Responses to RC2:

General comments:

This paper describes variations in zonal mean zonal wind related to the annual cycle, the semiannual cycle, a terannual cycle, the QBO, ENSO, solar activity, and overall trend during 2002-2019, in the layer 18-100 km and latitude band 50S–50N. The data set analyzed, named "BU", was created from SABER temperatures. Results compare favorably with results from applying the same analysis technique to MERRA2 data. This paper shows that using zonal mean SABER data, supplemented by a single station of Meteor wind station data above 80 km in the tropics, does a good job of characterizing atmospheric variations zonal mean zonal wind variations at time scales longer than a month or so. Several interesting aspects are described, including an unusual response in the summer SH, which will be useful for other investigators to compare and maybe puzzle over. I recommend publication with minor revision, but have a few questions and a few recommendations for helping the reader to grasp the main approach more quickly.

Response: Thanks for your valuable comments and recommendations on our manuscript. Please see the point-to-point responses below.

Questions and recommendations:

1. It took me several pages (line 137) to figure out what part of the atmosphere you were going to investigate. I would recommend including the altitude range in the title and abstract. The title could be something like "Variation in global zonal wind in the layer 18-100 km due to solar activity, the QBO, and ENSO during 2002-2019". I would recommend also adding the latitude range 50°S-50°N to the abstract.

Response: Following your suggestion, the title has been revised as "Variations in global zonal wind from 18 to 100 km due to solar activity, and QBO, ENSO during 2002–2019".

In the abstract, we have added the "from 50°S to 50°N", this sentence is revised as "Due to the difficulty of directly measuring zonal wind from the stratosphere to the lower thermosphere, we derived the global balance wind (BU) from 50°S to 50°N and during 2002–2019 using the gradient wind approximation and SABER temperatures and modified by meteor radar observations at the equator".

2. L33-37: It is hard to understand the mathematical sense of the relationships being described. Please explain more clearly. These include:

"The responses to QBO shift from positive to negative and extend from the equator to higher latitudes with the increasing height. " -What does this mean?

"The responses to ENSO and F10.7 are strongest (positive and negatively, respectively) in the southern stratospheric polar jet region below 70 km and exhibit hemispheric asymmetry."

"While above 70 km, the responses of BU to F10.7 and ENSO are mainly positive."

Perhaps it would be helpful to state, for example, that zonal winds are stronger in location x when y is happening.

"Both BU and MerU exhibit similar linear changes" – increasing? decreasing?

Response: Thanks for your suggestion. We have revised them in the text as "As the increasing of the QBO wind, both BU and MerU change from increasing to decreasing with the increasing height and extend from the equator to higher latitudes. Both BU and MerU increase with the increasing of MEI (an indicator of ENSO) and decrease with increasing F10.7 (an indicator of solar activity) in the southern stratospheric polar jet region below 70 km. The responses of winds to ENSO and F10.7 exhibit hemispheric asymmetry. While above 70 km, BU increases with the increasing of MEI and F10.7. The negative linear changes of BU at 50°N are absent in MerU during October–January".

3. L32, SAO: It might be good to add Delisi and Dunkerton (1985) as a reference regarding the time asymmetry of the SAO. Did they or Garcia et al. show a N/S hemispheric asymmetry?

Delisi, D. P., T. J. Dunkerton, Seasonal variation of the semiannual oscillation, J. Atmos. Sci., 45, 2772– 2787, 1988.

Response: Using the balance wind derived from the temperature observations by Nibums7 Stratospheric and Mesospheric Sounder, Delisi and Dunckerton (1998) showed that the SAO is stronger in the first cycle (December–May) than in the second cycle (June–November). Moreover, the seasonal asymmetry of SAO is related to hemispheric difference in planetary waves in winter.

We have added "This coincides with the balance wind derived from the temperature observations by Nibums7 Stratospheric and Mesospheric Sounder (Delisi and Dunkerton, 1988)…" in Sec.3.1.

Also, in the summary of Sec.3.1, we have revised as "The SAOs around 50 km and 80 km are hemispheric asymmetric and stronger in the SH, which coincides with the HRDI observations (Ray et al., 1998) and the balance winds derived from temperature observations by satellites (Delisi and Dunkerton, 1988; Smith et al., 2017)."

4. Introduction: It would be helpful to the reader if you described straight away what motivated you to do this study. (Why this data set?) Perhaps say that it is unique in that it involves SABER

data and it targets the upper stratosphere to mesosphere. Please include information about what other wind climatologies have been made with SABER data. Perhaps include a statement as to how this study extends or goes beyond what was described in Smith et al. (2017).

Response: Thanks for your suggestion. The description on the dataset in the Introduction has been revised as “The BU covers a latitude range of 50°S–50°N with step of 2.5° and height range 18–100 km with step of 1 km and a temporal range of 2002–2019. The BU coincided generally with re-analysis data, empirical wind models and observations by meteor radars and lidar (Liu et al., 2021) and with the balance wind derived by Smith et al. (2017) above the equator region. Thus, we focus on variations and responses of global zonal winds to various factors since the BU is a reasonable candidate to monthly mean zonal wind”.

Moreover, in Sec. 2.1, the following has been added “For the consistency of BU and the monthly averaged zonal wind observed at a single station, Figure 3 of Smith et al. (2017) showed that the monthly zonal wind from meteor radar at Ascension Island (8ºS) coincides well with the BU at 81 and 84 km. This indicates that the monthly averaged zonal wind at a single station can represent the zonal average at least below 84 km. While above 84 km, Fig. 2(a) of Liu et al. (2021) shows that the theoretical balance winds are mainly eastward. In contrast, the reconstructed winds (Fig. 2b and 2c of Liu et al. (2021)) from a meteor radar observation at Koto Tabang (0.2ºS) are mainly westward. The differences between the theoretical balance wind and meteor radar observations are mainly the tidal aliasing above 84 km (Hitchman and Leovy, 1986; Xu et al., 2009b; Smith et al., 2017)”.

5. L111-113: It might be helpful to include a sentence describing the nature of the diurnal tide bias that you find. For example, with sampling geometry of the LIMS instrument on Nimbus 7 ascending minus descending data orbit data can be used to estimate the tidal amplitude (e.g., Hitchman and Leovy 1986). Is there something like that in the SABER data?

Response: Sure, diurnal tides can be estimated from SABER data by ascending minus descending orbit data. However, the gradient wind theory (Eq. R1), which is used to retrieve the zonal mean wind, does not include the influence of tides.

$$\frac{\bar{u}^2}{a}\tan\varphi + f\bar{u} = -\frac{1}{a\bar{\rho}}\frac{\partial\bar{p}}{\partial\varphi} \qquad \text{(R1)}$$

This sentence has been revised as “To overcome the tidal alias above 80 over the equator (Hitchman and Leovy, 1986; Xu et al., 2009b; Smith et al., 2017), we replaced the BU with the zonal wind observed by a meteor radar at Koto Tabang (0.2°S, 100.3°E)”.

Hitchman, M. H. and Leovy, C. B.: Evolution of the zonal mean state in the equatorial middle atmosphere during October 1978-May 1979, J. Atmos. Sci., 43, 3159–3176,

https://doi.org/10.1175/1520-0469(1986)043<3159:EOTZMS>2.0.CO;2, 1986.

6. BU data, section 2.1: What is the approximate vertical resolution? What is the latitudinal resolution of the data set? How do you treat the lower boundary condition on geopotential height at the 18 km level? How do you treat the singularity at the equator? If you interpolate across the equator, do you smooth in y, and if so, how far out in latitude?

Response: (1) the vertical and latitudinal resolution: we have added in the text as “The BU dataset includes the monthly mean zonal wind in the height range of 18–100 km with step of 1 km and at latitudes of 50°S-50°N with step of 2.5° from 2002 to 2019”.

(2) lower boundary condition and the singularity at the equator: Equation (R1) is used to calculate the balance wind in the latitude ranges of 10°N–50°N and 10°S–50°S;

Above the equator, due to the singularity of Eq. (R1) at the equator, one need to differentiate Eq. (R1) with φ. As $\varphi \rightarrow 0$, we have $\tan\varphi \rightarrow \varphi$, $\sin\varphi \rightarrow \varphi$. Thus, Eq. (R1) can be simplified as (Fleming et al., 1990),

$$\frac{\bar{u}^2}{a} + 2\Omega\bar{u} = -\frac{1}{a\bar{p}}\frac{\partial^2\bar{p}}{\partial\varphi^2}. \tag{R2}$$

According to Fleming et al. (1990) and Smith et al. (2017), the monthly mean zonal mean wind is mainly in the range of ±75ms^{-1}. Thus, the term $\bar{u}^2/a$ is one to two orders smaller than $2\Omega\bar{u}$ and can be neglected. Then, $\bar{u}$ at the equator can be expressed as (Fleming et al. 1990; Swinbank & Ortland, 2003),

$$\bar{u} = -\frac{1}{2\Omega a\bar{p}}\frac{\partial^2\bar{p}}{\partial\varphi^2}. \tag{R3}$$

It is not necessary to use lower boundary condition in Eq. (R3). It should be noted that, the lower boundary is necessary if the thermal wind equation is expressed as (Eq. 3 of Xu et al., 2009a),

$$\frac{\partial\bar{u}}{\partial z} = -\frac{g}{2\Omega a\bar{T}}\frac{\partial^2\bar{T}}{\partial\varphi^2}. \tag{R3}$$

(3) Interpolation: At 2.5°N-7.5°N and 2.5°S-7.5°S, the BU is estimated by a cubic spline interpolation of the BU at 10°N-50°N, 10°S-50°S and the reconstructed BU at the equator.

In the text, we have clarified this point in the text as:

Equation (1) is used to calculate the BU in the latitude ranges of 10°N–50°N and 10°S–50°S. Above the equator, the BU is calculated as $\bar{u} = -(\partial^2\bar{p}/\partial\varphi^2)/(2\Omega a\bar{p})$. At 2.5°N–7.5°N and 2.5°S–7.5°S, the BU is estimated by a cubic spline interpolation of the BU at 10°N–50°N, 10°S–50°S and the reconstructed BU at the equator. The detailed description can be found in Liu et al. (2021).

Fleming, E. L., Chandra, S., Barnett, J. J., and Corney, M.: Zonal mean temperature, pressure, zonal wind and geopotential height as function of latitude, Adv. Space Res., 10, 11–59,

https://doi.org/10.1016/0273-1177(90)90386-E, 1990.

Swinbank, R. and Ortland, D. A.: Compilation of wind data for the Upper Atmosphere Research Satellite (UARS) Reference Atmosphere Project, J. Geophys. Res., 108, 4615, https://doi.org/10.1029/2002jd003135, 2003.

7. Figure 1 caption and text: You show results which must be for particular locations, but you don't say where they are! Each of the responses varies in latitude and altitude. For Fig. 1g, please state information about altitude, latitude, and the meaning of coefficients within the figure caption, instead of above the plot. For each of the plots in the right-hand column please state the latitude and altitude that you are referring to. In the text it seems important to clarify that these are sample points, not global indices, and that the response varies in space.

Response: Figure 1 is separated into two Figures (Fig. R1 and R2) in the new version. Now, the new Fig.R1 and its caption is revised as:

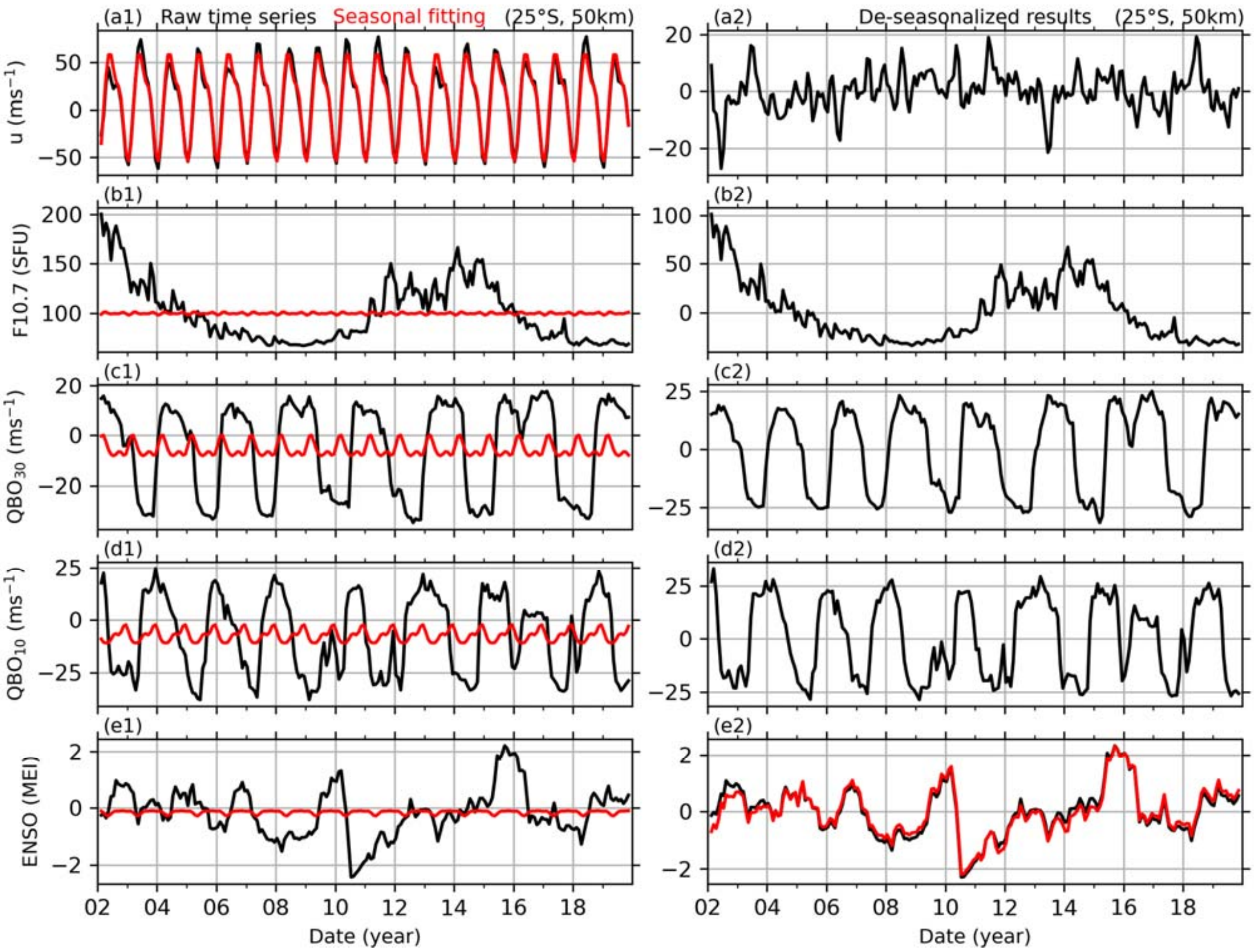

Figure R1: Example of the reference time series (left column) and their de-seasonalized results (right column). The first row: BU at 25°S and 50 km (black line in a1) and its seasonal fitting result (red line in a1), and the residual of BU (black line in a2)). The second, third, and fourth rows: same captions as the first row but for solar activity (indicated by F10.7), QBO at 30 hPa (QBO_{30} or QBOA) and at 10 hPa (QBO_{10} or QBOB), and ENSO (indicated by MEI index).

At the beginning of Sec.2.2, we have added “The detailed applications of MLR to retrieve the seasonal variations of winds and the responses of winds to F10.7, QBOA, QBOB, and MEI can be ascribed to the following three steps. For illustrative purpose, BU at 25°S and 50 km (black in Fig. 1a1) is taken as an example to show the procedure of MLR. This procedure is also applied to winds at other latitudes and heights, but results in different regressions coefficients due to the latitudinal and height dependencies of the seasonal variations and the responses of winds to F10.7, QBOA, QBOB, and MEI”.

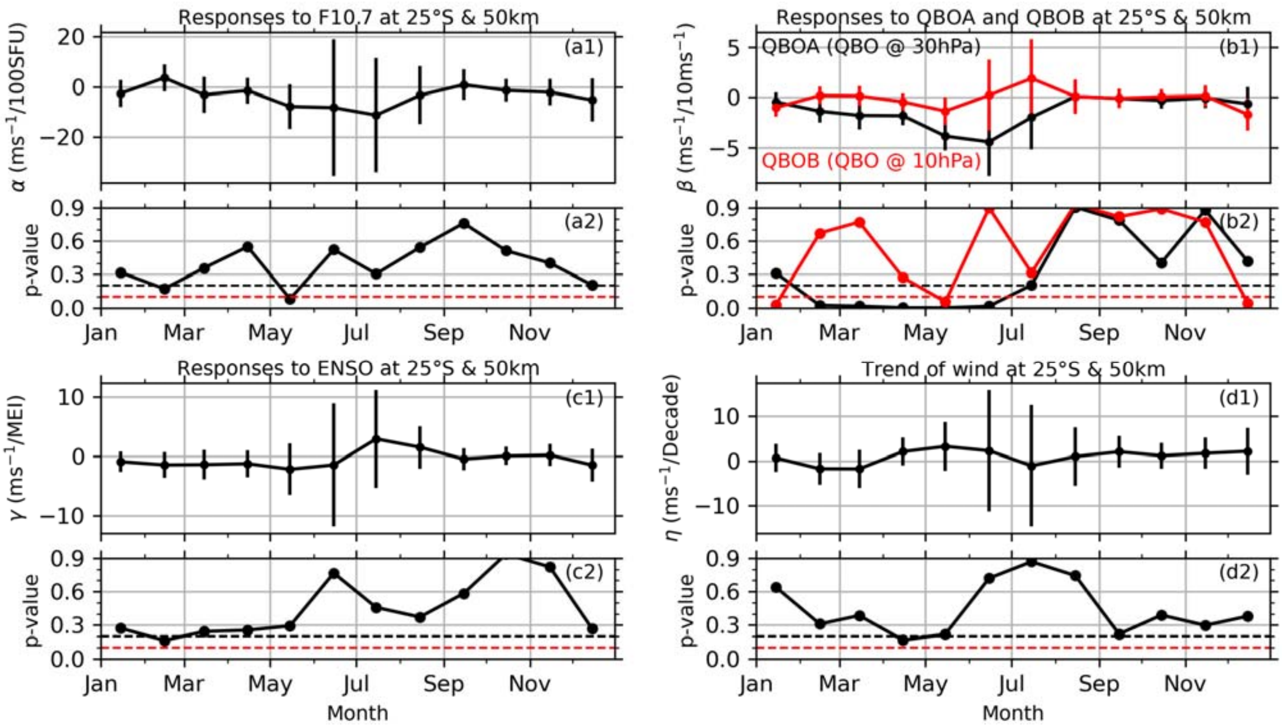

Figure R2: Example of retrieving the monthly responses of BU at 25°S and 50 km (upper subplot of each panel) and their p-values (lower subplot of each panel) to solar activity (a1 and a2) QBOA (black in b1 and b2) and QBOB (red in b1 and b2), ENSO (c1 and c2), and the linear variations (d1 and d2). The error bars are the confidence interval at 90% confidence level.

We have added the latitude and height in each plot and in the figure caption. Corresponding revisions have been made in the last paragraph of Sec.2.2.

8. L187-188: Fig. 1b shows that there is only a strong response during boreal summer.

Response: Following your suggestion, we have added this in the text as “The responses of BU at 25°S and 50 km to QBO_{30} and QBO_{10} (Fig. 2b1) have annual means of -1.2 ms^{-1}/10 ms^{-1} (p-value=0.0) and -0.3 ms^{-1}/10 ms^{-1} (p-value=0.22). The monthly responses of BU at 25°S and 50 km to QBO_{30} have negative peaks of ~3–5 ms^{-1}/10 ms^{-1} (p-value<0.1) in April-July, when QBO_{30} reaches its eastward or westward peaks. This indicate that the responses of BU at 25°S and 50 km to QBO_{30} are strong in the boreal summer. However, the monthly responses of BU at 25°S and 50 km to QBO_{10} is much weaker than that to QBO_{30}".

9. L188-189: Please say where these numbers pertain to and perhaps characterize how they vary in latitude/altitude.

Response: We have revised as "The responses of BU at 25°S and 50 km to ENSO (Fig. 2c1) have an annual mean of -0.31 ms^{-1}/MEI (p-value=0.56). The monthly responses of BU at 25°S and 50 km to ENSO have negative peak in May and positive peaks in July and August but have large p-values in May–November. The annual mean linear variations (Fig. 1h) is of 0.99 ms^{-1}/Decade (p-value=0.27). The monthly linear variations of BU at 25°S and 50 km reach a peak of 3 ms^{-1}/Decade (p-value<0.2) in May".

10. Fig. 2, right hand panels: How would short vertical structures, such as those associated with the QBO, be perceived by SABER sampling? Can that contribute to the pattern shown, with reduced "explained variance" in the tropics?

Response: In this version, to elucidate the MLR model better and to remove the collinearity of predictors, the seasonal variations and the responses of winds to F10.7, QBOA, QBOB, and MEI are retrieved through steps. Please find details in Sec.2.2 of the text. A summary is below:

First, we de-seasonalize the wind and reference time series by fitting the following harmonics through the least squares method. At each latitude and height, the wind series is fitted as,

$$u(t_i) = u_0 + \sum_{k=1}^{3} A_k \cos[k\omega(t_i - \varphi_k)] + u_{res}(t_i). \tag{R4}$$

Second, we check the multicollinearity among the predictor variables, which are the de-seasonalized F10.7, QBO_{30} (QBOA), QBO_{10} (QBOB), and MEI. The multicollinearity of F10.7 and MEI is removed through a linear regression with predictor variable of F10.7 and response variable of MEI.

Third, MLR is applied to get the responses of the de-seasonalized winds (i.e., u_{res} in Eq. R4) to the four predictor variables (F10.7_{res}, QBOA_{res}, QBOB_{res}, MEI_{res}) prepared in the second step. The MLR model is written as:

$$u_{res}(t_i) = \alpha \text{F10.7}_{res}(t_i) + \beta_A \text{QBOA}_{res}(t_i) + \beta_B \text{QBOB}_{res}(t_i) + \gamma \text{MEI}_{res}(t_i) + \eta t_i + \varepsilon(t_i) \tag{R5}$$

The monthly responses are obtained by selecting t_i in Eq. (4) only in that month of each of year. E.g., the response in January can be obtained by selecting the data only in January of each year. The annual responses are obtained by using all the data during 2002–2019.

The first step of this version does not include QBO, ENSO, and F10.7. This induces smaller R^2 scores and the disappearance of the small structure, as compared to the last version. Since the amplitudes of QBO is much larger than the those of seasonal variations (Fig. 1d1 and 1d2), we agree your statement that the short vertical structures in the tropics might be associated with QBO.

In this version, we have added "and (4) the strong QBO signals, which were not included in Eq. (2)" as a reason of smaller R^2 scores in the tropical region.

11. L251: I would expect this to vary in space because the zonal wind anomalies are vertical integrals of meridional gradients in temperature anomalies, which may be caused by solar heating anomalies. If most of the modulation of solar heating is in the ozone layer then one could work out or anticipate the corresponding spatial variation in zonal wind anomaly.

Response: Thanks for your suggestion. I agree your idea that the solar heating may influence the zonal wind through the ozone layer. Both ozone and temperature profiles have been measured by the SABER instrument. This provides an opportunity to study the responses of ozone and temperature, as well as their meridional gradient, to the solar heating. This idea will be tested in our future work. We have added this possible idea in the text as "Another possible mechanism is that the modulation of solar heating in the ozone layer, which influences the meridional gradient of temperature and thus the zonal wind. However, this mechanism should be validated through observations or simulations".

12. Figs. 3 and 5: It seems unusual that during July in the SH there is a strong signal in both F10.7 and ENSO.

Response: You are right. The responses of BU to F10.7 and ENSO are strong during July in the SH. A possible reason is that the waves (gravity waves, non-migrating tides, planetary waves) exhibit stronger variabilities and more complex spatial-temporal structures in the NH than those in the SH. This induces a more complex dynamical coupling between waves and zonal mean wind in the NH than that in the SH. Then the complex dynamical coupling might induce that influences of F10.7 and ENSO to wind are not as obvious in the NH as in the SH. Another possible reason is that the zonal mean wind is stronger in the SH than that in the NH during winter times. Thus, the responses of winds to F10.7 and ENSO are stronger during July in the SH than those in the NH counterpart. Moreover, the responses of winds to QBO_{10} are also stronger in the during July in the SH than those in the NH counterpart.

This has been added at the end of the Sec. 3.4.

13. Fig. 7: The vertical scale of the anomalies associated with the QBO scale like the QBO, but what can account for the pancake structures in the ENSO anomalies in the lower panels?

Response: Thanks for your careful reading. The pancake structures in ENSO anomalies can also be seen in the 40 years MERRA2 data (MerU40, middle row of Fig. R3) but are not as significant as that in the 18 years MERRA2 data (MerU18, lower row of Fig. R3). Moreover the pancake structures can also be seen in the responses of the zonal mean temperature to ENSO (Fig R4). The physics behind should be further explored.

We have added a note in the text as “We note that the pancake structures in the responses of winds to QBO are likely induce by the propagation nature of QBO. Similar pancake structures can also be seen in the responses of wind to ENSO”.

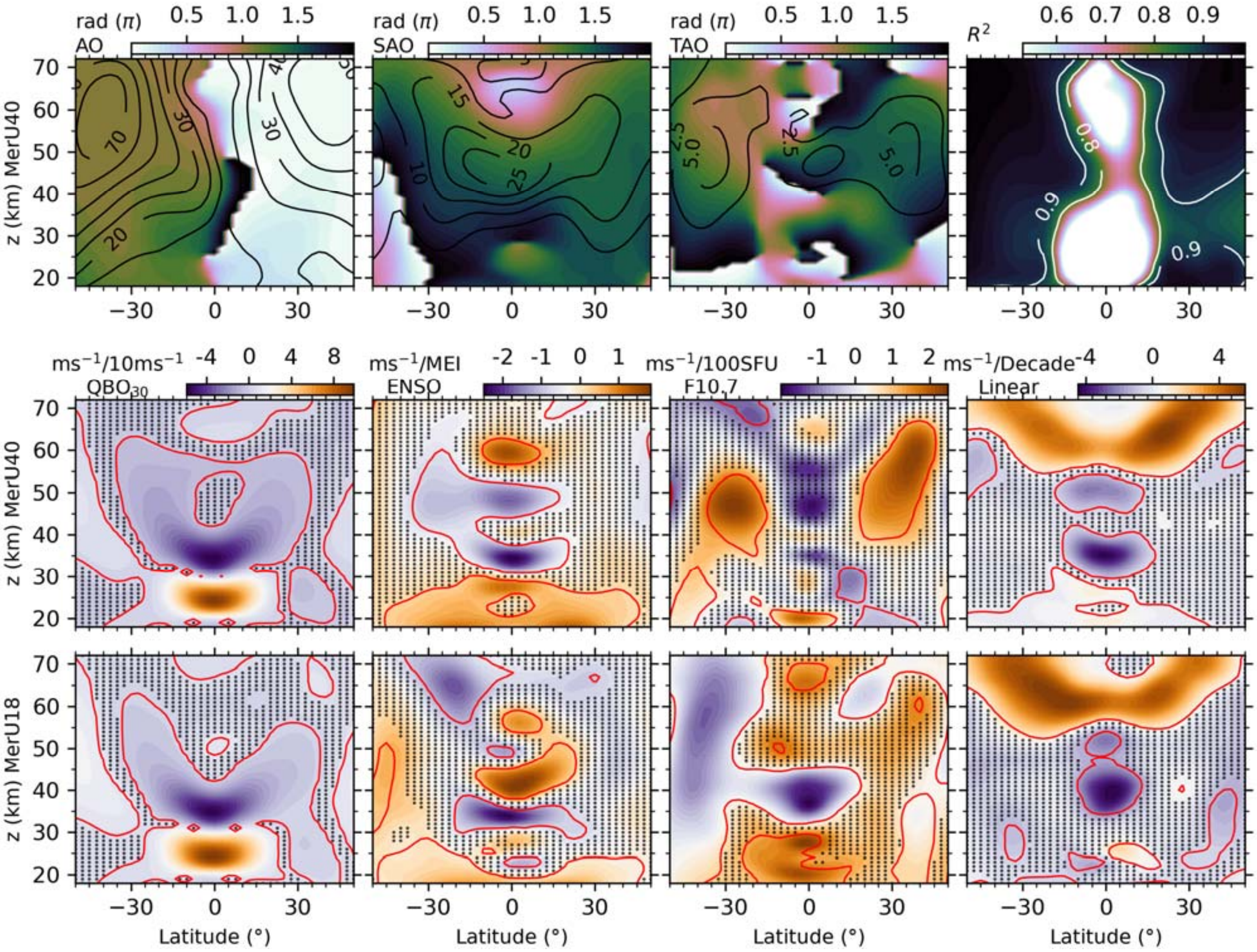

Figure R3: Upper row: the latitude-height distributions of the amplitudes (contour lines) and phases (color scale) of seasonal variations and the R^2 scores (from left to right) of MerU40. Middle row: the latitude-height distributions of the responses of MerU40 to QBOA, ENSO, F10.7 and linear variations (from left to right). Lower row: same caption as the middle row but for the MerU18. The black dots indicate that the regression coefficients with p-values larger than 0.2. The red lines indicate the regression coefficients with p-values of 0.1.

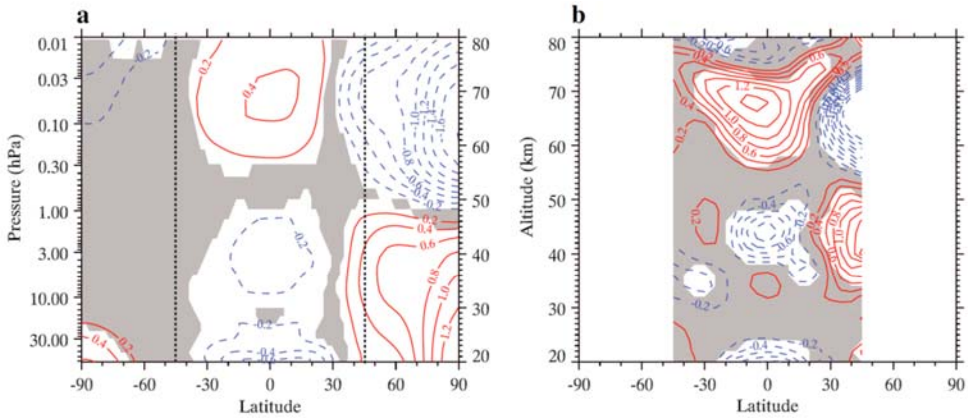

Figure 2. Meridional cross section of zonal mean temperature response to ENSO in winter derived from (a) the WACCM3.5 simulation and (b) the SABER observational data set. The contour interval is 0.2 K/MEI, the blue dash contour lines denote the negative values, and the red solid contour lines denote positive values. The white regions indicate that the results are significant above 95% (1.96σ) confidence level. The vertical black dashed lines denote 45°S and 45°N.

Figure R4: Adopted from Li et al. (2013)