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Global zonal wind variations and responses to solar activity, and QBO, ENSO during 2002–2019

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Key Points:

- The seasonal and linear variations of zonal winds coincide with those of MERRA2 with slight differences in magnitudes.
- The responses of zonal winds to QBO are approximately hemispheric symmetry and change from positive to negative with the increasing height.
- The responses of zonal winds to F10.7 and ENSO are more prominent in the southern stratospheric polar jet region as compared to that the northern counterpart.

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Abstract

Variations of global wind are important in changing the atmospheric structure and circulation, in the coupling of atmospheric layers, in influencing the wave propagations. Due to the difficulty of directly measuring zonal wind from the stratosphere to the lower thermosphere, we derived the global balance wind (BU) from 2002 to 2019 using the gradient wind approximation and SABER temperatures and modified by meteor radar observations at the equator. These capture the main feature of global monthly mean zonal wind and can be used to study the variations (i.e., annual, semiannual, terannual, and linear) of zonal wind and the responses of zonal wind to QBO (quasi-biennial oscillation), ENSO (El Niño/Southern Oscillation), and solar activity. Same procedure is performed on the MERRA2 zonal wind (MerU) to validate BU and its responses below 70 km. The annual, semiannual, terannual oscillations of BU and MerU have similar amplitudes and phases. The semi-annual oscillation of BU has peaks around 80 km, which are stronger in the southern tropical region and coincide with previous satellite observations. The responses to QBO shift from positive to negative and extend from the equator to higher latitudes with the increasing height. 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. Both BU and MerU exhibit similar linear changes, but the negative linear changes of BU at 50°N are absent in MerU during October–January. The discussions on the possible influences of the temporal intervals and sudden stratospheric warmings (SSWs) on the variations and responses of BU illustrate that: (1) the seasonal variations and the responses to QBO are almost independent on the temporal intervals selected; (2) the responses to ENSO and F10.7 are robust but slightly dependent on the temporal intervals; (3) the linear changes of both BU and MerU depend strongly on the temporal intervals; (4) SSWs affect the magnitudes but do not affect the hemispheric asymmetry of the variations and responses of BU at least in the monthly mean sense. The variations and responses of global zonal wind to various factors are based on BU, which is derived from observations, and thus provide a good complementary to model studies and ground-based observations.

1 Introduction

Atmospheric dynamics field (temperature, wind, etc.) and species not only exhibits latitude, longitude, and height variations, but also exhibits temporal variations with periods ranging from days, months to years, and even decade. The temporal variations can be ascribed into long-term variations, intra-annual and inter-annual variations. Here the long-term variations mean the linear term or linear changes in a regression model and on a time scale longer than one solar cycle in the middle and upper atmosphere. The long-term variations of the middle and upper atmosphere have been received attentions due to the greenhouse gas driven anthropogenic climate change and its influences on atmospheric drag and thus our space vehicles (Beig et al., 2003; Beig et al., 2008; Laštovička, 2017; Yue et al., 2019b; Mlynczak et al., 2022). The intra-annual variations mainly include annual (AO), semi-annual (SAO), and ter-annual (TAO) oscillations. These variations are mainly cause by the revolution of earth with oblique axis relative to the ecliptic plane. Their amplitudes depend on latitude and height (Dunkerton, 1982; Garcia et al., 1997; Randel et al., 2004; Smith et al., 2017).

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The inter-annual variations are mainly caused by the coupling among different atmospheric layers, sea surface temperature and solar activity. Such as: the QBO (quasi-biennial oscillations) in the tropical regions has periods of 2–3 years due to wave-mean flow interactions. QBO signal can also be seen in the mesosphere, which is anti-phase to the stratospheric QBO due to the selective critical-layer filtering (Baldwin et al., 2001; Burrage et al., 1996; Xu et al., 2007). Recent studies revealed that the mesospheric QBO is a seasonally locked phenomenon and occurs only in vernal equinox when the westward winds enhanced every 2 or 3 years and might be an ephemeral phenomenon (Venkateswara Rao et al., 2012; Kumar, 2021); the ENSO (El Niño/Southern Oscillation) is used to characterized the changes in sea surface pressure and temperature (Domeisen et al., 2019a). It has been reported that the slight change of ENSO can affect global middle and upper atmosphere through the coupling of atmosphere and ocean and wave propagation (Randel et al., 2009; Li et al., 2013; Baldwin and O'Sullivan, 1995; Lin and Qian, 2019); the solar activity can be represented by its radiation flux at 10.7 cm (F10.7), its can influence the atmosphere from upper to below through photon absorption and high energy particle precipitation and ion deposition (Li et al., 2011; Beig et al., 2008; Qian et al., 2019; Venkat Ratnam et al., 2019). Moreover, the temporal variations may be coupled among different time scales. Such as: the coupling between SAO and QBO is mainly due to the selectively filtering and absorbing of equatorial waves and gravity waves by QBO winds (Li et al., 2012; Smith et al., 2017); the coupling between QBO and ENSO is mainly due to the stronger wave activity during the warm phase ENSO, this accelerates downward propagation of QBO (Domeisen et al., 2019a; Taguchi, 2010).

The variations and responses of temperature and trace gases (e.g., $CO2$, $H2O$) in the middle and upper atmosphere have been well studied through observations and model simulations (Laštovička, 2017; Garcia et al., 2019; Lübken et al., 2018; Emmert et al., 2012; Yue et al., 2015, 2019a; Yuan et al., 2019; She et al., 2019; Mlynczak et al., 2022). In contrast, the variations and responses of wind field are more complex than those of temperature due to the direct external forcings and the indirect dynamical coupling of the atmospheric waves and mean flow (Qian et al., 2019). In fact, atmospheric wind field is an important atmospheric parameter since it is a direct driver of atmospheric circulation and influences the atmospheric structure. Moreover, wind field plays important roles in transporting mass and chemical species, in distributing and re-distributing momentum and energy, and in modulating the propagation and dissipation of atmospheric waves (i.e., gravity waves, tides, and planetary waves). This in turn affects the atmospheric circulation and structure indirectly. Thus, the variations and long-term variations of winds should also be studied.

Ground-based radar observations have revealed long-term variations of mean wind in the mesosphere and lower thermosphere (MLT) region at several stations. The medium frequency (MF) radar observations at Tirunelveli (8.7°N, 77.8°E) from 1993 to 2006 showed that the monthly mean zonal wind was dominated by SAO with eastward peak during solstice and exhibited QBO signal with periods 2–3 years (Sridharan et al., 2007). Using the observations by four MF radars and three meteor radars in the latitudes from 21°S to 22°N during 1990–2010, Venkateswara Rao et al. (2012) showed that the zonal wind exhibited both negative and positive trends, which magnitudes depended on stations and the temporal intervals of the observations. By combining the zonal wind at ~z=70–80 km observed by the rocketsonde, satellite and MST

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radar over the Indian region (8.5°N to 18.5°N and 69°E to 89°E), Venkat Ratnam et al. (2013) constructed a long-term dataset from 1977 to 2010. They showed a decreasing trend of 2 ms^{-1}/Year (or 20 ms^{-1}/Decade) in February and March at 72.5 and 77.5 km (Fig. 2 of their paper). However, the trends are not significant from May to August. These observations coincided with the results simulated by the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) after doubled the CO_2 concentration (Venkateswara Rao et al. 2013). Recently, after extending the observation data to 2016, Venkat Ratnam et al. (2019) found a decreasing trend at ~z=60–80 km and an increasing trend of 4–5 ms^{-1}/Decade at ~z=80–90 km and below ~60 km. Using the temperature and wind simulated by Whole Atmospheric Community Climate Model with eXtended thermosphere and ionosphere (WACCM-X) and the radar observations at Collm (51°N, 13°E) during 1980–2014, Qian et al. (2019) showed that the wind trends and the solar effects were, respectively, order of ~±5 ms^{-1}/Decade and ~±5 ms^{-1}/100SFU (1 SFU=10^{-22} $Wm^{-2}Hz^{-1}$) but with large standard deviations. Using the historical simulations by WACCM6 during 1850–2014 (165 years), Ramesh et al. (2020) showed the responses of the temperature and zonal wind to QBO, ENSO, solar activity, ozone depleting substance, carbon dioxide, and sulfate aerosol from the stratosphere to the lower thermosphere. They showed that the influences of solar activity are mainly in the mesosphere while the influences of QBO and ENSO are mainly in the stratosphere and mesosphere. Moreover, these influences depend on latitudes.

The above observations and modelling studies revealed seasonal variations of zonal winds and their responses to QBO, ENSO, solar activity in the mesosphere. However, the reported long-term (or linear) changes of zonal winds depended on specific locations and the temporal intervals of the data. At present, it is still a challenge to directly measure the atmospheric wind field from the stratosphere to the lower thermosphere. It is compelling to develop a wind dataset to represent the main features of global zonal winds and their temporal variations. Recently, we developed a dataset of global monthly zonal mean zonal wind (short for BU) based on the gradient balance wind theory (Fleming et al., 1990; Randel, 1987; Smith et al., 2017; Xu et al., 2009) and the temperature and pressure profiles measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument (Russell III et al., 1999). To overcome the tidal alias above 80 over the Equator (Smith et al., 2017; Xu et al., 2009a), we replaced the BU with the zonal wind observed by a meteor radar at Koto Tabang (0.2°S, 100.3°E) (Matsumoto et al., 2016; Hayashi et al., 2013). The BU covers a latitude range of 50°S–50°N and height range 18–100 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). Thus, the BU is a reasonable candidate to monthly mean zonal wind and can be used to study the variations and responses of global zonal winds to various factors.

The solar activity effects on winds in the MLT region are still unclear (Qian et al., 2019; Venkateswara Rao et al., 2012). It should be noted that the linear changes and solar activity have influences on other signals (i.e., QBO, ENSO), one must isolate the contributions of different signals to get a clearer picture of the variations and responses of zonal winds. The long temporal (18-year) and entire height (18–100 km) intervals of BU are suitable to study the variations of zonal winds and their responses to QBO, ENSO, and solar activity. To separate the relative contributions of the variations and effects of QBO, ENSO, and solar activity to zonal winds, the multiple linear regression (MLR) method will be used.

To evaluate the reliability of BU and the corresponding responses below 70 km in further, we will perform the same MLR on the zonal wind of Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA2). BU will provide the unique wind results at 70–100 km. MERRA2 provides assimilated meteorological field from surface to ~75 km (72 levels). It has temporal, longitude, and latitude interval of 3 hours, 0.625°, and 0.5°, respectively (Molod et al., 2015; Gelaro et al., 2017). Each MERRA2 zonal wind profile is interpolated to uniform vertical grid with a step of 1 km. Then the monthly zonal mean wind (MerU) is calculated by averaging these profiles in a latitude band of 5° with an overlap of 2.5° in each month. The variations of MerU and their responses to QBO, ENSO, and solar activity are studied to compare with those of BU below 70 km. MERRA2 is used here due to its good consistency with other data set. Such at the consistency of the monthly mean zonal winds between MERRA2 and the QBO wind at Singapore (Coy et al., 2016), the consistency of the changes in subtropical and polar jets between MERRA2 and other re-analyses (e.g., MERRA, ERA-Interim, JRA-55, and NCEP CFSR) (Manney and Hegglin, 2018).

2 Data and multiple linear regression

2.1 BU data and reference time series

The detailed description and validation of BU can be found in Liu et al. (2021). Here, we provide a short summary of this dataset. The BU dataset includes the monthly mean zonal wind in the height range of 18-100 km and at latitudes of 50°S-50°N from 2002 to 2019. BU is mainly derived from the temperature and pressure observations by the SABER instrument (Russell III et al., 1999) and based on the gradient wind theory (Fleming et al., 1990; Randel, 1987; Smith et al., 2017; Xu et al., 2009),

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

Here, $f = 2\Omega\sin\varphi$ is the Coriolis factor, $\Omega = 2\pi/(24\times60\times60)$ is the earth rotation frequency (unit of rad·s^{-1}), a is the radius of the earth. $\bar{u}$ and $\bar{\rho} = \bar{p}/R\bar{T}$ are the BU and zonal mean density, respectively. R is the gas constant for dry air. At the equator and above 80 km, the tidal alias on gradient wind is replaced by the monthly mean zonal wind measured by a meteor radar at 0.2°S (Matsumoto et al., 2016; Hayashi et al., 2013). The comparisons between BU and other data (MERRA2, HWM14 empirical model, meteor radar and lidar observations at seven stations from around 50°N to 29.7°S) illustrate good agreement. The good agreement suggests that BU is a reasonable candidate to monthly mean zonal wind. The large vertical extent and the 18-year internally consistent time series of BU makes it is suitable to study the variations and responses to solar activity, and QBO, ENSO.

The reference time series of solar activity, QBO, and ENSO are used to explore their possible influences on global zonal wind. The solar activity is represented by the solar radio flux at 10.7 cm in a 100-MHz band (F10.7, Fig. 1a, Tapping, 2013). The QBO is represented by the zonal wind at 30 hPa (~25 km) and 10 hPa (30 km) (referred as QBO_{30} and QBO_{10} in Fig. 1c) over Singapore (1°N, 104°E) (Baldwin et al., 2001). Due to the propagation nature of QBO with height, we use the QBO

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winds at two different heights to represent the phase information of QBO. ENSO is represented by the Multivariate ENSO index (MEI, Fig. 1e, Zhang et al., 2019; Wolter and Timlin, 2011). These reference time series play important roles in studying the atmospheric coupling and have been widely used to study their influences on temperature, gravity waves, ozone, and carbon dioxide in the stratosphere and mesosphere (e.g., Li et al., 2011; Randel et al., 2017; Liu et al., 2017; Randel and Cobb, 1994; Yue et al., 2015).

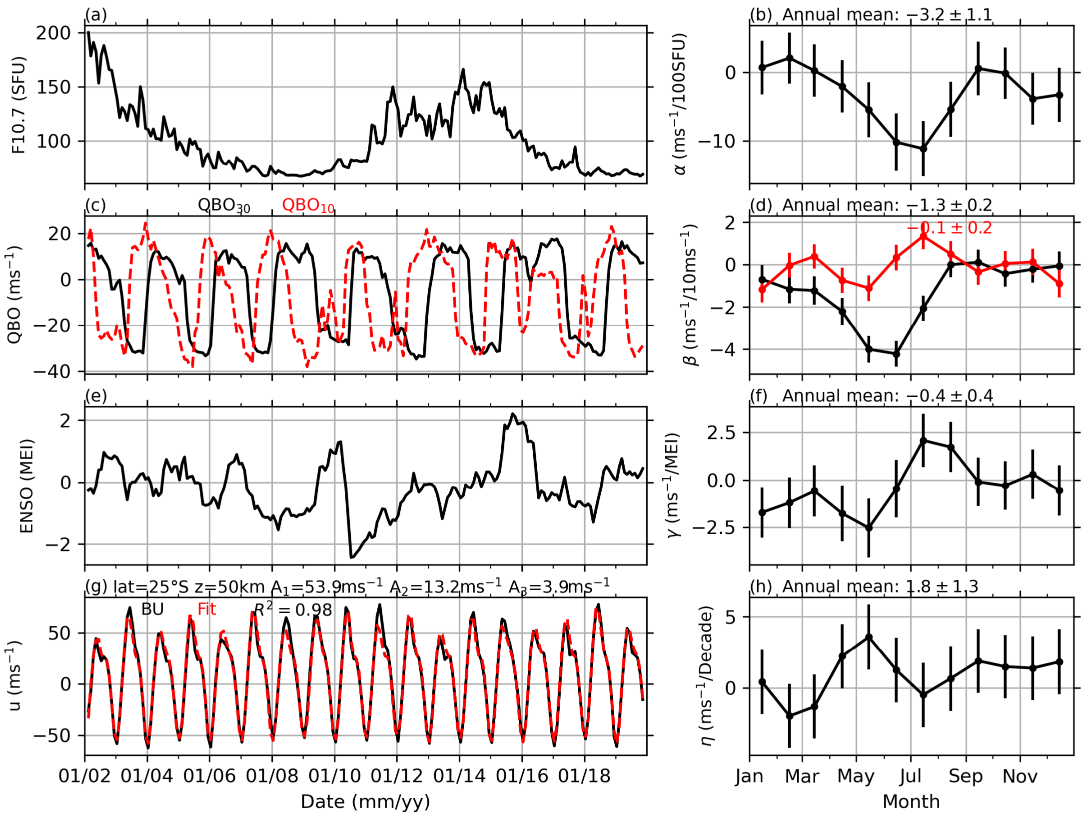

Figure 1: Reference time series and the results of MLR. Left column: **(a)** solar activity (F10.7), (c) QBO at 30 hPa (black) and 10 hPa (red), **(e)** ENSO, **(g)** BU (black solid) and its fitting result (red-dashed line). The amplitudes of AO (A_1), SAO (A_2), and TAO (A_3) and R^2 are labelled on the top of Fig. 1**g**. Right column: the monthly responses and their standard deviations (σ) of BU to solar activity **(b)**, QBO (**d**, black and red represent the responses to QBO wind at 30 and 10 hPa, respectively), ENSO **(f)**, and the linear variations of BU **(h)** in each month. The annual means of the responses and their standard deviations are labeled on the top of each panel.

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2.2 Multiple linear regression

Multiple linear regression (MLR) model is used to isolate the seasonal variations of BU and the possible influences of F10.7, QBO_{30}, QBO_{10} and MEI on BU (Liu et al., 2017; Li et al., 2011; Randel and Cobb, 1994; Venkat Ratnam et al., 2019). At each latitude and height, the regression model is written as:

$$u(t_i) = A_0 + \mathrm{Season}(t_i) + \alpha \mathrm{F10.7}(t_i) + \beta_{30}\mathrm{QBO}_{30}(t_i) + \beta_{10}\mathrm{QBO}_{10}(t_i) + \gamma \mathrm{ENSO}(t_i) + \eta t_i + \mathrm{Res}(t_i) \quad (2)$$

$$\mathrm{Season}(t_i) = \sum_{k=1}^{3} A_k \cos[k\omega(t_i - \varphi_k)]. \quad (3)$$

Here, t_i $(i = 1, 2 \cdots, N)$ is the month number since February 2002. A_0 is the mean wind over the entire temporal interval. $\omega = 2\pi/12$ (month), A_k and φ_k are the amplitude and phase of the annual (AO, $k = 1$), semiannual (SAO, $k = 2$), and terannual (TAO, $k = 3$) oscillations, respectively. The regression coefficients $\alpha, \beta_{30}, \beta_{10}, \gamma, \eta$ include the seasonal variations and have the same form as follows:

$$\alpha = \alpha_0 + \sum_{k=1}^{3}[\alpha_{2k-1}\cos(k\omega t) + \alpha_{2k}\sin(k\omega t)]. \quad (4)$$

Thus, there are 42 parameters to be fitted by the least-squares method. η is the linear variations or long-term trend (Randel and Cobb, 1994). $\mathrm{Res}(t)$ is the residual of the fitting and can be used to estimate the standard deviation of each coefficient with the help of variance-covariance matrix (Kutner et al., 2004). The rationality of the fitting result is quantified by R^2 score, which is the variations of the raw data explained by the model and defined as follows:

$$R^2 = 1 - \{\sum_{i=1}^{N}\mathrm{Res}^2(t_i)/\sum_{i=1}^{N}[u(t_i) - \bar{u}]^2\},\ \bar{u} = \frac{1}{N}\sum_{i=1}^{N}u(t_i). \quad (5)$$

The best fitting results in $R^2 = 1$, which means that the fitting result is the same as the raw data.For illustrative purpose, BU at 25°S and 50 km (black in Fig. 1g) is taken as an example to show the procedure of MLR. Figure 1(g) shows that the fitting result (red) coincides well with BU with $R^2 = 0.98$. This means that Eq. (2) explains 98% of the variations of BU. Thus, good consistency and large R^2 indicate that BU can be explained well by Eq. (2). The rationality of the fitting results (R^2) at other latitudes and heights will be shown in Sect. 3.1. Figure 1(g) also shows that the AO has amplitude of A1=53.9 $\mathrm{ms^{-1}}$ and is in the dominant position. Then the SAO has a smaller amplitude of 13.2 $\mathrm{ms^{-1}}$. While the TAO is weakest and has amplitude of 3.9 $\mathrm{ms^{-1}}$.

The right column of Fig. 1 shows the monthly responses of BU to solar activity (b), QBO (d), ENSO (f) and the linear variations of BU (h), as well as their standard deviations (σ). Their annual means are labelled on the top of each panel. The response of BU to solar activity (Fig. 1b) has an annual mean of -3.2±1.1 $\mathrm{ms^{-1}}$/100 SFU. This negative response is mainly contributed from May–August, in which the negative peaks reach a value of -10 $\mathrm{ms^{-1}}$/100 SFU in June and July. In January–April and September–October, the responses of BU to solar activity are less than the standard deviations (σ). This indicates that the responses of BU to solar activity are stronger in winter months and weaker in other months at least for the case shown here. The responses of BU to QBO_{30} and QBO_{10} (Fig. 1d) have annual means of -1.3±0.2 $\mathrm{ms^{-1}}$/10 $\mathrm{ms^{-1}}$ and -0.1±0.2 $\mathrm{ms^{-1}}$/10 $\mathrm{ms^{-1}}$. The monthly response of BU to QBO_{30} has negative peaks of -4 $\mathrm{ms^{-1}}$/10 $\mathrm{ms^{-1}}$ in April-July, when QBO_{30} reaches its eastward or westward peaks. The response of BU to ENSO (Fig. 1f) has an annual mean of -0.4±0.4 $\mathrm{ms^{-1}}$/MEI.

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The monthly responses of BU to ENSO have negative peak in April and positive peaks in July and August. The annual mean linear variations (Fig. 1h) is of 1.8±1.3 ms^{-1}/Decade. The monthly linear variation reaches a peak of 3 ms^{-1}/Decade in May. We note that the linear variation depends highly on the temporal span of the data and will be discussed in Sect. 4.1.

3 Seasonal variations and regression results

3.1 Seasonal variations

Figure 2 shows the amplitudes and phases of the seasonal variations of BU (upper row) and MerU (lower row). The R^2 scores (the fourth column) of both BU and MerU are larger than 0.8 in most region and indicate that the variations of BU and MerU can be explained well by Eq. (2). However, at 50°N/S around 90 km and in the tropical regions above 95 km, the R^2 scores of BU are less than 0.6. This indicates that the variabilities of BU are influenced by some other factors, which were not included in Eq. (2). These factors might include (1) the phase change (eastward peak shifting from winter to summer) of zonal wind caused by the strong gravity waves dissipation at high latitudes (Liu et al., 2022), (2) the strong tides and short-term variabilities of zonal wind in the equatorial lower thermosphere (Xu et al., 2009b; Smith et al., 2017; Liu et al., 2021), and (3) the imperfect BU in the extra-tropical lower thermosphere (Liu et al., 2021).

The latitude-height distributions of the amplitudes and phases of AO of BU and MerU exhibit general consistencies and slight discrepancy. The consistencies include that: (1) both BU and MerU have peaks around 55 km in July in the Southern Hemisphere (SH) and around 65 km in January in the Northern Hemisphere (NH); (2) both BU and MerU have small amplitude below ~30 km at all latitudes and throughout the height range in the tropical regions. The discrepancy is that the AO of MerU has larger amplitudes in the SH but smaller amplitudes in the NH than that of BU. The possible reason for the weaker AO in MerU in the NH has peak around 65 km, which might be caused by the damping layers of MERRA2 and reduced the zonal wind (Ern et al., 2021). Above 80 km, the amplitude of AO is small. This is because the magnitudes of zonal wind above 80 km are slower than those at around 60 km, where the stratospheric polar jet occurs.

The SAO of both BU and MerU have nearly identical phases in the regions where their amplitudes are prominent. The amplitudes of the SAO of both BU and MerU exhibit hemispheric asymmetry. At latitudes higher than 35°S, the SAOs of both BU and MerU have peaks at ~z=35–55 km. However, above 65 km, the SAO of BU is stronger than that of MerU. In the tropical regions, the SAOs of both BU and MerU are stronger in the SH than that in the NH. This coincides with the measurements by High Resolution Doppler Imager (HRDI) measurements, the assimilated data by U.K. Meteorological Office (UKMO) (Ray et al., 1998), and the balance wind derived from SABER and Microwave Limb Sounder (MLS) observations (Smith et al., 2017). Large discrepancies occur at latitudes higher than 40°N, where the SAO of MerU is much stronger than that of BU below ~70 km. Above 70 km, the SAO of BU reproduces the same pattern as that at around 40 km but has larger magnitudes and anti-phase.

The TAOs of both BU and MerU have same phases and peaks at ~z=30–60 km and at latitudes higher than 25°S. In the tropical regions and around 45 km, the TAO of BU has two peaks, which are approximately symmetric to the equator, but

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the TAO of MerU has one peak over the equator. At ~z=50–70 km, the TAO of BU has larger amplitude than that of MerU. Above 80 km, the TAO of BU is asymmetric to the equator and has larger peak in the SH tropical region.

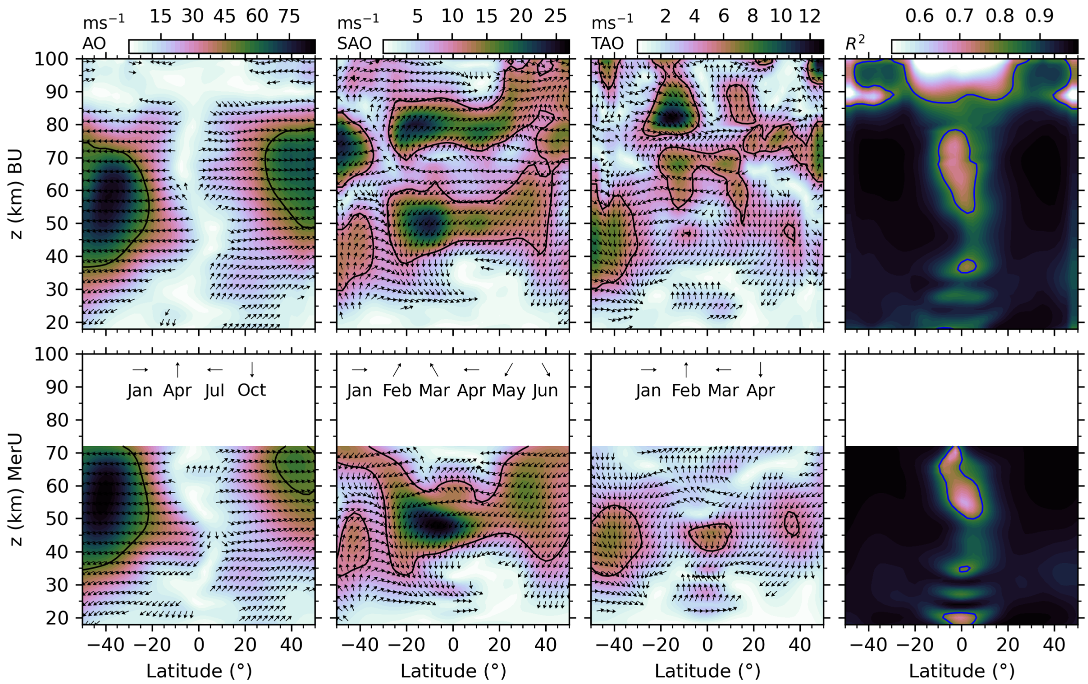

Figure 2: The latitude-height distributions of the amplitudes (color) and phases (indicated by arrow directions) of the AO, SAO, TAO, and the R^2 scores (from left to right). The contour lines of the AO, SAO, TAO, and the R^2 scores indicate 50 ms^{-1}, 10 ms^{-1}, 5 ms^{-1}, and 0.8, respectively.

A short summary is that AO, SAO, and TAO of both BU and MerU have nearly identical phases in the regions where their amplitudes are prominent. Their consistencies are better in the SH than in the NH on the aspects of both patterns and magnitudes. The discrepancies of these seasonal variations are mainly in the NH. Above 70 km, the weak AO due to the weaker wind as compared to that in the stratospheric jet region. 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 wind (Smith et al., 2017). The TAO of BU above 80 km is hemispheric asymmetric and stronger in the SH.

3.2 Responses to solar activity

The latitude-height distributions of the responses of BU and MerU to F10.7 (upper two rows of Fig. 3) exhibit general

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consistencies in January and July and in the annual mean. These consistencies include: (1) the positive response at ~z=40–60 km and around 40°N in January; (2) the negative response above 60 km at ~20°S in January; (3) the negative response in July extending from the SH stratospheric jet region to ~30°N. In contrast, the discrepancies are: (1) stronger negative response of BU in January at 50°N, as compared to that of MerU; (2) the negative responses of BU in October around 65 km and above the equator, which cannot be seen in MerU. The annual mean responses of BU and MerU are: (1) mainly negative in the regions extending from ~30°S/N to higher latitudes with the increasing height; (2) mainly positive (negative) in the tropical regions below ~30 km (around ~40 km). Above ~80 km, an interesting feature is that the positive responses of BU to F10.7 are approximately hemispheric symmetry, i.e., at 25°S–5°S in January and at 5°N–25°N in July. The annual mean responses of BU to F10.7 are mainly positive at 60–80 km. Above ~90 km, the annual mean responses of BU to F10.7 are mainly positive around the equator and negative at higher latitudes. This feature has a similar pattern but larger amplitude as compared to the results simulated by WACCM-X (Ramesh et al., 2020).

The monthly-height distributions of the responses of BU and MerU to F10.7 (lower two rows of Fig. 3) exhibit general consistencies below ~70 km. However, the discrepancies should be clarified. Such as: the stronger negative responses of BU in winter months (June–September at 50°S and December–January at 50°N); the weaker positive responses of BU at the equatorial lower height as compared to that of MerU. It should be noted that the negative responses of winds at the southern and northern high latitudes can also be seen in the results simulated by WACCM-X (Ramesh et al., 2020).

The MF radar observations at Langfang (39.4°N, 116.7°E) revealed a positive correlation between zonal wind and solar activity from 2009 to 2020 during spring and summer at 80–84 km (Cai et al., 2021). However, another MF radar observations at Juliusruh (54.6°N, 13.4°E) revealed that the correlations between zonal wind and solar activity from 1990 and 2005 were positive during winter but negative in summer (Keuer et al., 2007). Our results coincide with the observations at Langfang but different from those at Juliusruh. The simulation study by Qian et al. (2019) showed that the solar activity effects on global zonal wind are sporadic in latitude and height distributions. They suggested that the zonal wind might be influenced by both the direct effects of solar radiance and the indirect effects of dynamic process such as wave-mean flow interaction. Qian et al. (2019) also proposed that the temporal intervals of data should be specified when we study the trends and solar activity effects since the trend drivers are different in different periods. This will be discussed in Sect. 4.1.

A short summary is that the annual mean responses of both BU and MerU to F10.7 are more negative in the stratospheric polar jet region of SH than that of NH. Above the stratospheric polar jet, the responses of BU change from negative to positive with the increasing height at latitudes higher than 15°N/S. Around ~80 km, the annual responses of BU to F10.7 are mainly positive in the tropical region.

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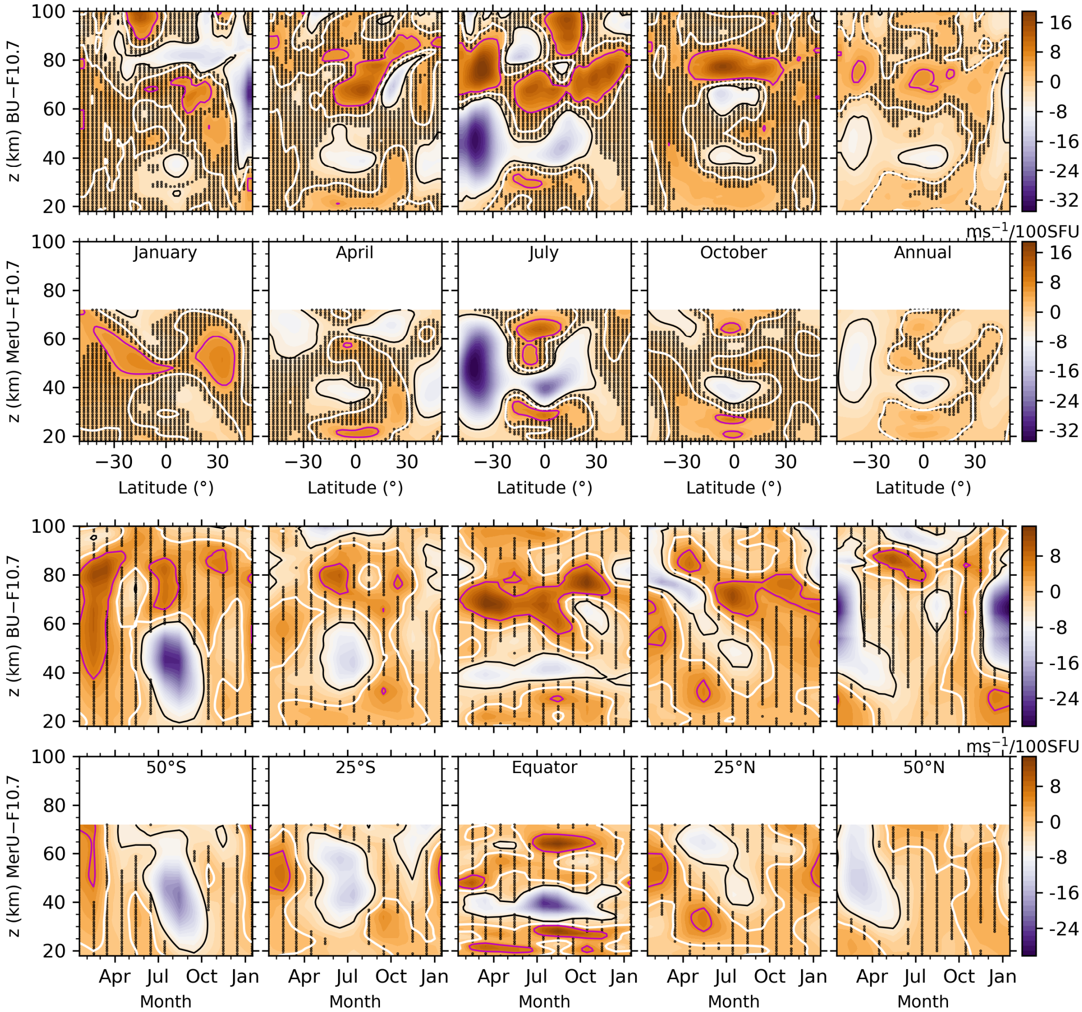

Figure 3: Upper two rows: latitude-height distributions of the regression coefficients of BU (the first row) and MerU (the second row) to F10.7 in January, April, July, October, and annual mean (from left to right). Lower two rows: monthly-height (lower two rows) distributions of the regression coefficients of BU (the third row) and MerU (the fourth row) to F10.7 at 50°S–50°N with interval of 25° (from left to right). The black dots indicate that the regression coefficients are less than one σ. The magenta, white, and black contour lines indicate the regression coefficients of 5, 0, and -5 ms^{-1}/100 SFU,

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respectively.

262 ### 3.3 Responses to QBO

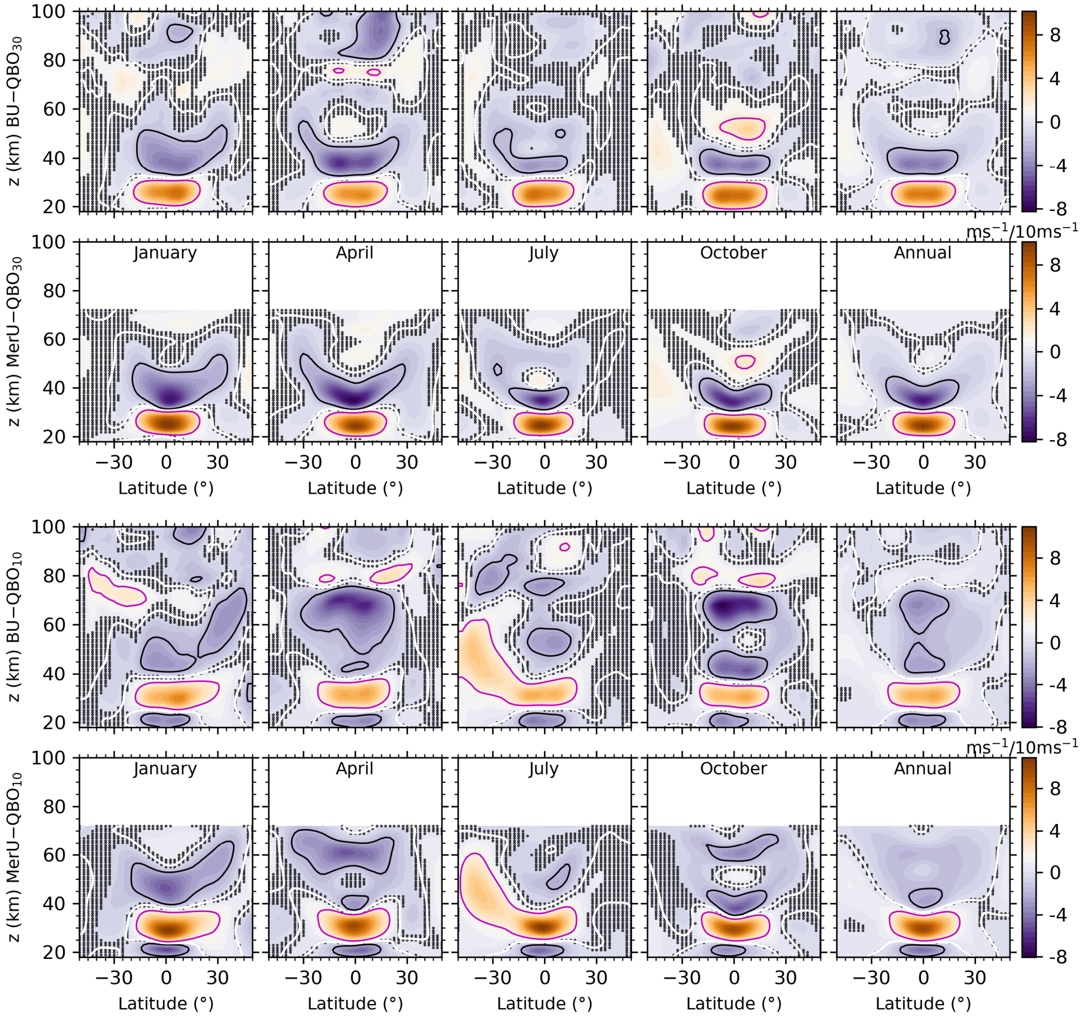

Figure 4: Same captions as the upper two rows of Fig. 3 but for the responses to QBO_{30} and QBO_{10}, respectively. The magenta, white, and black contour lines indicate the regression coefficient of 2, 0, and -2 ms^{-1}/10 ms^{-1}, respectively.

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The latitude-height distributions of the responses of BU and MerU to QBO_{30} (upper two rows of Fig. 4) exhibit general consistencies in all months and in the annual mean below ~50 km. Such as the responses of BU and MerU to QBO_{30} change from positive below 30 km to negative at ~z=30–50 km and 25°S–25°N. The varying responses with height are mainly due to the downward propagation of QBO phase with time. This can be confirmed by the responses of BU and MerU to QBO_{10} at a higher height (lower two rows of Fig. 4), where the responses of BU and MerU to QBO_{10} change from negative to positive and then negative again. The discrepancy is that the responses of BU to QBO_{30} and QBO_{10} are slightly weaker than those of MerU below ~50 km.

The responses of BU to QBO_{30} are weaker at ~50–80 km. As the height increases, the responses of BU to QBO_{30} become stronger again and have peak around ~90 km. This coincides with the mesospheric QBO, which is antiphase with the stratospheric QBO and extends to 30°S–30°N as revealed by High Resolution Doppler Imager observations (HRDI) (Burrage et al., 1996), TIMED Doppler Interferometer observations (Kumar, 2021) and reviewed by Baldwin et al., (2001). This coincides also with the results simulated by WACCM6 on the aspects of the hemispheric asymmetry, i.e., the responses extending to higher southern (northern) latitudes in summer (winter) (Ramesh et al., 2020). Moreover, the annual mean responses of BU and MerU to QBO_{30} and QBO_{10} are positive and are more significant at 50°S than those at 50°N at ~z=50–80 km. The significant positive responses at 50°S are mainly contributed by those in July and October around 50 km, where and when the stratospheric polar jet occurred.

A short summary is that the influences of the stratospheric QBO extend from the equator to higher latitudes. The influences can be positive or negative, which depend on heights and latitudes. Such as the negative influences above ~80 km in the tropical region and the positive influences at the southern high latitudes. Above ~80 km, the negative responses of winds to the stratospheric QBO are hemispheric asymmetry and are more negative in the NH tropical regions.

3.4 Responses to ENSO

The latitude-height distributions of the responses of BU and MerU to MEI (upper two rows of Fig. 5) generally coincide with each other in all months and in the annual mean. In January and at ~z=40–60 km and latitudes higher than 40°N, although the responses of MerU and BU to MEI are positive, the responses of BU to MEI are not significant. This coincides with the results simulated by WACCM6, which were positive but were lower than the 95% confidence level (Ramesh et al., 2020). In April and October, and at ~35 km, the negative responses of winds to MEI are approximately hemispheric symmetric. The annual mean responses of both winds to MEI are stronger and wider in the SH than those in the NH. In July and at ~50 km, the responses of both winds are positive with peaks around ~40°S. This indicates that the positive MEI index (warm phase of ENSO or El Niño event) increases the eastward zonal winds. In July and at ~z=65–80 km, the negative responses have peaks around the equator and 35°N/S. Above 60 km, the positive responses of winds to MEI tilt from higher height (~90 km) at 35°S to a lower height (~80 km) at 35°N in January. This pattern continues in April and July. Above ~90 km and around ~15°S, the responses of BU to MEI are positive in January and negative in July. The annual mean responses

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are mainly positive in most latitudes.

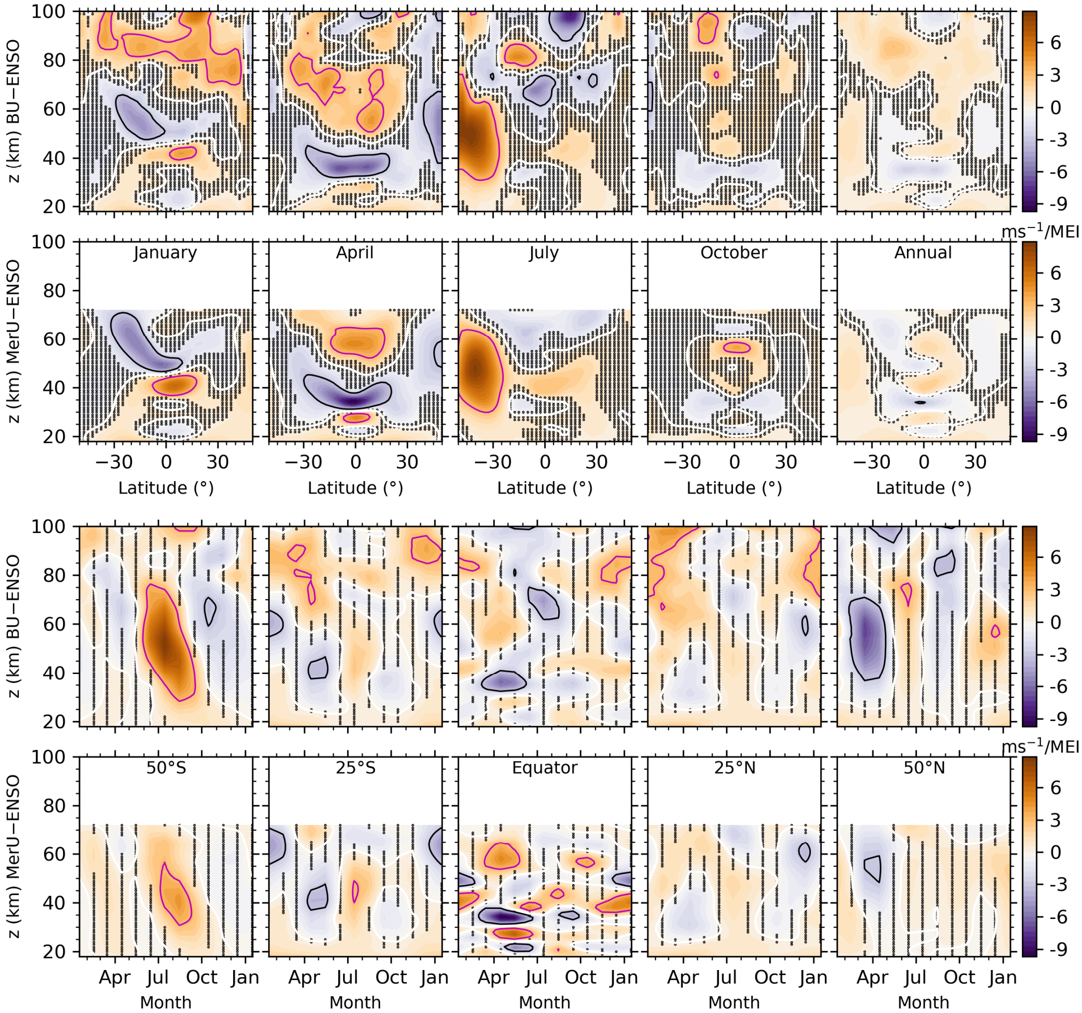

Figure 5: Same caption as Figure 3 but for the responses to ENSO. The magenta, white, and black contour lines indicate the regression coefficient of 3, 0, and -3 ms^{-1}/MEI, respectively.

The monthly-height distributions of the responses of BU and MerU to MEI (lower two rows of Fig. 5) generally

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coincide with each other at each latitude, except that the responses of BU to MEI have stronger peaks than those of MerU at 50°N/S. The prominent responses of winds to MEI are positive at 50°S (tilting from July at higher height to October at lower height) and are negative at 50°N (mainly in March and April). At 25°N/S, the responses of winds to MEI are mainly positive (extending upward to ~50 km and then tilting backward with the increasing height in July and August) and are negative (extending backward and forward below ~60 km). At the equator, the responses of MerU to MEI exhibit larger variabilities than those of BU below ~40 km.

Previous studies showed that during EI Niño (warm phase of ENSO), the warm sea surface temperature increases the wave activity, which has a high probability of leading to sudden stratospheric warming (SSW) events (Polvani and Waugh, 2004). Then the warm temperature and decelerated zonal wind anomalies can be observed in the stratosphere from January to April at 60°N (Manzini et al., 2006; Domeisen et al., 2019b). This can be summarized as a negative response of zonal wind to ENSO at northern high latitudes. This negative response can also be seen at 50°N (lower-right two panels of Fig. 5). Using the WACCM simulations and SABER observations, T. Li et al., (2016) showed that the stratospheric zonal wind is weekend due to the increased stratosphere meridional temperature gradient at the southern high latitudes in December and in the warm phase of ENSO. This supports the weak negative responses of zonal wind to ENSO at 50°S in December (lower-left two panels of Fig. 5). However, Both BU and MerU showed that the responses zonal wind to ENSO are positive from July to October at 50°S. The physics behind this positive response should be further explored through simulation studies.

A short summary is that both BU and MerU exhibit similar responses to MEI. Whereas the responses of BU to MEI are stronger than those of MerU at 50°N/S. An interesting feature is that the responses of winds to MEI propagate downward with increasing time at 50°N/S and 25°N/S, especially the positive responses of BU to MEI at 50°S and 25°S.

3.5 Linear variations

The latitude-height distributions of the linear variations of BU and MerU (upper two rows of Fig. 6) generally coincide with each other in regions where their magnitudes larger than one σ. The consistencies include: (1) in April and around the equator, the positive variations at ~20 km and ~60 km and negative variations at ~35 km; (2) in April and in the annual mean, the negative variations having peaks at 40°N and extending to the northern higher latitudes. The discrepancies of the linear variations between BU and MerU include that: (1) the negative variations of BU around 50°N (50°S) cannot be seen in MerU in January (April); (2) the positive variations of MerU are larger than those of BU above ~55 km. Above 70 km, the patterns of the linear variations of BU are sporadic and strongly dependent on months, latitudes and heights.

The monthly-height distributions of the linear variations of BU and MerU (lower two rows of Fig. 6) generally coincide with each other. The negative variations of BU and MerU coincide with each other at 50°S in August–October and at 25°S in May–July. However, the large discrepancy is that the negative variation of BU at 50°N cannot be seen in MerU in October–January. Above ~70 km, the positive variations last a longer time interval as compared to the negative variations.

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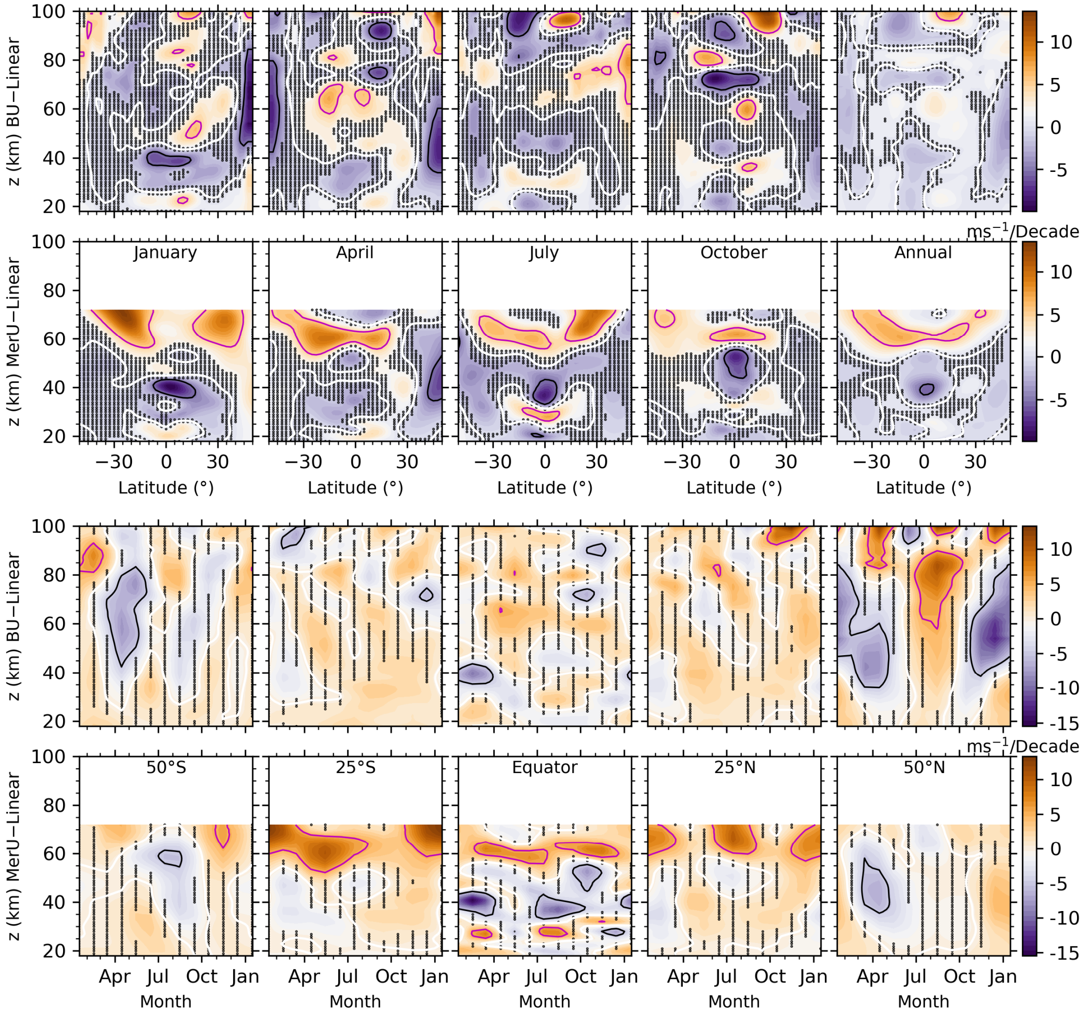

Figure 6: Same caption as Figure 3 but for the linear variations. The magenta, white, and black contour lines indicate the regression coefficient of 5, 0, and -5 ms^{-1}/Decade, respectively.

Using the MF radar observations at Juliusruh (54.6°N; 13.4°E) during 1990–2005, Keuer et al. (2007) showed that the zonal wind below 80 km exhibited a negative trend of ~-5 ms^{-1}/Decade in summer and a positive trend of ~4 ms^{-1}/Decade in winter (Fig. 14 of their paper). This result does not coincide with our analysis. By combining the radar, rocketsondes and

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satellite observations over Indian region and simulation results by WACCM-X, Venkat Ratnam et al. (2019) show a negative trend of ~-5 ms^{-1}/Decade) between 70 and 80 km. This result coincides with our analysis only during April and October. It should be noted that linear variations of zonal wind depend on the station, height range, measuring techniques, and the temporal interval of the data (Keuer et al., 2007; Ramesh et al., 2020). This illustrates the complexity of the linear variations of zonal wind. Moreover, the inhibited linear variations of regressors used in the MLR model and the dynamics (such as SSW) are also important in retrieving the linear variations of zonal winds (Qian et al., 2019). The effects of the temporal coverage of the data and SSWs in the NH on the responses will be discussed in Sect. 4.

A short summary is that both BU and MerU exhibit similar linear variations. But this consistency is not as good as that the seasonal variations, the responses to F10.7, QBO, and ENSO. The large discrepancy is that the negative variations of BU at 50°N cannot be seen in MerU in October–January. Above 70 km, the patterns of the linear variations of BU are sporadic and strongly dependent on months, latitudes and heights.

4 Discussions

4.1 Influences of temporal intervals of data

Robust responses or linear variations should not depend on the temporal intervals of the data (Souleymane et al., 2021; Mudelsee, 2019; Qian et al., 2019). This means that the temporal interval of the data should be long enough, which is difficult to be satisfied since the atmospheric variations or oscillations have multiple temporal scales (ranging from month to decade). To test the robustness of the regression results described in Sect. 3, we change the temporal intervals of both BU and MerU according to solar activity, which exhibits nearly 11-year variations. One is 2002–2015, which covers an interval from solar maximum to minimum and then to maximum. The other is 2008–2019, which covers an interval from solar minimum to maximum and then to minimum. After August 2004, the MLS data have been assimilated into MERRA2 (Molod et al., 2015; Gelaro et al., 2017). To test the sensitivity to this change, we introduce the third temporal interval of 2005–2019. Finally, the fourth temporal interval is 2002–2019, which is the entire data used here.

Figure 7 shows the annual mean responses of winds to QBO_{30} and ENSO in the four temporal intervals. The responses of BU to QBO_{30} (the first row) are nearly identical among the four temporal intervals throughout the height range. The slight difference is the weaker positive responses of BU to QBO_{30} during 2005–2019 at ~55 km around the equator. The responses of MerU to QBO30 (the second row) are also nearly identical among the four temporal intervals throughout the height range. The slight difference is the weaker positive responses (less than one σ) of MerU to QBO_{30} at ~60 km around the equator in the temporal span of 2005–2019. These comparisons show that the responses of winds to QBO_{30} are robust and are almost independent on the temporal intervals.

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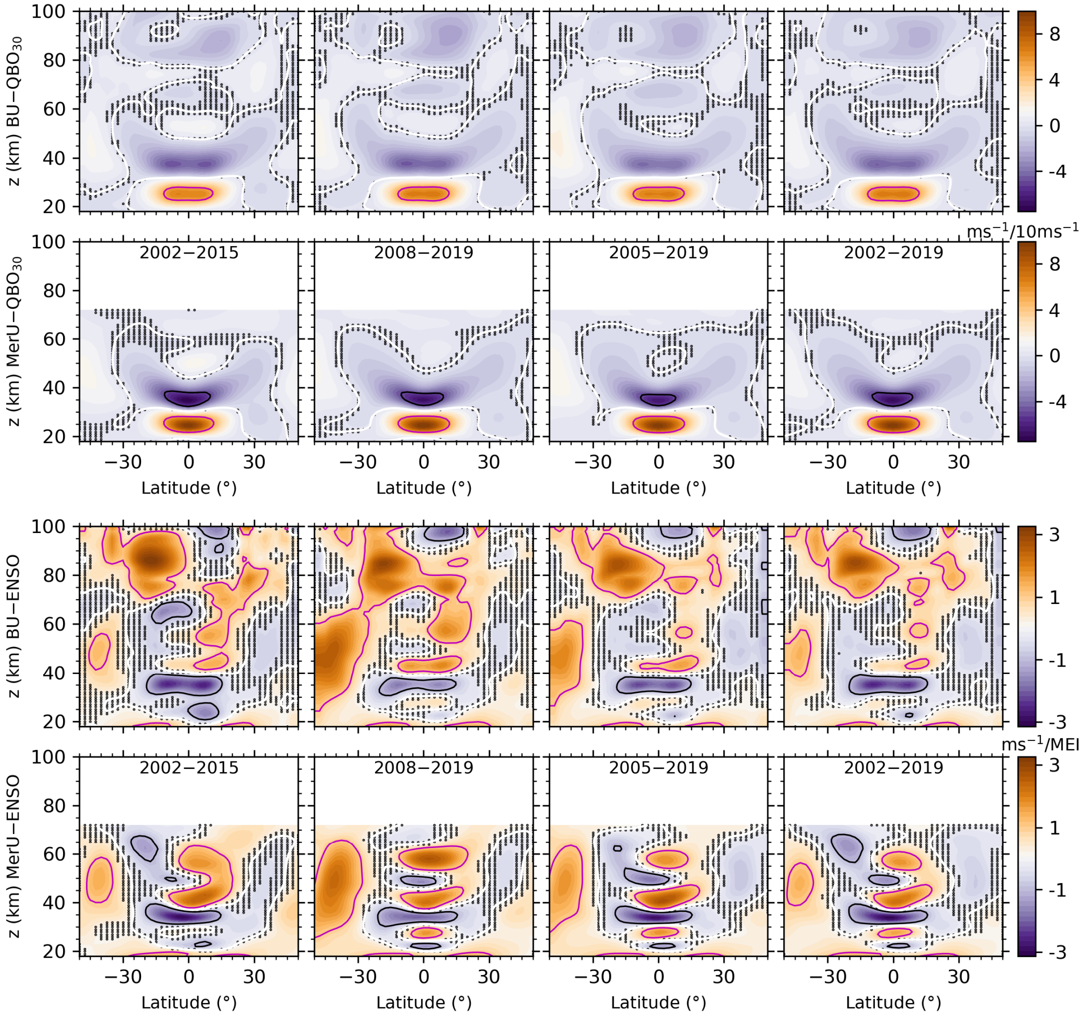

Figure 7: Latitude-height distributions of the annual mean regressions of BU (the first and third rows) and MerU (the second and fourth rows) to QBO30 (upper two row) and ENSO (the lower two rows). The black dots indicate where the regression coefficients less than standard deviations. The magenta, white, and black contour lines in the upper (lower) two rows indicate the regression coefficients of 5, 0, and -5 $ms^{-1}/10\ ms^{-1}$ (1, 0, and -1 ms^{-1}/MEI), respectively.

362 The annual mean responses of BU to ENSO (the third row) have similar patterns among the four temporal intervals.

Such as: (1) the positive responses extending from the southern high latitudes at lower height to lower latitudes at higher height, (2) the positive responses extend from the tropical regions at ~40 km to middle latitudes at higher height, (3) the positive and negative responses shifting with height in the tropical regions below ~40 km. The slight difference is the weaker positive at the southern high latitudes and around ~50 km during 2002-2015 and 2002-2019, as compared to the other two temporal intervals. The responses of MerU to ENSO (the fourth row) have also similar patterns of responses among the four temporal intervals. This is similar to that of BU and might be caused by the larger variabilities of MEI index after 2008. The negative responses of both winds to ENSO are stronger around ~20°S and ~60 km during 2002–2015 and 2002–2019, as compared to other temporal intervals. In a word, the responses of winds to ENSO are robust but slightly depend on the temporal intervals.

Figure 8 shows the annual mean responses of winds to F10.7 (upper two rows) and the linear variations of winds (lower two rows) in the four temporal intervals. In the temporal intervals of 2002–2015 and 2002–2019, both BU and MerU exhibit similar responses to F10.7. In the temporal intervals of 2008–2019 and 2005–2019, both BU and MerU also exhibit similar responses to F10.7. In the four temporal spans, the responses of MerU to F10.7 are more negative at latitudes higher than ~30°S and extend to a higher height than those of BU. Around the tropical region and at ~40 km, the responses MerU to F10.7 are more negative than those BU. At latitudes higher than ~30°S and around the tropical regions, the positive responses of BU to F10.7 have peaks at ~z=70–85 km, which are larger in the temporal intervals of 2002–2015 and 2002–2019, as compared to other temporal intervals. The stronger responses in the temporal intervals of 2002–2015 and 2002–2019 might be caused by the fact that the solar activity has a higher peak in 2002 than in 2014 (Fig. 1a).

The linear variations of both BU and MerU depend strongly on the temporal intervals. Among the four temporal intervals, the regions and magnitudes of negative variations are largest and strongest in the temporal span of 2008–2019, and are larger and stronger in the temporal interval of 2005–2019, and then in the temporal interval of 2002–2019. In contrast, the regions and magnitudes of positive variations are largest and strongest in the temporal interval of 2002–2015. Because the dependencies of the linear variations of BU and their dependencies on different temporal interval are similar to those of MerU, we cannot determine whether or not the assimilation of MLS data into MERRA2 influences the linear variations. The possible reasons, which are responsible for the strong dependencies of the linear variations on different temporal intervals, can be ascribed to the different linear variations inhibited in the regressors and the unstable regressors in different temporal intervals (Qian et al., 2019).

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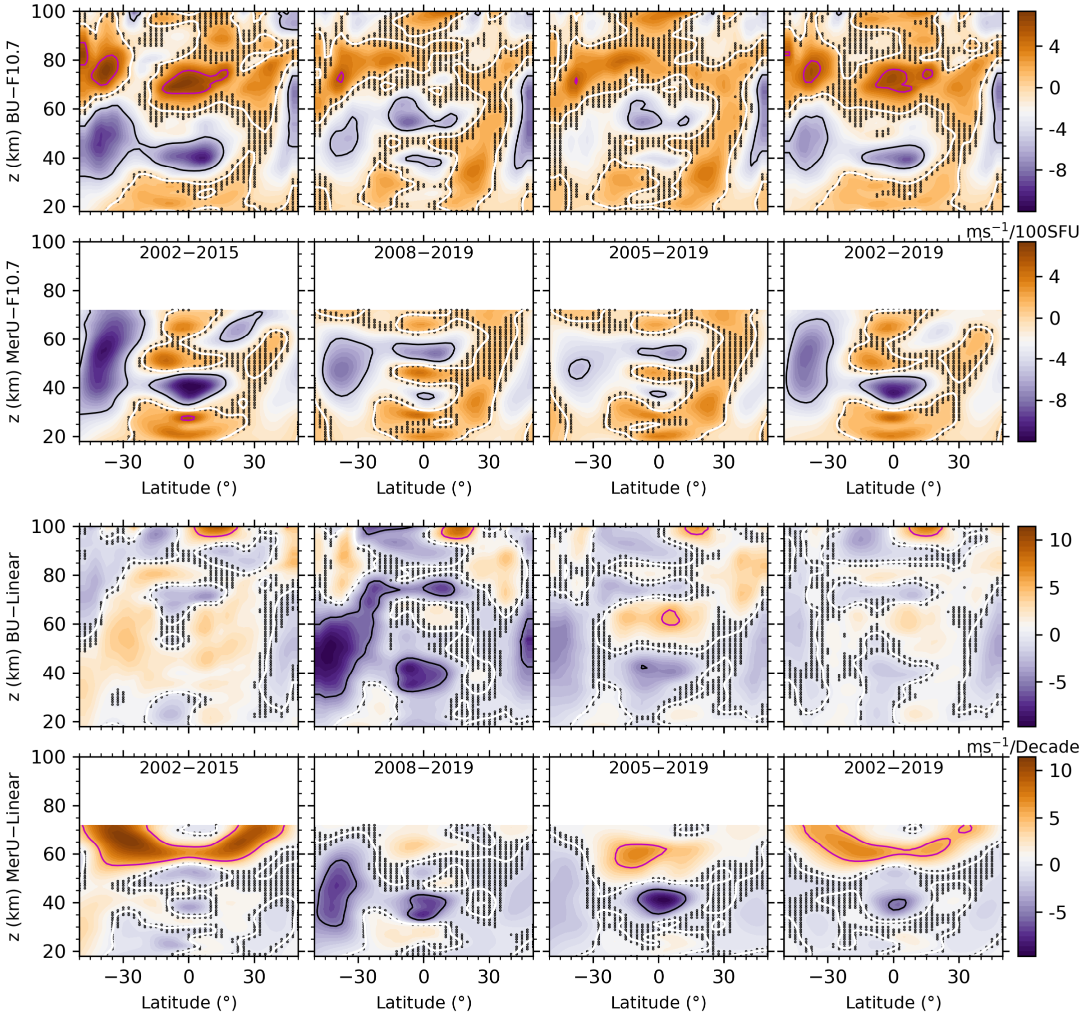

Figure 8: Same caption as Figure 7 but for the responses to F10.7 (upper two rows) and linear trend (lower two rows). The magenta, white, and black contour lines in the upper (lower) two rows indicate the regression coefficients of 5, 0, and -5 ms^{-1}/100 SFU (5, 0, and -5 ms^{-1}/Decade), respectively.

First, we examine the linear variations inhibited in the regressors (F10.7, QBO, and ENSO) and list their linear slopes in Table 1. The values in Table 1 are approximate values and are derived through the following steps. From the upper two rows

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of Fig. 8, we see that the maximum responses of winds to F10.7 is 10 ms^{-1}/100SFU (0.1 ms^{-1}/SFU). According to this conversion rule, one unit of the linear variation of F10.7 (SFU/Decade) can induce the wind variation of 0.1 ms^{-1}/Decade. Approximately, one unit of the linear variation of ENSO (MEI/Decade) can induce the wind variation of 1 ms^{-1}/Decade. Thus, in quality, the combination influences of these regressors can be summarized and listed in the last row of Table 1. We see that the inhibited linear variations of these regressors provide negative (positive) variations in the temporal spans of 2002–2015 and 2002–2019 (2008–2019 and 2005–2019). These inhibited linear variations share the linear variations of winds in Eq. (2). The positive (negative) inhibited linear variations make the linear variations winds more negative (positive). This is confirmed by the fact that the regions and magnitudes of linear variations decrease if we remove the linear variations of each regressors (not shown here). This explains partially the strong dependencies of the linear variations on different temporal spans.

Table 1: Linear variations of F10.7, QBO30, QBO10, and ENSO in different temporal spans and their combination effects on the linear variations of BU

Regressors (unit)	2002–2015	2008–2019	2005–2019	2002–2019
F10.7 (SFU/Decade)	1.1	-3.2	6.7	-17.3
QBO_{30} (ms^{-1}/Decade)	-2.5	0.7	5.6	1.5
QBO_{10} (ms^{-1}/Decade)	2.2	3.6	3.1	0.1
ENSO (MEI/Decade)	-0.1	1.1	0.5	0.1
Combination (ms^{-1}/Decade)	-0.29	5.08	9.87	-0.03

Second, even if we remove the linear variations of each regressors, the dependencies of the linear variations on different temporal spans cannot be removed completely. This might be induced by the fact that the regressors are not stable time series and have varying magnitudes and periodicities in different temporal intervals. Such as the MEI index, which has larger variations after 2009 than before (Fig. 1c); F10.7, which has larger peaks in 2002 than in 2014 (Fig. 1a). It should be noted that each regressor has its own linear variations and varying magnitudes and periodicities, which are the physical nature of the regressor and should not be removed. Such that one can get a reliable response of the winds to each regressor although the responses depend on the temporal interval of the data.

The dependencies of winds to QBO are almost identical in different temporal intervals. The dependencies of winds to ENSO on temporal intervals are slightly stronger than to QBO. The dependencies of winds to F10.7 on temporal intervals are stronger than to QBO. The dependency of the linear variations of winds on temporal intervals are the strongest one. Comparing among these responses and the linear variations, we can conclude that the MLR can capture robust responses if the regressor has relatively stable oscillation period and amplitude (i.e., QBO) and the data length is long enough to cover the main features of the regressor. The robustness decreases as the stability (i.e., the magnitudes and periodicities) of the regressor decreases (such as ENSO and F10.7). For the linear variation, its oscillation period can be regard as infinite. Thus, the data length should be infinite to get a reliable linear variation. However, this is not possible in reality. Consequently, we propose that the linear variations should be examined in different temporal spans, such that one can get a more comprehensive impression on the linear variations although the exact long-term linear variations are unknown.

4.2 Possible reasons of hemispheric asymmetry

The responses of both BU and MerU to F10.7 and ENSO exhibit hemispheric asymmetry. Specifically, the negative (positive) responses of winds to F10.7 are stronger in the SH than those in the NH above the stratospheric polar jet region (around 80 km). The responses of winds to ENSO are positive in the SH stratospheric jet region but are negative in the NH counterpart. Above 80 km, the responses of BU to ENSO are more positive in the SH sub-tropical region than those in NH counterpart. The positive responses of winds to QBO extend to a wider latitude range in the SH stratospheric jet region than those in the NH counterpart. Moreover, the seasonal and linear variations of BU and MerU also exhibit hemispheric asymmetry. Specifically, the peaks of AO of both BU and MerU have larger amplitudes and at lower heights in SH than those in the NH. Although the linear variations of winds depend on the temporal intervals of data, the linear variations are hemispheric asymmetry on aspects of magnitudes and patterns in each temporal interval.

Since the regressors are same at all latitudes and heights, the hemispheric asymmetric responses come from the hemispheric asymmetry of zonal winds. Figures 3 and 4 of Liu et al. (2021) have shown that both BU and MerU were faster in the SH than those in the NH, especially when the wind is eastward in winter of each hemisphere. Moreover, the winds at middle and high latitudes of the SH were faster and more stable than those in the NH. One reason is that the SSW occurs frequently (6–7 times per decade) in the NH. During SSW, the eastward wind becomes weak or even reversal (Butler et al., 2015; Baldwin et al., 2021). We note that SSWs in the NH mainly occurred in the phase when the zonal wind was eastward (i.e., the zonal wind was eastward before and after SSWs, while the zonal wind becomes weak or reversed during SSWs). In contrast, the SSW rarely occurred in the SH (only 3 time during 2002–2019, i.e., major SSW in September 2002, minor SSWs in August 2010 and September 2019), mainly due to the weaker land-sea contrast and smaller planetary wave amplitudes in the SH than those in the NH (Eswaraiah et al., 2016; Li et al., 2021; Rao et al., 2020; Butler et al., 2015).

The MerU at 60°N/S and 30 km (Fig. 9) show that the SSWs in the NH have influence on the zonal wind at least in the monthly mean sense. However, the influence of SSWs on the zonal wind in the SH is neglectable. If we simply use the zonal wind at 60°N/S and 30 km as a regressor to represent SSW, the prominent responses appear in summer but not in winter (when the SSW occur). This is because SSWs occur only in a limited temporal interval (1-2 weeks) in winter, the zonal wind at 60°N/S and 30 km throughout the temporal interval include both SSWs and other variations. It is desired to develop an index to represent the main features of SSW. This is out of the scope of this work and will be our future work. To illustrate the possible influences of SSWs on BU, we show in Fig. 9 the residuals of BU (BU_{Res}) of Eq. (2) and their absolute values

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(|BU_{Res}|) in a composite year. BU_{Res} may represent the effects SSWs on BU to some extent since we did not include SSW as a regressor in Eq. (2).

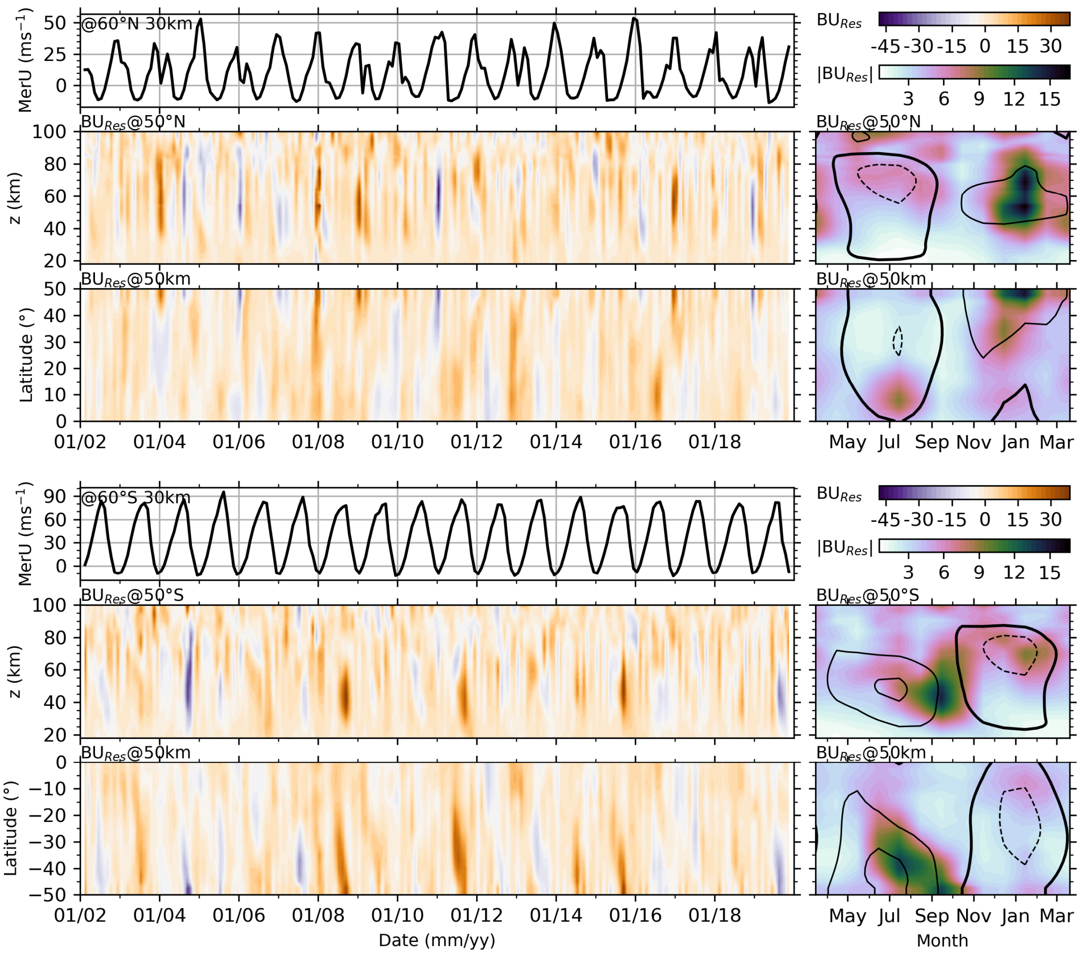

Figure 9: Upper three rows: MerU at 60°N and 30 km (first row) and the residuals of BU (BU_{res}, the upper color bar in the top-right corner) at 50°N (the second row) and 50 km (the third row), and the absolute values BU_{res} (|BU_{res}|, the lower color bar in the top-right corner) in a composite year. Lower three rows: same caption as the upper three rows but for the winds in the southern counterpart. The dashed, thick, and solid contour lines indicate the BU of -40, 0, 40 and 80 ms^{-1}, respectively.

From Fig. 9, we see that BU_{Res} have larger magnitudes (positive or negative) in the NH when SSWs occur. Meanwhile,

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the magnitudes of BU_{Res} decrease with the decreasing latitudes. $|BU_{Res}|$ in a composite year has peak around January, when SSWs occur more frequently as revealed from the MerU at 60°N. This indicates that the influences of SSWs on the regression results decrease with the decreasing latitudes in the NH. In contrast, BU_{Res} have larger magnitudes when the zonal winds decelerate from their eastward peaks in the SH. Further examination on the $|BU_{Res}|$ in a composite year, we see that their peaks shift from September at 50°S to July at lower latitudes. The larger $|BU_{Res}|$ is mainly due to the seasonal asymmetry of zonal winds, i.e., the zonal winds take a longer time to reach their eastward peak than that to reach their westward peak.

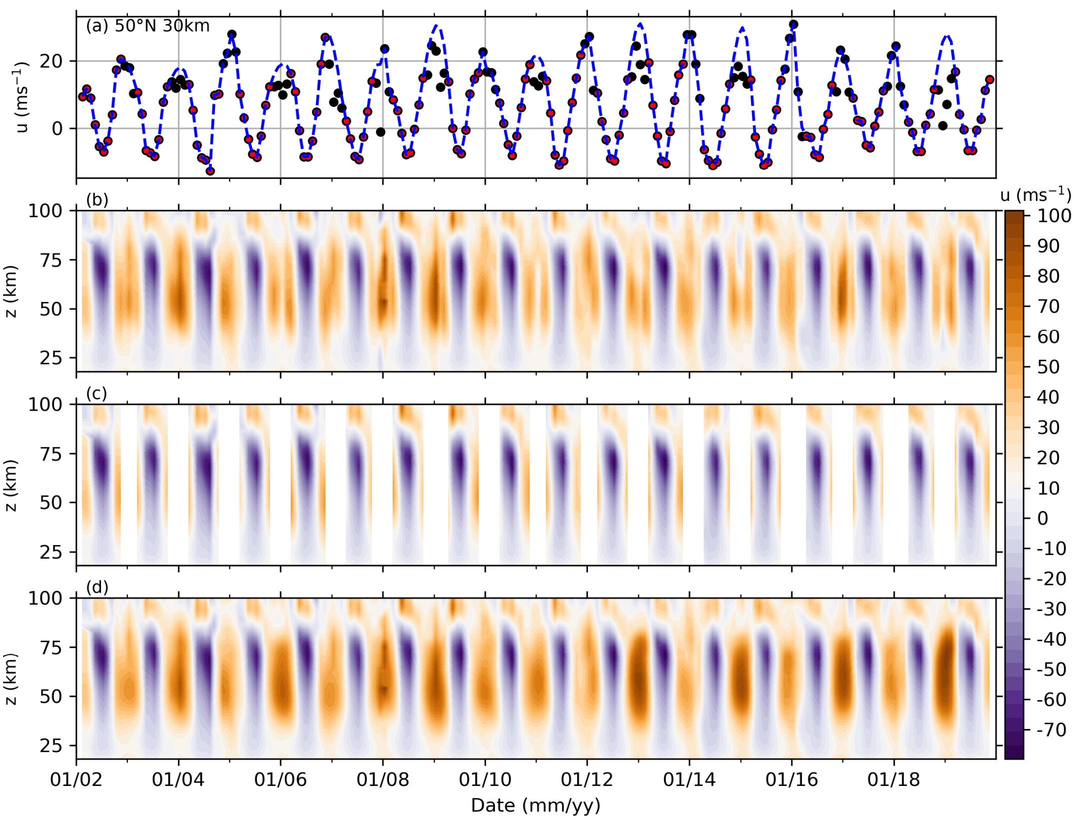

Figure 10: Removing SSWs from the raw BU and the reconstructed BU at 50°N. (a): the remaining data (red dots), which is obtained by removing the data affected by SSWs from raw BU (black dots), and the reconstructed BU (blue dotted line, see text for detail). (b-d): the raw BU, remaining and reconstructed BU, respectively.

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458 To test the possible influences of SSWs on the hemispheric asymmetry of the variations and responses, we reconstruct
459 the BU in the NH during 2002–2019 through the following two steps. First, at each height and latitude, we remove the wind
460 data during SSWs (i.e., the BU in winter does not increase monotonically before December or decrease monotonically after
461 December) from the raw wind (shown as black dots in Fig. 10a). Second, cubic spline interpolation is applied on the
462 remaining data (red dots in Fig. 10a) to get a reconstructed wind series in winter (i.e., it increases monotonically before
463 December and decreases monotonically after December, shown as blue dashed line in Fig. 10a). Figures 10(b-d) show the
464 raw BU, remaining and the reconstructed BU, respectively. We see that the decelerated eastward winds during SSWs (Fig.
465 10b) have been replaced by the reconstructed BU, i.e., the eastward winds accelerate before December and decelerate after
466 December (Fig. 10d).

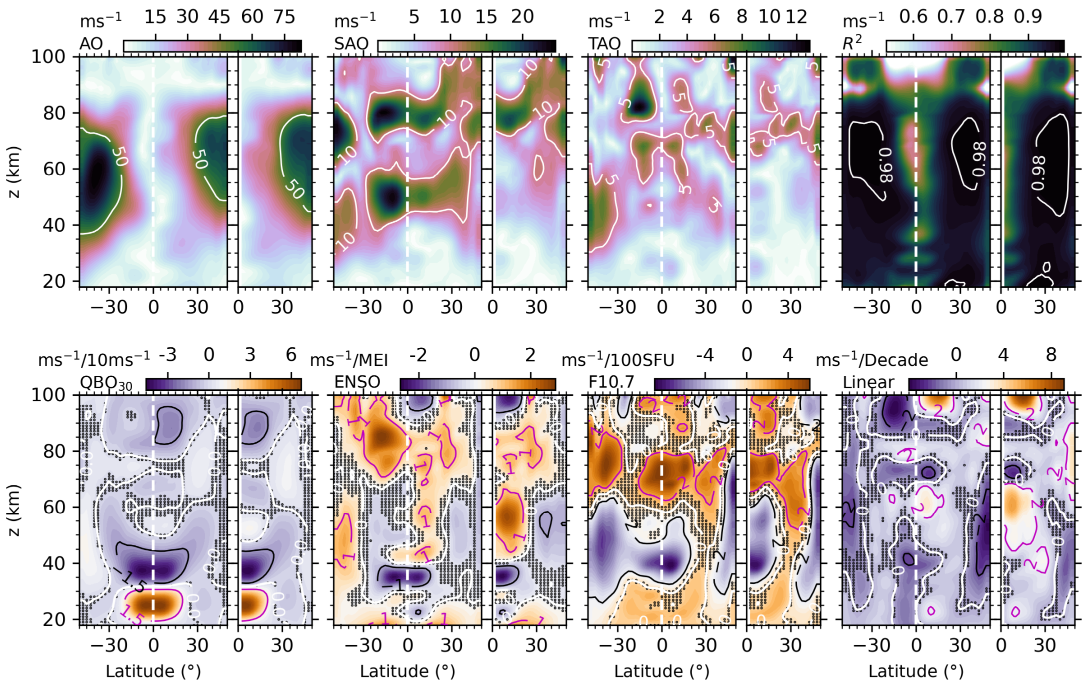

Figure 11: Regression results of the raw (50°S–50°N, left panel of each subplot) and reconstructed BU (0°–50°N, right panel of each subplot) in the NH during 2002–2019. Upper row: same caption as Figure 2. Lower row: same caption as Figure 7.

467 Using Eq. (2), we performed the same regression on the reconstructed winds in the NH. Figure 11 shows the amplitudes
468 of seasonal variations and R^2, and the responses of reconstructed winds to QBO, ENSO, F10.7, and the linear variations. For

comparison purpose, we also show in Fig. 11 the regression results of the raw BU. The R^2 indicates that Eq. (2) explains the reconstructed winds more accurately than the raw BU in the NH stratospheric polar jet region. The amplitudes of AO of the reconstructed winds are larger than those of the raw BU. However, the amplitudes of SAO and TAO of the reconstructed winds are smaller than those of the raw BU in the NH stratospheric polar jet region. Above 80 km, the amplitudes AO, SAO, TAO of both the reconstructed and raw BUs are nearly identical. The influences of SSWs on the seasonal variations mainly in the stratospheric polar jet region and around ~65 km. The influences of QBO_{30} on the reconstructed winds are similar to those of the raw BU on the aspects of both patterns and magnitudes. The influences of ENSO on the reconstructed winds have similar patterns to those of the raw BU but have larger magnitudes at ~55 km. While above ~70 km, the influences of ENSO on the reconstructed winds have similar patterns and magnitudes to those of the raw BU. The negative influences of F10.7 on the reconstructed winds extend to ~30–60 km as compared to the ~z=30–50 km for the raw BU in the NH tropical region. The linear variations of the reconstructed winds are more positive at ~60 km in the subtropic region but less negative at latitudes higher than 30°N. In a word, compared to the raw BU, the reconstructed wind increases the amplitudes of AO but decreases the amplitudes of SAO and TAO in the NH stratospheric polar jet region. The responses of the reconstructed winds to QBO, ENSO, F10.7, and the linear variations slightly changed on the aspect of magnitudes. However, the hemispheric asymmetry of the responses is not affected by SSWs at least in the monthly mean sense.

5 Conclusions

A global balance wind dataset (BU) is used to study the variations of the monthly zonal mean winds and responses of the monthly zonal mean winds to solar activity, QBO, ENSO at ~z=18–100 km and 50°S–50°N and from 2002 to 2019. The variations and responses are extracted by MLR method, which is also applied to the MERRA2 zonal wind (MerU) to test the reliability of BU and their responses.

The seasonal variations (AO, SAO, and TAO) of BU and MerU have nearly identical phases in the regions where their amplitudes are prominent. Their consistencies are better in the SH than in the NH on the aspects of both patterns and magnitudes. The SAO of BU has peak around 80 km is hemispheric asymmetry and stronger in the SH. The TAO of BU above 80 km is also hemispheric asymmetry and stronger in the SH. The annual mean responses of BU and MerU to F10.7 are more negative in the SH stratospheric polar jet region of SH than that of the NH counterpart. Around ~80 km, the annual responses of BU to F10.7 are mainly positive in the tropical region. The influences of the stratospheric QBO extend from the equator to higher latitudes with the increasing height. The influences can be positive or negative, which depend on heights and latitudes. Above ~80 km, the negative responses of winds to the stratospheric QBO are hemispheric asymmetry and are more negative in the NH tropical regions. Both BU and MerU exhibit similar responses to MEI. Whereas the responses of BU to MEI are stronger than those of MerU at 50°N/S. The responses of winds to MEI propagate downward with the increasing time at 50°N/S and 25°N/S. Both BU and MerU exhibit similar linear variations. The large discrepancy is that the negative variations of BU at 50°N cannot be seen in MerU during October–January. Above 70 km, the patterns of the linear variations of BU are sporadic and strongly dependent on months, latitudes and heights.

The robustness of the responses of winds to QBO, ENSO, and F10.7, and the linear variations of winds are examined by changing the temporal interval of the data. We found that the responses of winds to QBO are robust and are almost independent on the temporal intervals. The responses of winds to ENSO are robust but slightly dependent on the temporal intervals. Although the responses of wind to F10.7 have similar patterns in different temporal intervals, the responses are stronger in the temporal intervals of 2002–2015 and 2002–2019 than the other two temporal intervals. The linear variations of both BU and MerU depend strongly on the temporal intervals. The possible reasons might be the different linear variations inhibited in the regressors and (2) the unstable regressors in different temporal intervals. Thus, it is desired to examine the responses and linear variations in different temporal intervals, such that one can get a more comprehensive impression on the linear variations although the exact linear variations are unknown. The influences of SSWs on the seasonal variations are mainly in the NH stratospheric polar jet region. However, the hemispheric asymmetry of the seasonal and linear variations, and the hemispheric asymmetric responses of BU to QBO, ENSO, and F10.7 are not affected by SSWs at least in the monthly mean sense.

Data availability

The global balance wind data can be obtained from National Space Science Data Center (https://doi.org/10.12176/01.99.00574) (Last access: March 2022, Liu et al., 2021). The F10.7 data were obtained from https://spdf.gsfc.nasa.gov/pub/data/omni/ (last access: March 2022, Tapping, 2013).The MERRA2 data were obtained from http://disc.sci.gsfc.nasa.gov/mdisc (last access: March 2022, Molod et al., 2015; Gelaro et al., 2017). The QBO data were obtained from https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/ (last access: March 2022, Baldwin et al., 2001). The ENSO data were obtained from https://www.psl.noaa.gov/enso/mei/ (last access: March 2022, Zhang et al., 2019; Wolter and Timlin, 2011).

Author contributions

XL analyzed the data and prepared the paper with assistance from co-authors. JX and JY design the study. All authors reviewed and commented on the paper.

Competing interests

The authors declare that they have no conflict of interest.

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