Replies to the Reviewer#2

Dear Reviewer,

Thank you very much for your feedback and constructive comments. I sincerely appreciate the time and effort you devoted to reviewing my manuscript. I would like to respond to the points you raised as follows (in this reply, the comments of the referee are marked in black color, and the replies in blue color):

Comments 1： The title does not clearly describe the article. The radar data cover the lower stratosphere and the MERRA data are not mentioned.

Reply 1：

Adopted.

We have accepted your suggestion and revised the title to: "Research on 16-day Planetary Waves in the Mid-latitude Troposphere, Stratosphere, Mesosphere, and Lower Thermosphere with Langfang Dual-frequency ST-M Radar Data and MERRA-2 Reanalysis Data."

Comments 2： Extracting Daily Mean Wind:

Why do the authors use the criterion of 10 hours? What are the errors of the daily wind speeds obtained with the method proposed by the authors?

Reply 2：

Adopted and explanation below.

To reduce potential biases in the estimated values caused by diurnal variations, we derived the daily mean wind fields using at least ten hourly mean wind measurements evenly distributed throughout the day and night. A preliminary estimate indicates that the standard deviation of the daily mean wind in the MLT region is within 3–6 m/s, while that in the ST region is within 0.1–2 m/s. Previous studies have also adopted similar approaches to maximize the use of observational data, such as using six hourly wind measurements to estimate the daily mean wind for analyzing the 16-day planetary wave (Luo et al., 2002), or using three hourly wind measurements for the same purpose (Jiang, Xiong, Wan, Ning, & Liu, 2005).

To improve the accuracy of the daily mean wind estimation, we raised the standard in the manuscript to include data from eighteen hourly measurements per day. As a result, the updated analysis led to five additional days of missing data; however, this does not affect the main analysis or the overall conclusions.

Comments 3： Detrending

The MLT winds are characterized by the strong seasonal course and strong changes in spring, sometime in autumn and during SSW (for example, in January 2024). The wind behavior model with a simple linear trend is not correct for these cases. Therefore, the 16-day wave parameters may be obtained with large errors or may be completely incorrect. I recommend removing the seasonal course first.

Reply 3：

We have accepted the suggestion.

We analyzed the wind field data with the seasonal course removed. While some differences in detail were observed between the results of band-pass filtering and Lomb-Scargle (LS) analysis, the overall results are improved.
These differences do not affect the main analysis or the conclusions of the study.

Comments 4： Spectral analysis
The time series of the zonal and meridional wind speeds have large gaps from month 3 to month 5 (figure 1). On the one hand, such gaps may easily distort the spectrum obtained with the Lomb-Scargle method. On the other hand, the authors fill in the gaps for their further analysis.
I recommend removing the data with these large gaps.

Reply 4：

Adopted.

There are data gaps in the observations from March to May, which may affect the LS spectrum. However, we decided to retain the spectral results for this period **in order to provide a reference for the annual variation of planetary wave**. The analysis following Section 3.2 is primarily focused on the characteristics of planetary wave activity during autumn and winter.

Comments 5： Figure 3. Please, indicate units of the color levels. What level is significant?

Reply 5：

The color scale unit in Figure 3 is m/s, which has now been explicitly labeled in the figure. In addition, the 90% confidence level has been indicated with white dotted lines.

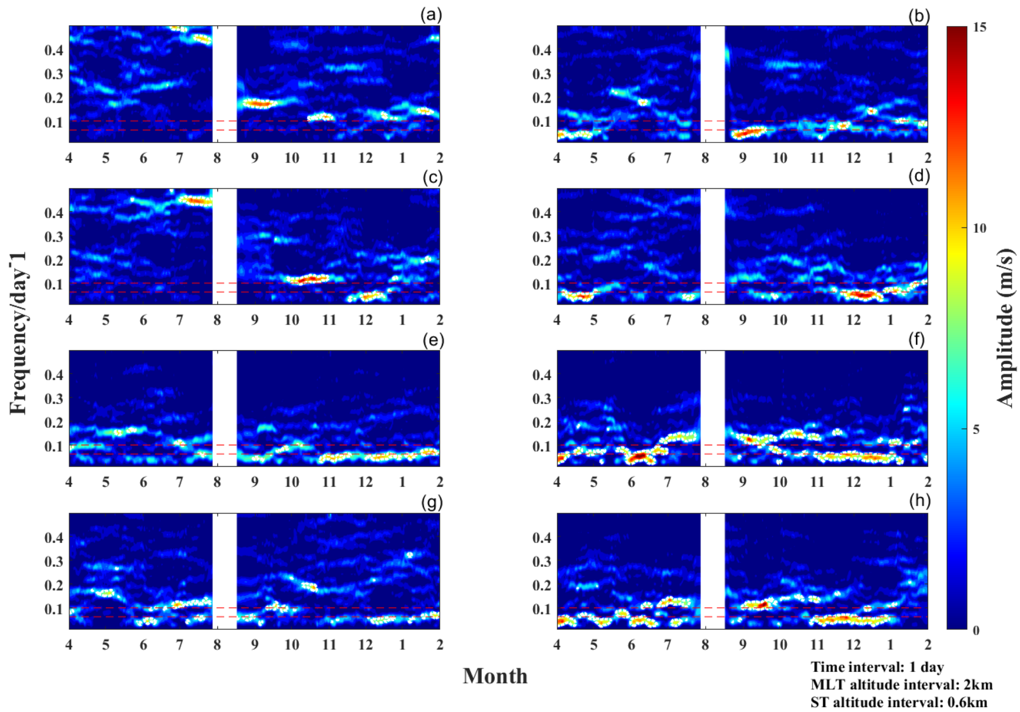

Figure 3: LS spectral analysis results of horizontal wind perturbations at different altitudes over Langfang from March 2023 to February 2024: (a)(c)(e)(g) are the results of the LS spectrum analysis of the meridional wind disturbance at 96 km, 84 km, 13.8 km, and 7.2 km,

respectively; (b)(d)(f)(h) are the results of the LS spectrum analysis of the zonal wind disturbance at 96 km, 84 km, 13.8 km, and 7.2 km, respectively. (The red dashed lines from top to bottom correspond to the frequencies of 10-day and 16-day planetary waves. The white dotted line represents 90% confidence level.)

Comments 6： L.325-330 “No significant planetary wave activity is observed in the MLT during summer…”
How do the authors separate significant and non-significant wave activity?

Reply 6：

We have added confidence level information to the LS spectrum. The planetary wave amplitudes during summer are all below the 90% confidence level, indicating that the planetary wave activity in summer is not significant.

In the revised version, we have updated the height–time distribution of the 16-day wave amplitude, as shown in Figure 5.

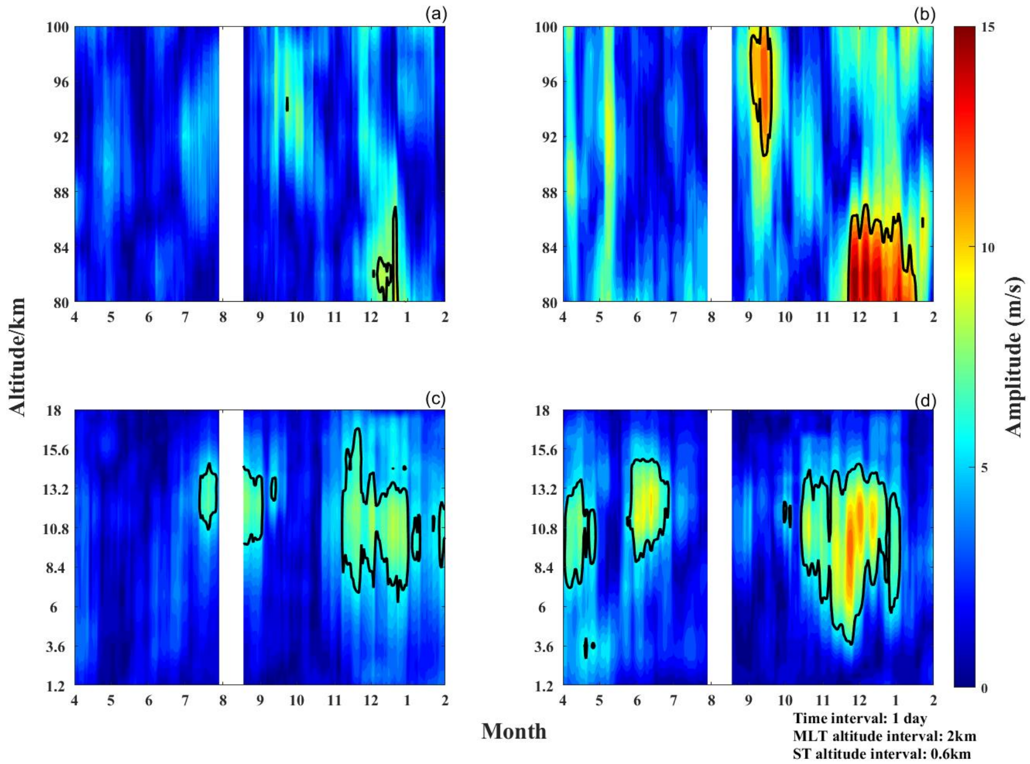

Figure.5 Amplitudes of 16-day waves with 90% confidence level versus height and time: (a)(c) results of LS processing of daily-mean meridional wind perturbations; (b)(d) results of LS processing of daily-mean zonal wind perturbations (the blank area indicates the time period when the data coverage is less than 50%, and the black solid line represents 90% confidence level)

Comments 7： Ln. 350-365 Please, indicate errors of the vertical wavelength you found.

Reply 7：

We have added the errors of the planetary wave vertical wavelength in the manuscript.

We calculated the phase slope and subsequently derived the vertical wavelength. Using the bootstrap method, we estimated the errors and 95% confidence intervals for both the phase slope and vertical wavelength. The results for the MLT and ST regions are presented in Tables 3 and 4, respectively.

Table.3 Dates, altitude ranges and calculations of significant 16-day wave in the MLT

Date	Altitude (km)	Slope (km/rad)	Wavelength (km)
9.3~9.18	90~100	-16.37 ± 2.43 95% CI: [-21.41, -13.40]	102.84 ± 15.25 95% CI: [84.21, 134.53]
11.22~12.23	80~85	19.36 ± 10.89 95% CI: [13.34, 32.00]	121.62 ± 59.99 95% CI: [86.52, 203.54]
12.24~1.14	80~85	14.28 ± 1.08 95% CI: [13.11, 15.57]	89.75 ± 4.31 95% CI: [82.38, 97.82]

Table.4 Dates, altitude ranges and calculations of significant 16-day wave in the ST

Date	Altitude (km)	Slope (km/rad)	Wavelength (km)
10.12~11.5	8.4~12.6	15.00 ± 2.28 95% CI: [12.17, 21.26])	94.23 ± 14.34 95%CI: [76.44, 133.59]
11.7~12.2	6~12	13.50 ± 1.27 95% CI: [11.61, 16.35]	84.80 ± 7.97 95%CI: [72.97, 102.74]
12.6~12.23	9.6~13.2	-9.61 ± 1.33 95% CI: [-11.35, -7.76]	60.37 ± 8.36 95% CI: [48.78, 71.34]
12.24~1.3	6~12	-5.52 ± 0.42 95% CI: [-6.65, -4.91]	34.70 ± 2.65 95% CI: [30.86, 41.76]

Comments 8： Ln.367-376 It is very important for the analysis provided in this part and below that the errors of the phase speeds are small enough to draw any conclusion.

Reply 8：

We have included the errors of the apparent vertical phase speed. The results show that the errors do not affect the propagation direction of the apparent vertical phase speed. Therefore, our analysis remains valid, and the conclusions of the manuscript are unchanged.

The errors of the apparent vertical phase speed are presented in Tables 5 and 6.

Table.5 Relationship between m, k, apparent phase speed $c_{pz,a}$ and c_{gz} of the significant 16-day wave in the ST

Date	Altitude (km)	Positive and negative of m	k	$c_{pz,a}$ (cm/s)	Direction of $c_{pz,a}$	Direction of c_{gz}
10.12~11.5	8.4~12.6	+	3	6.82 ± 1.04 95%CI: [5.53, 9.66]	↑	↑
11.7~12.2	6~12	+	3	6.13 ± 0.58 95%CI: [5.28, 7.43]	↑	↑
12.6~12.23	9.6~13.2	-	-2	-4.37 ± 0.60 95%CI: [-5.16, -3.53]	↓	↑
12.24~1.3	6~12	-	-2	-2.51 ± 0.19 95%CI: [-3.02, -2.23]	↓	↑

Table.6 Relationship between m, k, apparent phase speed $c_{pz,a}$ and c_{gz} of the significant 16-day wave in the MLT

Date	Altitude (km)	Positive and negative of m	k	$c_{pz,a}$ (cm/s)	Direction of $c_{pz,a}$	Direction of c_{gz}
9.3~9.18	90~100	-	-3	-7.44±1.10 95%CI: [-9.73,-6.09]	↓	↑
11.22~12.23	80~85	+	3	8.80±4.34 95%CI: [6.26,14.72]	↑	↑
12.24~1.14	80~85	+	3	6.50±0.31 95%CI: [6.25,6.12]	↑	↑

Comments 9: Ln.380 $Q_y < 0$ is not sufficient for the instability.

Reply 9:

Accepted.

We have removed this sentence.

Comments 10: Ln.380-383 The authors use the result of the quasi-geostrophic theory. The conclusion from eq.3 is not correct. The vertical phase speed is opposite to the vertical group speed in the coordinate system that moves with the zonal flow (Qy > 0). If one takes into account the background zonal flow U_0, then the result will be complex and will depend on U_0.

By the way, the authors should explain the notation in the equation and provide a reference.

Reply 10:

Adopted.

We have added the $1/4H^2$ term in eq.3. There was a mistake in the value of c_p given in the manuscript. We have added descriptions and explanations of the apparent vertical phase speed $c_{pz,a} = \sigma/m$ and the intrinsic vertical phase speed $c_{pz,i} = \omega/m$.

Our results show that the apparent vertical phase speed undergoes a reversal from upward to downward propagation, whereas the vertical group velocity consistently propagates upward without any change in direction.

Although the intrinsic vertical phase speed and the vertical group velocity propagate in opposite directions, this relationship does not hold for the apparent vertical phase speed. The apparent vertical phase speed is influenced in a more complex way by the background wind.

The descriptions and explanations of the apparent vertical phase speed $c_{pz,a} = \sigma/m$ and the intrinsic vertical phase speed $c_{pz,i} = \omega/m$ are as follows:

The perturbation potential vorticity equation for wave motion on a β plane(Salby, 1995):

$$\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial}{\partial z}\left(\frac{f_0^2}{N^2}\frac{\partial}{\partial z}\right)\right]\psi' + \beta\frac{\partial \psi'}{\partial x} = 0 \tag{1}$$

where U represents the background zonal wind, z refers to log-pressure height, f_0 is the Coriolis parameter, N is the Brunt–Väisälä frequency, ψ' is the geostrophic streamfunction, and β is the planetary vorticity gradient.

Since coefficients are constant, we consider solutions of the form $e^{[(z/2H)+i(kx+ly+mz-\sigma t)]}$, where H is the atmospheric density scale height, k、l、m are the zonal, meridional, and vertical wavenumbers, respectively, and σ is the apparent frequency. Substituting into the above equation gives the **apparent frequency σ**:

$$\sigma = Uk - \frac{\beta k}{k^2 + l^2 + \left(\frac{f_0^2}{N^2}\right)\left(m^2 + \frac{1}{4H^2}\right)} \tag{2}$$

The **intrinsic frequency ω** is given by:

$$\omega = \sigma - Uk = -\frac{\beta k}{k^2 + l^2 + \left(\frac{f_0^2}{N^2}\right)\left(m^2 + \frac{1}{4H^2}\right)} \tag{3}$$

The data measured by the ST-M radar, after frequency-domain processing, yield the apparent frequency. From this, the **apparent vertical phase speed** can be further derived as:

$$c_{pz,a} = \frac{\sigma}{\mathrm{m}} \tag{5}$$

The **intrinsic vertical phase speed** is given by:

$$c_{pz,i} = \frac{\omega}{\mathrm{m}} \tag{6}$$

For the 16-day wave, $\sigma 为 \frac{2\pi}{16} rad/day$, and the direction of the apparent phase speed depends on the sign of m.

The **vertical group velocity** is given by:

$$c_{gz} = \frac{\partial \omega}{\partial \mathrm{m}} = \frac{2\beta m\, k(\frac{f_0^2}{N^2})}{[k^2+l^2+(\frac{f_0^2}{N^2})(m^2+\frac{1}{4H^2})]^2} = (\frac{f_0^2}{N^2})\frac{2m\omega^2}{\beta k} \tag{7}$$

The direction of the group velocity depends on the sign of mk.

Comments 11： L.385 “Fig.5. Assuming that the frequency-wavenumber spectrum in the MLT is consistent with that at the 79 km altitude, the dominant wavenumber for each time was selected as the wavenumber for that period. “

Why are the spectra consistent? The MERRA-2 data are given at the model level, but the MR winds are given at altitudes. The difference between the true heights may be significant.

Reply 11：

The wavenumber can vary with altitude. In the ST region, we obtained the frequency–wavenumber spectra at different altitudes using MERRA-2 reanalysis data. However, due to the lack of other data sources, we were unable to obtain the frequency–wavenumber spectra in the MLT region. As a simple reference, we used the spectrum at approximately 79 km derived from MERRA-2 reanalysis data.

This approximation may be inaccurate for regions with large altitude differences and is only intended as a possible explanation for the observed reversal in phase propagation direction in the MLT region.

Comments 12： There is no confidence that oscillations presented in Fig.5 are statistically significant.

Reply 12：

We used the **Monte Carlo method** to estimate the confidence levels of the wavenumber. The regions outlined by solid white lines in the figure indicate wavenumbers with a 90% confidence level.

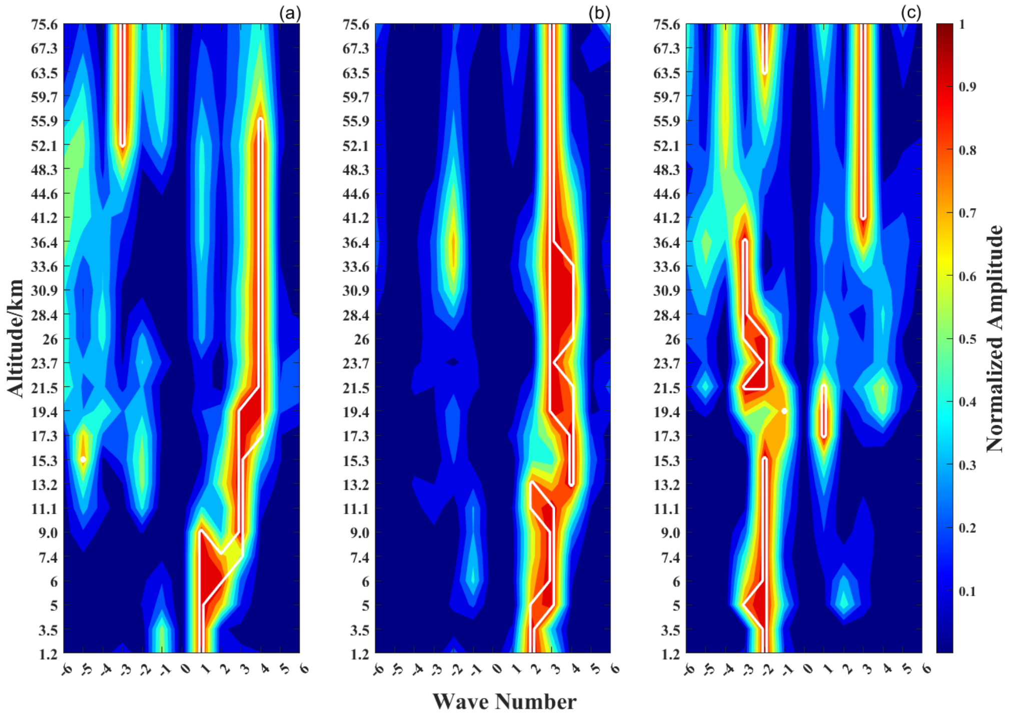

Figure.7 Frequency-wavenumber spectrum with a 90% confidence level: (a), (b), and (c) are the frequency-wavenumber spectra from 1.2 to 75.6 km for the periods September 3 to October 4, October 12 to December 2, and December 6 to January 14, respectively (negative wavenumber indicates westward wave propagation).

Comments 13： The aim of this part is “To investigate the location of the wave source in the ST” and “the relationship between the planetary waves in the two regions”.

The analysis is confined in latitude and longitude to the region where the radar is located. Therefore, the authors (and the readers) do not know how 16-day waves propagate in the neighboring region. Hence, the authors can’t really reach their aim.

Additional note, the real atmospheric 16-day waves are transient, their amplitudes are changing with time as observed. The theory used in this part does not work for such waves.

I propose to find and plot the E-P flux for the waves.

Reply 13：

We have made corresponding adjustments to the objective of this study.

The aim of the paper is to use ST-M radar observations to reveal the characteristics of 16-day planetary wave activity in the ST and MLT regions above Langfang, and to attempt to explain a newly observed phenomenon—namely, the reversal of the vertical phase propagation direction of the 16-day wave in the ST region.

The ST-M radar at the Langfang observation station is a newly developed instrument for detecting wind fields in the ST and MLT regions over mid-latitudes. Observational data reveal that the 16-day wave simultaneously exists in both regions above Langfang.

To explore whether there is a connection between the planetary waves observed in the ST and MLT regions above Langfang, we introduced MERRA-2 reanalysis data to extract the zonal wavenumber and analyze the background wind conditions associated with the upward propagation of the 16-day wave. This provides a useful reference for understanding the relationship between planetary waves in the ST and MLT regions over Langfang.

The identification of planetary wave sources and the study of their propagation require global data and the application of Eliassen–Palm (E-P) flux analysis. In future work, we plan to conduct a dedicated analysis of planetary wave propagation across different longitudes and atmospheric layers by utilizing reanalysis datasets such as MERRA-2 and employing methods including E-P flux analysis.

Comments 14： Ln.465 “The quasi-16-day and quasi-10-day waves dominate in both the ST and MLT regions” – this conclusion may be a result of the 32-day segment used for the analysis and a linear trend model. The waves with shorter periods are just averaged over the segment and their transient behavior is not taken into account.

Reply 14：

We have revised it to: “The quasi-16-day and quasi-10-day waves behavior obviously in both the ST and MLT regions.”

Comments 15： Conclusions (2) and (3) repeat the first one. The errors of phase speeds are not clear. Therefore, the statements about their changes are not supported in the text.

Reply 15：

We have added the estimation uncertainty of the apparent vertical phase speed, which provides additional support for our analysis. The supplementary results are presented in **Comments 8**.

Comments 16： Ln.475-479 Please, see above. The authors’ statements are incorrect.

Reply 16：

After correcting the mistake in the value of c_p, our conclusion remains valid. The explanation is as follows:

In **Comments 10**, we discussed the relationships among the zonal wavenumber k, vertical wavenumber m, apparent vertical phase speed $c_{pz,a}$, intrinsic vertical phase speed $c_{pz,i}$ and vertical group velocity c_{gz}. The results are as follows:

The direction of the apparent vertical phase speed $c_{pz,a}$ depends on the sign of the vertical wavenumber m, while the direction of the vertical group velocity c_{gz} depends on the sign of mk.

Although the intrinsic vertical phase speed $c_{pz,i}$ and the vertical group velocity c_{gz} propagate in opposite directions, this relationship does not apply to the apparent vertical phase speed $c_{pz,a}$, which is influenced in a more complex manner by the background wind.

Comments 17： Ln. 480 Conclusion (4). This conclusion does not have a solid support from the analysis as it is noted above. The sign of speeds, the wavenumber estimations are in question.

Reply 17：

After distinguishing between the apparent phase speed and the intrinsic phase speed, we maintain that the conclusion is valid. The reasons are as follows:

(1) As discussed in Comments 10, the intrinsic vertical phase speed $c_{pz,i}$ and the vertical group velocity c_{gz} propagate in opposite directions. However, this relationship does not apply to the apparent vertical phase speed $c_{pz,a}$, which is influenced in a more complex way by the background wind.

(2) In Comments 8, we supplemented the analysis with errors of the apparent vertical phase speed. The results show that the errors do not affect the propagation direction of the apparent vertical phase speed.

(3) In Comments 12, we used the Monte Carlo method to estimate the 90% confidence level of the zonal wavenumber k.

Based on the above conclusions and results, and in combination with the zonal background wind shown in Figure 6 of the manuscript, we analyzed the apparent vertical phase speed $c_{pz,a}$, the intrinsic vertical phase speed $c_{pz,i}$ and the vertical group velocity c_{gz} of the significant 16-day waves in the ST region during November 7–December 2 and December 6–23.

The apparent frequency σ of the significant 16-day wave, $\sigma \approx 4.55 * 10^{-6}\, rad/s$.

The intrinsic frequency ω, $\omega = \sigma - Uk$.

During November 7 to December 2, the zonal background wind was approximately $U \approx 38 m/s$, with a zonal wavenumber of 3, $k \approx 6.10 * 10^{-7}\, rad/m$, and $\omega \approx -2.23 * 10^{-5}\, rad/s$. In this case, since ω<0 and m>0, the intrinsic vertical phase speed $c_{pz,i} < 0$, indicating that the energy of the 16-day wave propagates upward.

During December 6 to December 23, the zonal background wind was approximately $U \approx 44 m/s$, with a zonal wavenumber of -2, $k \approx -4.07 * 10^{-7}\, rad/m$, and $\omega \approx 2.24 * 10^{-5}\, rad/s$. In this case, since ω>0 and m<0, the intrinsic vertical phase speed $c_{pz,i} < 0$, indicating that the energy of the 16-day wave propagates upward.

These results further confirm that the apparent vertical phase speed $c_{pz,a}$ of the significant 16-day wave underwent a reversal. However, due to the change in the zonal wavenumber k, the direction of energy propagation remained unchanged. Before and after the reversal of $c_{pz,a}$, the energy of the 16-day wave consistently propagated upward.

Comments 18： Please, directly indicate height intervals and/or time intervals on each plot.

Reply 18：

We have indicated the height and/or time intervals in the figure.

To improve clarity for readers, we simplified the data processing approach by using the Lomb-Scargle method to derive the amplitude, phase, and vertical wavelength of the 16-day planetary wave, and we also added information on the significance level.

Once again, we sincerely thank you for your valuable comments.

References

Jiang, G. Y., Xiong, J. G., Wan, W. X., Ning, B. Q., & Liu, L. B. (2005). The quasi 16-day waves in the mesosphere and lower thermosphere at Wuhan. *Chinese Journal of Space Science, 25*(1), 44-51. doi:https://doi.org/0254-6124(2005)25:1<44:WHSKMZ>2.0.TX;2-M

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