised manuscript) have been replotted to draw the error bars for fitted amplitudes and phases according to this comment. The annual mean profiles of N^2 and E_p are omitted in Fig. 4c and 5c in order not to mess the picture.

20 Comments from referees:

Figure 4: I recommend plotting the GWPED per volume. For linear propagation this should be conserved. The strong increase of GWPED close to 100 km would be less pronounced.

Author's response: Thank you for this suggestion. We have plotted the seasonal mean of GWPE per volume in Fig.6 of the revised manuscript and discussed the damp of GWPE in section 5.2.

25 Comments from referees:

Technical comments / Typos:

1. 3/19: "exhibits" should read "exhibited"

Author's response: thank you for pointing out this wrong spelling.

4/8: "evenly" should read "even"
 Author's response: It is corrected.

Comments from referees:

5 l. 5/2: "is" should read "are"Author's response: It is corrected.

Comments from referees:

l. 6/14: It is Fig. 4a

Author's response: It has been updated as Fig. 5a.

17

Response to Editor Hibbins

Interactive comment on "Long-term Lidar Observations of the Gravity Wave Activity near the Mesopause at Arecibo" by Xianchang Yue et al.

R. E. Hibbins (Editor) robert.hibbins@ntnu.no

5 Received and published: 28 September 2018

Comments from referees:

Before preparing and submitting a revised manuscript would the authors please provide a response to referee#1's specific comments relating to figures 2a and4a, and referee #2's first general comment. For clarity, these comments are reproduced below:

10 **Referee #1**

Figure 2a - can you plot the MIL you refer to on the text on the figure

Author's response: This comment has been replied in the renewed response to the comments of referee #1.

Comments from referees:

Figure 4a – it might be easier to compare with other sites/lidar gw studies if you plot the lognormal of the GW PE.

15 Author's response: This comment has been replied in the renewed response to the comments of referee #1.

Comments from referees:

Referee #2

The authors describe in the Discussion a relation between the wind field as published by Garcia et al. (1997) and Smith (2012) and the observed variation of GWPED. While there is indeed a pronounced altitudinal and temporal correlation, the

20 paper lacks a description of the mechanism that relates the GW activity and zonal wind velocity. All statements are true, but remain vague and unspecific. The interpretation seems to imply pure zonal propagation of the waves, but the lidar data contain waves of all directions. Is the westerly wind between 60 and 70 km taken into account that may filter a lot of the eastward propagating GW?

Author's response: This comment has been replied in the renewed response to the comments of referee #2.



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

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- 10 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°N, 66.75°W)___, are used to estimate seasonal variations of the mean temperature, the squared Brunt-Väisälä frequency, N², 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.) Temperature Inversion Layers (TILs) occur at ~96 km
- 15 in spring, at ~ 91 km in summer and early autumn, and at ~94 km in winter; The profiles of N² usually reach the maxima at or just below the temperature inversion layer when that layer is present. 3. The first complete range-resolved climatology of Gravity Wave pPotential Eenergy (GWPE) -derived fromof temperature fluctuations-data in the tropical MLT exhibits an altitude dependent combination of annual oscillation (AO) and semiannual oscillation (SAO). The maximum occurs in spring and the minimum in summer, a second maximum is in autumn and a second minimum in winter. 4. The GWPE per
- 20 unit volume damps below ~ 97 km altitude in all seasons. The damp of GWPE is significant at and below the TILs but becomes faint above, this provide strong support to the mechanism that the formation of upper mesospheric TIL is due mainly to the damp of GWPE. The climatology of GWPE shows an indeed pronounced altitudinal and temporal correlation with the wind field in the equator mesopause region published in the literature. This suggests the GW activity in the tropical mesopause region should be manifested mainly by the filtering effect of critical level of the local background wind. Between
- 25 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
- 30 mean zonal winds reported in the literature.

1 Introduction

Gravity <u>waves_Waves</u> (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 <u>usually</u> often originate from copious tropospheric sources and

- 5 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
- 10 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 altitude ranges, where GWs interact with the background wind dissipating and deposing energy and momentum is of high interest to researchers. This happens mainly in the middle atmosphere near or between stratopause and mesopause. Above 35
- 15 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, 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.
- 20 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 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
- 25 above and below about 80 kmfrom 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 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 MLTshowed that, the easterly winds were prevailing in equinoxes seasons near 80 km
- 30 <u>altitude. They then decreased with altitude from 80 km above and turned to increase above ~ 925 km, while the westerly winds prevailed in 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 will enhance damping or dissipating of zonal propagating gravity wave with low to moderate phase speed.</u>

Temperature is a crucial parameter indicating the state of the atmosphere. To measure the temperature in the MLT region, satellite and lidar techniques arehave 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

- 5 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
- 10 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 annual variation with maximum in winter and minimum in summer, they damped significantly at the upper mesosphere
- 15 altitudes above ~ 70 km in all seasons, while the damping below ~ 70 km is not so eminentevident. Mzé et al. (2014) almost observed a nearly undamped the conservation 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
- 20 results suggest more attention should be paid to the GW parameterization about these kind of -observations ofin the upper mesosphere and mesopause region to improve the GW parameterization in the atmospherie-model results. Seasonal variations of GW activities based on lidar temperature measurements have been investigated at <u>a</u> 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
- 25 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 <u>different transitionforming</u> of the mean zonal wind <u>in the range above 80-95</u> km in the tropical region noted above, the seasonal variability of GW activity in the tropical upper mesosphere is expected to be different from either the lower altitudes or the mid- and high-latitude regions.
- 30 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°N, 66.75°W), Puerto Rico (Friedman and Chu, 2007; Yue et al., 2013, 2016, 2017). Since December 2003, the Arecibo Observatory K Doppler lidar has operated routinely, producing high-quality temperature data. In this
 - 21

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 wave in the MLT are discussed.

2 Observations

5

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
- 20 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.

25 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 estimate from temperature observations and then is chosen as a measure of GW activity. and E_p -is defined as (see, e.g.,

30 Vincent et al., 1997)

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

where

$$N^{2} = \frac{g}{\overline{T}} \left(\frac{d\overline{T}}{dz} + \frac{g}{c_{p}} \right), \tag{2}$$

Here g equals to 9.5 ms⁻², is the gravitational acceleration in MLT; N is the Brunt-Väisälä frequency calculated according

(1)

- 5 to Eq. (2); \overline{T} is the mean temperature averaging over altitude; T' is the temperature perturbation; and C_p is the constantpressure heat capacity, equals to 1004 JK⁻¹kg⁻¹. In Eq. (1), the calculation of Ep depends on the estimations of N, \overline{T} and T'. The procedure adopted by Gardner and Liu (2007) is closely followed here for the estimation of T'. It includes 4 steps. Step 1: for each night of observation, data points with photon noise errors larger than 30 K in temperature are discarded. The value of 30 K is set based on the fact that the root mean square errors (RMSE) due to photon noise often reach to about 40-
- 10 50 K near the edges (~80 km on the bottom and ~105 km on the top) of the temperature profile. Step 2: the linear trend in time at each altitude in the temperature profile is then subtracted to eliminate the potential biases associated with GWs with periods longer than about twice the observation period. Step 3: Perturbations exceeding three standard deviations from the nightly mean are discarded from the resulted temperature perturbation series at each altitude to remove occasional outliers. Step 4: the vertical mean is subtracted from each temperature perturbation profile to eliminate the influences of the waves
- 15 with vertical wave length longer than about twice the profile height range (~ 25 km). The resulted temperature perturbation profiles usually cover the height range 80-105 km. Therefore, the weekly composite nights of temperature, N^2 and the consequential E_p usually cover the height range 80-105km. To avoid the uncertainty of the analysis, we focus on the height range 85-100 km where the RMSE of each instantaneous observed temperature usually less than 10 K.
- The unified 0.9 km and 0.5 h30 minutes resolution temperature profiles and the extracted temperature perturbation profiles 20 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 \overline{T} is shown in Fig. 2. Temperature Inversion Layers (TILs) can be found in most months.

The weekly composite night data of \overline{T} and T^{t} are is 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

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

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.

4 Results and Discussion

- 5 In the following the results of the analysis is are 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 \overline{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 leftright panels) and 23d, 34d and 45d (bottom right
- 10 panels), respectively. The annual mean profiles of N² and E_p are also plotted in Fig. 3c and 4c. 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 N², 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 lefttop right)
- 15 <u>altitude in this range.</u> The averaged results and the fitted curves are plotted in Fig. 23b, 34b and 45b (<u>bottom lefttop right</u> panels). The statistical parameters for this fit are summarized in Table 2.

4.1 Seasonal Variation of the Mean Temperature

Figure 2 shows the profiles of the weekly mean temperature *T*, the corresponding harmonically fitted temperature is shown in Fig. 3a. ItFigure 2a shows that the Arecibo climatology is warmer in late-autumn-early-winter and colder in summer throughout all altitudes. An inversion layer<u>TILs</u> is present in most of the time, which are represented by the black cross in Fig. 3a. In spring, The altitude of the local maximum of the temperature inversion layer<u>TILs</u> occurs at ~95-96 km from late February to May April. In summer, and <u>TILs</u> descendappears to at ~ 91 km in-from late May to the first half of early June, after which it maintains this altitude until September. In winter, TILs occur at ~94 km from the second half of September to the first half of February. 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.

- Figure 3c shows that the amplitudes of the AO are obviously larger than that of the SAO. Fig. 3d shows that the phase (defined as the time of the maximum perturbation) of AO oscillates in a not wide range between day of year (DOY) -60 and 10, while that of SAO varies between DOY 110 and 150. The amplitudes of the AO are obviously larger than that of the SAO as shown in Fig. 2c. The phases (defined as the time of the maximum perturbation) of both AO and SAO are
- 30 independent of height and located near DOY 110 and 330, respectively. Figure .13b shows that the mean temperature is

warmest between October and November and coldest in July. An insignificant<u>A</u> 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

- 5 more than 10 nights, they help to keep the confidence level of the harmonic fit. Moreover, the temperature structure shown 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
- 10 amplitude shown in Fig. 3c agree quite well with that observed by SABER in both magnitude and vertical structure. The 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 <u>phase of SAO</u>, the <u>amplitude and phase of</u> A<u>O</u>seasonal variation of the mean temperature is consistent with a previous study by Friedman and Chu (2007) (see their Fig.

- 6 to 7), who used data collected between December 2003 and September 2006. <u>Comparing Fig. 3a here to the Fig. 6 in</u> 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 lack of adding
- 20 the smoothed residual temperature back to T(z, t) estimated by using (3) 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).

4.2 Square of the Brunt-Väisälä frequency

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 $3a \cdot 4a$ shows that the atmosphere is statically stable on average throughout the height range from 85 to 100 km. The region of greater average stability lay just at and below the temperature inversion layers (shown in Fig. $2a \cdot 3a$) 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. <u>3b-4b</u> 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 N^2 is larger than 3.5×10^{-4} s 2 in all months, which indicate that the atmosphere is highly stable in this region over Arecibo.

Figure 3c 4c shows that the annual mean N^2 is larger than 4.0×10.4 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. . we allow negative amplitudes to

- 5 make the phase oscillation of the two components look in order as shown in Fig. 4d. There are several turning points at altitudes ~87 km, ~ 92km, ~94 km, ~96 km in the profiles of AO and SAO phases. The last three of these altitudes correspond to the altitudes of TILs., but their phases fluctuate. This agrees with the fact that the TILs locate at different altitude and N^2 becomes large just below TIL (increased dynamical stability).randomly with altitude as shown in Fig. 3d. 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
- 10 oscillates in a wide range between DOY 0 (near the bottom) and 290 (75 in the 96 to 98 km range). 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 15 GW 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

20 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 5c shows that the amplitudes of both the 12-month and the 6-month oscillations are comparable at most altitudes. The amplitude of 6-month oscillation becomes smaller in the altitude range 94-98 km. The SAO amplitude decreases to almost 0

- 25 J. kg⁻¹ at 97-98 km. Fig. 5d shows the phase of 6-month oscillation is almost independent of altitude. It is quite close to DOY 100 at most altitude. The AO has almost the same phase as the SAO 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. The RMSE of the AO/SAO phase becomes oddly large near 87/97 km altitudes, respectively, where the AO/SAO amplitude reaches. 0 J. kg⁻¹. It can be seen in Fig. 5a that the seasonal variations of E_n are flat at these two altitudes. Figure 4c shows that the annual mean profile of potential
- 30 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 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.

5 As the seasonal variations of E_p show semi-annual oscillation dominated features with the approximated phases in the 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 J. kg⁻¹ near vernal equinox and the minimum of 264 J. kg⁻¹ in the end of November. The maximum is a factor of 1.5 larger than the minimum.

10 5 Discussion

45.41 Mesospheric Temperature Inversion Layer Discussion

We have noticed that obvious TILs occur at ~96 km in spring, at ~ 91 km in summer and early autumn, and at ~94 km in winter. The TIL in the upper mesosphere over Arecibo had been reported both in case study and/or study of climatology by using subset of the data used in this study (Yue, et al., 2016; Friedman and Chu, 2007). The formation mechanism for TIL in

- 15 the mesopause region 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 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 decrease of the GW
- 20 E_p are expected at and just below the locations where DW1 amplitude is large. Climatology of WACCM Simulations showed that, at 20° 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 their Fig. 10 match perfectly with the TILs in Fig. 3a.

5.2 Damp of GW Potential Energy

- 25 For freely propagating GWs, the potential energy per unit mass (J. kg⁻¹) 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 ~ 97 km in all seasons. Above ~ 97 km, the GW potential energy enhanced significantly with altitude. The solid curve decreases below ~ 92 km and turn to increases above. The increase become significant above 97 km altitude. This behavior of mean potential energy is much similar to that retrieved from satellite temperature data (Offermann et al., This behavior of mean potential energy is much similar to that retrieved from satellite temperature data (Offermann et al., Solid curve decreases).
- 30 2006, see their Figures 10 and 11). The altitude of ~ 97 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 deposing 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.

- To learn in depth the dissipation of GW in the mesopause region at Arecibo, we multiplied the harmonic fitted E_p with the
- 5 air density taken from the CIRA-86 reference atmosphere [Fleming et al., 1990], and average every 13 weekly profiles (period of a season) centring at each equinox or solstice. The resulted profiles of the potential energy per unit volume (in J. m⁻³) in four seasons are plotted in Fig. 6. If GWs propagate upward without energy dissipation, the lines of energy per unit volume would be vertical. Therefore, the overall left-sloping lines in Fig. 6 indicate that the damps of GW potential energy occur below ~97 km in all seasons. The damp of GW potential energy in the mesosphere had been reported by lidar
- 10 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. The damp of GW E_p in the mesopause region is assumed to be caused by the interaction between DW1 tide and GW (Xu et al. 2009), the larger the amplitude of tide, the larger the energy damp. The climatology of the DW1 tide amplitude at 20°N was shown in Fig. 10 of Smith (2012), which showed the DW1 tide amplitudes in winter were significantly smaller than the
- 15 other three seasons, this matches with the smallest damp of $GW E_p$ in winter as shown in Fig. 6 here. The damp of $GW E_p$ indicates the deposition of GW energy and momentum into the background atmosphere, which would lead to the increase of background temperature and/or even the occurrence of TIL. This drives us to investigate the relationship between the damp of $GW E_p$ and the temperature structure in depth. We are excited to find that each profile of the GW potential energy per unit volume ((in J. m⁻³) as shown in Fig. 6 shows a rapider damp of energy at and below the TIL altitude of the corresponding
- 20 season and turns to a much slower damp and/or even conservation of energy above. For examples, the behaviours of the green curve (profile for winter) around 94 km altitude (the altitude of TILs in winter), the blue curve (profile for summer) around 91 km altitude (the altitude of TILs in summer). The black curve (profile for spring) around 96 km altitude (the altitude of TILs in spring). These close connections of the mesospheric TILs with the damp of GW potential energy provide strong support to the mechanism that the upper mesosphere TIL formed due to the interaction of GW with the upper
- 25 mesospheric wind/diurnal tides through critical level effects. We notice that in the altitude range 85-95 km, where the GW potential energy damps significantly in all seasons, the background temperature decreases in an oscillational way from ~ 195 K to ~185 K. The corresponding mean temperature decreasing rate is of ~ 1 K/km which is extremely smaller than the lapse rate of ~ 9.5 K/km in this altitude region. Above 97 km, the GW potential energy per unit volume either conserves with altitude in summer and winter or turn to increase with
- 30 altitude in spring as shown in Fig.6. Correspondingly, the background temperatures in Fig. 3a decrease sharper in seasons spring, summer and winter. It is worth to note that in autumn the GW potential energy per unit volume turn to increase at ~ 96 km altitude where the mesopause occurs as shown in Fig. 3a. These results are very valuable in helping to improve the parameterisation of GW in the mesopause region in global circulation models.

5.3 Seasonal variations of GW Potential Energy

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 stations. Gavrilov et

- 5 al. (2003) studied the GW seasonal variations by using Medium-Frequency (MF) radar observation over Hawaii (22° N, 160°
 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 station of 54° N
- 10 latitude 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-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⁻¹ on average at 75.5 km in August while the minimum of E_p is about a
- 15 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. 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
- 20 the dependence of GW generation and propagation on background wind and temperature by numerical simulations. In a midlatitude station Juliusruh (55° N, 13° 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
- 25 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. 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 literatures reported studies about seasonal variation in of SAO-mean zonal wind studies in the tropical mesopause region (see e.g., Fig. 3 in Garcia et al. 1997; Fig. 3 in Smith 2012)₅, the monthly mean HRDI equatorial
- 30 zonal wind 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 km, while the westerly winds prevailed in in the range 80-94 km in solstice seasons, they then turn to be easterly. the reversal is at about 95 km (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

- 5 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 J. kg⁻¹ is a factor of 1.3 larger than the second maximum of 319 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
- 10 altitude and at almost the same time. Fourthly, the zero wind line near 96 km altitude throughout a whole year is accordance to the almost equal E_p at almost the same altitude in all seasons. Fifthly, the transition of mean zonal winds to easterly winds 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 an indeed pronounced correlation between the local mean zonal wind field and the lidar observed GW E_p . This relationship agrees perfectly with the connection of wind and GW in the middle atmosphere
- 15 demonstrated by Lindzen (1981). Correlation between GW potential energy and local winds has been suggested by Wright et al. (2016) in their multi-instrument GW measurements over Tierra del Fuego (54°S, 68°W), which was devoted to the Doppler shifting of waves into the observational filters of the instruments by these winds. 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
- 20 then increase of gravity wave potential energy relates closely to the fact that the prevailing easterly winds decreases with altitude below -91 km and then shifts to increase with altitudes above and reaches a maximum just below 100 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
- 25 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
- 30 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.kg-1) should increase exponentially with altitude for the conservation of energy. Fig 4a 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. 4c. The solid curve varies slightly below ~ 95 km

- 5 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 deposing energy below about the mesopause (or the wave turbopause defined by Offermann et al. 2016), but it propagates upward almost freely after 10 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
- 15 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.

56 Summary and Conclusion

The first complete range-resolved climatology of potential energy 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 \overline{T} , the square of the Brunt-Väisälä frequency N^2 and the potential energy of perturbations 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 harmonies, the phases of AO and SAO are random with altitude for \overline{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

25 energy reaches the minimum at 91 to 92 km altitude range. The amplitudes of AO and SAO for potential energy reach the minima at 97 to 98 km altitude. The main characteristics of the observations are as follows.

1. Mesospheric TILs occur in the altitude range 90-95 km in most months except October and November. The decrease rate of background temperature in altitude range 85-95 km is extremely smaller than the lapse rate.

2. The GW potential energy per unit volume (in J. m⁻³) damps in the altitude range 85-97 km in all seasons. Close
 30 relationship exists between the damp of GW potential energy and the TILs. This provides strong support to the mechanism of the TIL formation in the mesopause region.

3. The seasonal variations of GW potential energy are dominated by the combination of annual and semiannual oscillation at most altitudes. The maxima occur in spring and autumn and the minima occur during solstices. The observed GW potential energy is compared to the wind field as published by Garcia et al. (1997) and Smith (2002), There is indeed a pronounced altitudinal and temporal correlation between them. This suggests that the seasonal variation of GW activity should be

5 determined mainly by the local wind field through the influence of critical level filtering of GW by the background wind.

The seasonal variations and vertical structures of E_p relate closely to the HRDI zonal winds reported in the literature. These relationships 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-

- 10 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.
- 15 *Competing interests.* The authors declare that they have no conflict of interest.

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

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

 $^{\rm a}$ D/H stands for Days/Hours; $^{\rm b}$ Observed in 2003; $^{\rm c}$ Including the observations in 2003.

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

	Annual	Amplitude		Phase	RMS	
	Mean	12-month	6-month	12-month	6-month	Residual <u>-</u> 0
Mean temperature (K)	188.7	3.6	1.8	-34	-57	5.5
$\overline{N^2}$ (10 ⁻⁴ s ⁻²)	4.37	0.09	0.12	160	22	0.37
Potential Energy (Jkg ⁻¹)	351.8	55.9	42.1	119	-89	141.6

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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.



Figure 2: the weekly mean temperature profiles in the mesopause region at Arecibo.





Figure 2<u>3</u>: (a) Seasonal variations of <u>the harmonic fitted nocturnalight time</u> temperature plotted versus altitude and month, <u>the crosses represent the altitude of temperature inversion layer</u>, (b) <u>observed (dotted curve) and harmonic fitted (thick solid curve)</u>
 mean temperature between 87 and 97 km, the width between the thin solid curves and the thick solid curve is 1σ₃seasonal variation of mean temperature between 87 and 97 km, (c) 12-month (dashed <u>curve</u>) and 6-month (dotted <u>curve</u>) amplitudes and (d) 12-month (solid <u>curve</u>) and 6-month (dotted <u>curve</u>) phases.





Figure 34: (a) Seasonal variations of <u>the harmonic fitted</u> squared Brunt-Väisälä frequency N²N2 plotted versus altitude and month, (b) <u>observed (dotted curve) and harmonic fitted (thick solid curve) mean N² between 87 and 97 km, the width between the thin solid curves and the thick solid curve is 1σ₃seasonal variation of mean N2 between 87 and 97 km, (c) annual mean profile (solid) and 12-month (red dashed) and 6-month (blue dotted) amplitudes and <u>their 1</u> σ deviations (thin lines), (d) 12-month (red dashed) and 6-month (blue dotted) phases and their 1 σ deviations (thin lines),
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Figure 45: (a) Seasonal variations of <u>harmonic fitted squared</u>-potential energies plotted versus altitude and month, (b) <u>seasonal</u> variation of <u>observed</u> (dotted curve) and harmonic fitted (thick solid curve) mean potential energy between 87 and 97 km, the width between the thin solid curves and the thick solid curve is 1σ , (c) 12-month (red dashed) and 6-month (blue dotted) amplitudes and their 1σ deviations (thin lines), (d) 12-month (red dashed) and 6-month (blue dotted) phases and their 1σ deviations (thin lines), (d) 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 J. m⁻³) averaged over spring (13 weeks mean centred at vernal equinox, black line), summer (13 weeks mean centred at summer solstice, blue line), autumn (13 weeks mean centred at autumn equinox, red line), winter (13 weeks mean centred at winter solstice, green line).

