Gravity Waves induced Wind Shears Derived from SABER Temperature Observations

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Abstract. Large wind shears around the mesopause region play important roles in atmospheric neutral dynamics and ionospheric electrodynamics. Based on previous observations using sounding rockets, lidars, radars and model simulations, large shears are mainly attributed to gravity waves (GWs) and modulated by tides (Liu, 2017). Based on the dispersion and polarization relations of linear GWs and the SABER temperature data from 2002 to 2019, a method of deriving GW-induced wind shears is proposed. The zonal mean GW-induced shears have peaks (13-17 ms^{-1}km^{-1}) at around the mesopause region, i.e., at z=90-100 km at most latitudes and at z=80-90 km around the cold summer mesopause. This latitude-height pattern is robust over the 18 years and agrees with model simulations. The magnitudes of the GW-induced shears exhibit year-to-year variations and agree with the lidar and sounding rocket observations on climatology sense but are 60-70% of the model results in the zonal mean sense. The GW-induced shears are hemispheric asymmetric and have strong annual oscillation (AO) at around 80 km (above 92 km) at the northern (southern) middle and high latitudes. At middle to high latitudes, the peaks of AO shift from winter to summer and then to winter again with increasing height. However, these GW-induced shears may be overestimated because the GW propagation direction cannot be resolved by the method and may be underestimated due to the observational filter, sampling distance and cutoff criterion of the vertical wavelength of GWs.

1 Introduction

In the mesosphere and lower thermosphere (MLT), large horizontal winds and their vertical shears (or wind shears, short for shears) have been revealed from more than 500 wind profiles observed by sounding rockets (Larsen, 2002; Larsen & Fesen, 2009) and ground-based lidar and radar observations globally (Larsen & Fesen, 2009; Oppenheim et al., 2009, 2014; Yue el al., 2010). The large horizontal winds (≥100-200 ms^{-1}) and shears (≥40 ms^{-1}km^{-1}) occur in the height range of z~95-115 km at lower and middle latitudes. Using the lidar and falling sphere observations at high latitudes (the Andøya Rocket Range and

the ALOMAR observatory at 69.3°N) in July 2002, Fritts et al. (2004) showed large winds and shears at z~85-95 km and ascribed them to strong gravity waves (GWs) activity. These GWs were generated by convection, orography, jet and front in the troposphere and stratosphere and had increasing wave amplitude and shears when they propagated into the lower thermosphere. It is now accepted that the large winds and shears are a common phenomenon in the MLT region (Liu, 2007;

5   2017). The large winds and shears play important roles in forming the middle latitudes sporadic E layers and driving the equatorial electrojet (Mathews 1998; Hysell et al., 2002; Haldoupis, 2012; Shinagawa et al., 2017; Yu et al., 2019), in controlling atmospheric stabilities and the propagation of GWs, and in transporting and mixing tracers locally and/or globally (Fritts et al., 2004; Liu 2007, 2017; Yue et al., 2013; Stevens et al., 2014).

Based on the theory of dynamic instability, Liu (2007) showed that the maximum wind shears derived from $S = 2N$ (N:

10   the buoyancy frequency, S: the vertical shear) agree well with the observed large wind shears. However, the global scale models (e.g., TIME-GCM: Thermosphere, Ionosphere, Mesosphere, Electrodynamics General Circulation Model) cannot reproduce the observed large winds and wind shears but can increase the amplitudes of winds and wind shears with finer spatial resolutions (Larsen & Fesen, 2009). This indicates that the model resolution and thus tides and small-scale waves (e.g., GWs) are important in driving large winds and shears. Using a local numerical model, Liu et al. (2014a) showed that the nonlinear

15   interactions between GWs and tides can produce large winds and shears in the MLT region. The tidal phases modulate the peak height of large winds and shears. Using the spectral element version of NCAR Whole Atmosphere Community Climate Model (WACCM) with horizontal resolution of ~25 km and vertical resolution of 0.1 scale height, Liu (2017) reproduced the large wind shears, which are in good agreement with observations. Through scale separation, Liu (2017) proposed that small-scale waves (with zonal wavenumber > 6), likely GWs, play a dominant role in producing large shears. The high resolution

20   WACCM can resolve GWs with scales longer than ~100 km. Tidal waves make secondary contribution to the magnitudes of shears but can modulate the shears produced by GWs.

Large winds and shears have been observed both by sounding rocket and ground based lidar and radar, all locally and cannot provide a global morphology. High resolution GCM (e.g., WACCM) simulations can provide a global picture of large winds and shears but need be validated through global observations (e.g., satellites). Moreover, it is still a challenging to study

25   the intra-annual and/or the inter-annual variations of large winds and shears through high resolution GCM simulations due to the computational cost (Liu, 2017, 2019).

Satellite observations provide a good opportunity to study the climatology of global winds. The Wind Imaging Interferometer (WINDII) and the High Resolution Doppler Imager (HRDI) instruments onboard the Upper Atmospheric Research Satellite (UARS) provide global observations of winds in the MLT region (McLandress et al, 1996; Zhang et al.,

30   2007; Shepherd et al., 2012). Combining the winds observed by HRDI and data assimilation system, Swinbank & Ortland (2003) developed a climatology that describes the monthly zonal mean zonal winds from the surface to the upper mesosphere. The TIMED Doppler Interferometer (TIDI) instrument on board the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite measures global winds in the MLT region (Killeen et al., 2006; Niciejewski et al., 2006). These observations advanced our knowledge on the global winds in the MLT region. However, the global characteristics of shears

are poorly known. Since large shears play important roles in the atmospheric dynamics and in the MLT region and ionospheric E region and are likely caused by GWs (Fritts, 2004; Liu, 2007, 2017; Yue et al., 2010), it should be possible to derive wind shears by combining the GW theory and GWs derived from other observed physical quantities (e.g., temperature).

The focus of this paper is to propose a method of deriving shears from GWs, while the GWs are derived from temperature 5 profiles. The temperature profiles, which are measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument (Russell et al., 1999) onboard the TIMED satellite, have covered a period of 18 years (2002-2019) and are remarkably stable until now (Mlynczak et al., 2020). These profiles cover an altitude range of ~15-110 km and latitude range of 53°S-83°N or 83°S-53°N. The temperature accuracy is 1-3 K from 30 to 80 km and 5-10 K from 90 to 100 km as reported at http://saber.gats-inc.com/ website (Remsburg et al., 2008).

10 The remainder of this paper is organized as follows. Section 2 presents the method of deriving wind shears (short for GW-induced shears) induced by GWs, and the uncertainties will be presented. Section 3 presents the comparisons of the GW-induced shears with the model and observational results. Then the latitudinal and intra-annual variations of the GW-induced shears are presented in Section 4. The limitations of the method and their possible influences on the GW-induced shears are discussed in Section 5. A short summary is given in Section 6.

15 2 Method of Deriving GW-induced Wind Shears and Validations

2.1 Theory of Deriving GW-induced Shears

The basic idea of deriving GW-induced shears is the linear GW theory, which includes the dispersion and polarization relations of a monochromatic GW. A monochromatic linear GW has the form of (Fritts & Alexander, 2003),

$$\left(u'_j, v'_j \ T'_j/\bar{T}\right) = \left(\tilde{u}_j, \tilde{v}_j, \tilde{T}_j\right) \times e^{i\varphi_j + z/2H}, \tag{1}$$

20 here, $i = \sqrt{-1}$ is the imaginary unit. The subscript j denotes a monochromatic GW, u'_j and v'_j are the horizontal wind perturbations. T'_j and $\bar{T}$ are the perturbation and background temperatures, respectively. $\tilde{u}_j$, $\tilde{v}_j$ and $\tilde{T}_j$ are the amplitudes of u'_j, v'_j and $T'_j/\bar{T}$, respectively. $\varphi_j = k_j x + l_j y + m_j z - \omega_j t$ is the phase of GW. k_j, l_j and m_j are the wavenumbers in the horizontal (x, y) and vertical (z) directions, respectively. ω_j and t are the ground-based frequency and time.

Based on the polarization of the monochromatic linear GWs with lower and medium frequencies (Fritts & Rastogi, 1985; 25 Fritts & Alexander, 2003), the relations between $\tilde{u}_j$, $\tilde{v}_j$ and $\tilde{T}_j$ can be derived as (Eckermann et al., 1995; Liou et al., 2003; Gubenko et al., 2008),

$$\tilde{u}_j \approx i \frac{g}{N} \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j, \tag{2}$$

$$\tilde{v}_j = \frac{f}{\widehat{\omega}_j} \frac{g}{N} \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j. \tag{3}$$

here $\widehat{\omega}_j$ and $f = 2\Omega \sin \phi$ ($\Omega = 7.292 \times 10^{-5} \text{s}^{-1}$, ϕ is latitude) are the intrinsic and inertial frequencies, respectively. The 30 wind shear of each monochromatic GW can be written as,

$$\frac{\partial u'_j}{\partial z} = \frac{g}{N} m_j \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j e^{i(\varphi_j + \pi)}, \tag{4}$$

$$\frac{\partial v'_j}{\partial z} = \frac{f}{\widehat{\omega}_j} \frac{g}{N} m_j \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j e^{i(\varphi_j + \pi/2)}. \tag{5}$$

In real atmosphere, a GW profile consists multiple spectra and can be regarded as a superposition of monochromatic GWs. For each monochromatic GW, Eq. (2-5) are valid. Here, we use u' to represent observed GWs, which contains multiple monochromatic GWs (e.g., many u'_j) and can be expressed as,

$$u' = \sum_j u'_j = \sum_j \tilde{u}_j e^{i\varphi_j} = \frac{g}{N} \sum_j \left[\left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j e^{i(\varphi_j + \pi/2)} \right]. \tag{6}$$

In the same way, the component v' of an observed GWs can be expressed as,

$$v' = \frac{g}{N} \sum_j \left[\frac{f}{\widehat{\omega}_j} \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j e^{i\varphi_j} \right]. \tag{7}$$

For the GW-induced shears of u' and v', we have

$$\frac{\partial u'}{\partial z} = \sum_j \frac{\partial u'_j}{\partial z} = \frac{g}{N} \sum_j \left[m_j \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j e^{i(\varphi_j + \pi)} \right], \tag{8}$$

$$\frac{\partial v'}{\partial z} = \sum_j \frac{\partial v'_j}{\partial z} = \frac{g}{N} \sum_j \left[\frac{f m_j}{\widehat{\omega}_j} \left(1 - f^2/\widehat{\omega}_j^2\right)^{-1/2} \tilde{T}_j e^{i(\varphi_j + \pi/2)} \right]. \tag{9}$$

Finally, the GW-induced shear can be written as

$$S = \sqrt{(\partial u'/\partial z)^2 + (\partial v'/\partial z)^2}. \tag{10}$$

2.2 GW-induced Shear Derived from Synthesized GW Profiles and Validations

To demonstrate the applicability of the theory and the procedure of retrieval the GW-induced shears, we construct two synthesized temperature perturbation profiles (shown in Fig. 1a). Each profile is the sum of three monochromatic GWs with three different vertical wavelengths and height dependent amplitudes,

$$\begin{cases} T'_{w1}(z) = \sum_{j=1,3} T'_j(z) = \sum_{j=1,3} \tilde{T}_j \cos(m_j z + \varphi_j) \\ m_1 = 2\pi/(6\ \text{km}), m_2 = 2\pi/(10\ \text{km}), m_3 = 2\pi/(15\ \text{km}) \\ \varphi_1 = \varphi_2 = \varphi_3 = 0 \\ A_1 = 2 \times exp[(z - 70\ \text{km})/(25\ \text{km})] \\ A_2 = 2 \times exp[-(z - 60\ \text{km})^2/(20\ \text{km})^2], A_3 = 1 \end{cases}. \tag{11}$$

The background temperature $\overline{T}(z) = 240$ K. The black line in Fig. 1a show the $T'_{w1}(z)$ and noted as T'_{w1}. The profile T'_{w2} (red line in Fig. 1a) has the same amplitudes and vertical wavenumbers as T'_{w1} but setting $\varphi_1 = \varphi_2 = \varphi_3 = \pi/2$. $T'_{w1}(z)$ and $T'_{w2}(z)$ are used to represent two adjacent SABER measurements. It should be noted that we set the three monochromatic GWs in $T'_{w2}(z)$ having the same phase shift of $\pi/2$ only for the convenience of theoretical representation. In real atmosphere, GWs with different vertical wavelengths may have different horizontal wavelengths and thus different phase shifts. These phase shifts can be calculated by comparing the phases of the two monochromatic GWs with same vertical wavelength embedded in the two adjacent GW profiles. While the phase of each monochromatic GW can be derived through discrete Fourier transformation (DFT, Press et al., 1992). Then the phase shifts can be used to estimate horizontal wavenumber (e.g., Preusse

et al., 2002; Ern et al., 2004; Alexander et al., 2008, 2018; Wang and Alexander, 2010). For example, if we assume the horizontal distance (Δr) between the two profiles is 300 km, the phase shift of $\Delta \varphi = \pi/2$ indicates the horizontal wavenumber $k_h = \Delta \varphi / \Delta r = (\pi/2)/(300 \text{ km}) = 2\pi/(1200 \text{ km})$. For the lower and medium frequency GWs, the dispersion relation can be simplified as (Fritts & Alexander, 2003),

$$\widehat{\omega}_j^2 = N^2 \frac{k_{j,h}^2}{m_j^2} + f^2. \tag{12}$$

After we get the horizontal wavenumber $k_{j,h}$ from a GW profiles pair, then the intrinsic frequency for $T_j'(z)$ can be calculated by Eq. (12). Using Eq. (2-5) and the prescribed amplitude and vertical wavenumber of each monochromatic GW, we can get the zonal and meridional winds components and their shears. Then, according to Eq. (6-9), the vector sum of the three monochromatic GW-induced wind profiles can be obtained and are shown as black lines in Fig. 1b for zonal wind and 1(c) for meridional wind. Here we assume the latitude is at 30ºN, which is a typical latitude at middle latitudes. The corresponding shears are also shown as black lines in Fig. 1d-e. Since the amplitude, vertical and horizontal wavenumbers of GW profile pairs are prescribed and are not derived through DFT, which is a key step of the spectral decomposition method described below, the retrieved winds and shears are referred to as theoretical results. These theoretical results can be used to measure the results obtained from the spectral decomposition method proposed below. It should be noted that the zonal and meridional winds are the winds along and cross the orbit track directions, respectively, and may not coincide with the eastward and northward directions, but are the winds along and cross the orbit track directions, respectively. Here zonal direction is points from the location of $T_{w1}'(z)$ to that of $T_{w2}'(z)$. The meridional direction is 90° counterclockwise from the zonal direction.

Now we describe the method of retrieving winds and wind shears induced by GW profile pairs, whose amplitudes, vertical and horizontal wavenumbers are not prescribed but should be evaluated. We named this method as "spectral decomposition method" since the principle ideas are: (1) decomposing an observed GW profile into multiple monochromatic waves; (2) applying linear GW theory on each monochromatic wave to get monochromatic wind and shear of each wave component; (3) finding the vector sum of monochromatic winds and shears to get the wind perturbations and shears induced by the observed GW. The detailed application of this method is described as the following three steps.

The first step is to evaluate the amplitude and vertical wavenumbers of each GW profile by the method of DFT (Press et al., 1992). The amplitude ($\tilde{T}_{j,w1}$) and phase ($\varphi_{j,w1}$) at the vertical wavenumber (m_j) can be calculated through,

$$\left[\tilde{T}_{j,w1}, \varphi_{j,w1}\right]_{j=3}^{18} = \left[DFT[T_{r1}'(z)]\right]_{z=18 \text{ km}}^{108 \text{ km}}, \tag{13}$$

here the vertical wavenumbers $m_j = 2j\pi/(90 \text{ km})$, which corresponds the vertical wavelength ranging from ~5 km to ~30 km for a vertical extent of 90 km, which is the height coverage (18-108 km) of the SABER temperature profiles. In a same manner, we can get the amplitude ($\tilde{T}_{j,w2}$) and phase ($\varphi_{j,w2}$) of GW profile $T_{w2}'(z)$ at m_j.

The second step is to evaluate the horizontal wavenumber through the phase shift between two adjacent GW profiles. For each Fourier component of m_j, the phase shift is $\Delta \varphi_j = \varphi_{j,w1} - \varphi_{j,w2}$. According to the distance between the two adjacent profiles $\Delta r = 300$ km, we can get $k_{j,h} = \Delta \varphi / \Delta r = (\Delta \varphi_j)/(300 \text{ km})$. Then the intrinsic frequency $\widehat{\omega}_j$ for the component of

m_j can be calculated by Eq. (12). Here we note that the horizontal wavelengths of GWs in real atmosphere may be shorter than $2\Delta r$, only GWs with horizontal wavelengths longer than $2\Delta r$ are considered due to the sampling distances and the limb scanning mode of the SABER instrument (Preusse et al., 2002; Ern et al., 2004).

5 The third step is to calculate the GW-induced wind (shown as red dashed lines in Fig. 1b-c) and shears perturbations (red dashed lines in Fig. 1d-e) by Eq. (6-9). Then we can get the amplitudes of zonal and meridional wind shears, which are the modules of $\partial u'/\partial z$ and $\partial v'/\partial z$, respectively. Finally, the GW-induced shear (S) can be calculated by Eq. (10).

A brief summary of the results from the spectral decomposition method (red) and theory (black) are shown in Fig. 1. From Fig. 1, we can see that the GW-induced winds and shears derived from spectral decomposition method (red dashed lines) agree well with the theoretical results (black solid lines) below 100 km. The bad consistencies occur at around the upper 10 boundary. Thus, we will focus on the results below 100 km in the following analysis.

2.3 GW-induced Shear Derived from SABER GW profiles and Uncertainties

A key step to derive the GW-induced shears is the extraction of GWs from the SABER temperature profile. The extraction methods of GWs from satellite data have been developed by Fetzer and Gille (1994) and improved greatly since (e.g., Preusse et al., 2002; Ern et al., 2004, 2011, 2018; Chen et al., 2019; Alexander et al., 2008, 2018, Wang & Alexander, 2010; Alexander, 15 2015). We have developed a similar method in our previous studies (Liu et al., 2014b, 2017, 2019), which is summarized here. First, the daily SABER temperature profiles $T(z)$ in a latitude band of 5° are selected. Second, at each altitude, these selected data are fitted by harmonics with zonal wavenumbers ranging from 0 to 6, which are mainly planetary waves and non-migrating tides and are removed from $T(z)$ to get the residual temperature $T_r(z)$. The component of wavenumber 0 is considered as the zonal mean temperature $\bar{T}(z)$. Third, DFT (Eq. (13)) is applied on each residual profile to amplitude ($\tilde{T}_{j,r}$) and phase ($\varphi_{j,r}$) at 20 the vertical wavenumber (m_j) with $j = 3, \cdots, 18$. The corresponding vertical wavelengths are from ~5 km to ~30 km. From these monochromatic waves, we reconstruct a GW profile $T'_w(z)$. The above three steps are applied on both the ascending and descending nodes, respectively, such that it minimizes the influences of migrating tides on GWs (Preusse et al., 2002).

A GW profiles pair is defined as the two adjacent SABER GW profiles, whose along-track distance is less than 400 km. The 400 km criterion is fulfilled only for the short-distance pairs for SABER measurement (Fig. 1 of Ern et al. 2011). Then 25 from a given GW profiles pair, we can get pairs of GW-induced winds and shears by the spectral decomposition method. Figure 2 shows the flow chart of derivation winds and shears from a GW profiles pair at (42.55ºN, 56.48ºE) and (44.97ºN, 56.34ºE) on 1st January 2018. Figures 2(b) and 2(c) show the GW-induced winds in the along and cross track directions, respectively, through Eq. (6) and (7). Figures 2(d) and 2(e) show the GW-induced shears in the along and cross track directions, respectively, through Eq. (8) and (9). Figure 2(f) shows the GW-induced shears calculated by Eq. (10). From Fig. 2, we can 30 see that the peak heights of the temperature, wind and shear are not at the same height due to their phase differences shown by the polarization relations. The winds and shears in the along-track direction are larger than those in the cross-track direction due to the factor of $f/\hat{\omega} < 1$ in Eq. (3).

The horizontal wavenumber k_h, which is derived from GW profiles pair, is in the along-track direction. It is smaller than the real wavenumbers since GWs may not propagate exactly in the along-track direction. This will induce uncertainties in deriving the GW-induced shears since the GW propagation direction cannot be determined from a GW profiles pair (Ern et al., 2004). The uncertainties of the GW-induced shears are estimated in below.

The relation of the horizontal wavenumber in the along-track direction (k_{ha}) and that of in the GW propagation direction (k_{hr}) can be expressed as $k_{ha} = k_{hr} \cos \alpha$. The subscripts "a" and "r" denote the along-track and real physical quantities, respectively. The angle (α) between the along-track direction and GW propagation direction can vary from 0 ° to 360°. Here, the angle α is restricted in the range of 0-90°. This restriction maps the angle of four quadrants into the first quadrant since only the magnitude of k_{ha} and k_{hr} are considered here. If $\alpha \neq 0$, this will induce uncertainties of intrinsic frequencies ($\hat{\omega}$) and thus GW-induced shear (S). Here the uncertainty of S (noted by Se) is defined as ratio between the along-track S (noted by S_a) and real S (noted by S_r). According to Eq. (10) and (4-5), we get,

$$S_e = \frac{S_a}{S_r} = \frac{\tilde{u}'_a}{\tilde{u}'_r} \sqrt{\frac{1+f^2/\hat{\omega}_a^2}{1+f^2/\hat{\omega}_r^2}} = \sqrt{\frac{(N^2 k_{hr}^2/m^2)+2f^2/\cos^2\alpha}{(N^2 k_{hr}^2/m^2)+2f^2}}. \tag{14}$$

Equation (14) shows that if $\alpha = 0$ or $f = 0$, then $S_e = 1$ and the GW-induced shear is accurate. if $\alpha \neq 0$ and $f = 2\Omega \sin \phi \neq 0$, then $Se > 1$ and the total wind shear is overestimated.

Figure 3 shows the dependencies of S_e on horizontal (λ_h) and vertical wavelengths (λ_z), the angle α and latitude ϕ. From Fig. 3a, we can see that S_e increases with the increasing λ_h and the decreasing λ_z. Figure 3(b) shows that S_e increases with the increasing λ_h and the increasing ϕ. Figure 3(c) shows that S_e increases with the increasing λ_h and the increasing α. Comparisons the relative importance of λ_z, λ_h, α, and ϕ in changing S_e, the angle α is the most important one. If we assume that GW propagates in an arbitrary direction, S_e is less than 1.2 (indicated by a red contour line) for a large fraction of GWs at $\phi = 30°$. The fractions of GWs, which are overestimated by a factor of 0.2, increase with the increasing latitudes. This indicates that the method proposed here can be used to estimate GW-induced shears even though the wave propagation direction cannot be determined from a GW profiles pair. When we analysed the derived total wind shears, the overestimation at high latitudes should be considered.

3 Comparisons GW-induced Shears with Model and Observational Results

Due to the uncertainties, the GW-induced shears will be further examined by comparing with models and observational results. According to the wind shears during 1-10 July simulated by WACCM (Liu, 2017) and observations, we take the GW-induced shears during May-August of 2018 as an example for the purpose of comparison. The longer date coverage is chosen to cover a wider latitude range. Figure 5 shows the zonal mean and standard deviations (stds) of GW-induced shears and the top 10% largest shears during three periods of 2018. The latitude band used for zonal mean has a width of 5° with overlap of 2.5°. The latitude coverage is from 52.5°S-82.5°N or 82.5°S-52.5°N due to the yaw cycle of the SABER measurement. The three periods have centers in July and extend one or two months, such that the results can illustrate the main features during summer.

Three main features can be found in the zonal mean S shown in Fig. 4. Firstly, the maxima of S are ~13-17 ms^{-1}km^{-1} with stds of ~9-11 ms^{-1}km^{-1} at z~90-100 km (around the mesopause) at all latitudes of the three different time intervals. Especially, the GW-induced shears reach their maxima at around 70°S. The maxima S are ~10-13 ms^{-1}km^{-1} with std of ~8-10 ms^{-1}km^{-1} at z~80-90 km at latitudes higher than 40°N, where is near the summer mesopause (referred to contour lines of the zonal mean temperature). Secondly, the zonal mean shears have similar latitude-height patterns during the three different time intervals although they are averaged over different time interval lengths (e.g., 31 days during 0701-0731 and 62 days during 0629-0830). The same is true during the intervals of 0506-0627 and 0629-0830, respectively, at latitudes of 52.5°S-52.5°N. The GW-induced shears during the continuous two yaw cycles (0506-0627 and 0629-0830) exhibit a smooth extension from 52.5°S-52.5°N to higher latitudes, respectively. This shows GW-induced shears are a comment phenomenon around the mesopause region (Larson, 2002; Fritts et al., 2004; Larsen & Fesen, 2009; Yue el al., 2010; Liu, 2007, 2017). Thirdly, the top 10% largest S reach maxima of ~30 ms^{-1}km^{-1} around the mesopause. In general, at each height, the GW-induced shears reach their minima at lower latitudes and reach their maxima at high latitudes.

3.1 Comparisons with Model Results

The latitude-height patterns of S derived here agree well those simulated by WACCM during 1-10 July (Liu, 2017). Specifically, the GW-induced shears derived here have peaks at ~z=80-90 km at latitudes higher than 50°N during 0506-0627. Moreover, there is another peak at ~z=90-100 km of the southern high latitudes during 0629-0830. These peaks agree with the WACCM simulation results that the large shears have peaks at around the mesopause (Xu et al., 2007; Fig. 2a of Liu (2017)). However, the shear peaks derived here are at a slightly lower height than the WACCM results (Liu, 2017).

Compared to the WACCM simulation results, the differences pertain to the magnitudes of the zonal mean S and specifically: (1) the maxima of the zonal mean S. Figure 2(a) of Liu (2017) showed that the maxima of the zonal mean S are 20–40 ms^{-1}km^{-1} near the mesopause at latitudes higher than 50°N/S and are ~20-25 ms^{-1}km^{-1} at latitudes lower than 50°N/S. This indicates that the GW-induced zonal mean S derived here are about 70% smaller than those of the WACCM simulation results. (2) the top 10% largest S. The simulated top 10% largest S (e.g., the minima of the total 10% largest S) are larger than 50 ms^{-1}km^{-1} at high latitudes and 35 ms^{-1}km^{-1} over the equator (Fig. 5 of Liu, 2017). Thus, the top 10% largest S derived here (with maxima of ~30 ms^{-1}km^{-1}) is about 60% of the simulated results. (3) the stds. The simulated stds reach their maxima of ~1.4 times of the shears (Fig. 2b of Liu, 2017). The ratio of 1.4 indicates that the maxima of the simulated std is about 40 ms^{-1}km^{-1}, which is larger than those derived from observations (~12-14 ms^{-1}km^{-1}, see the middle row of Fig. 4) at latitudes lower than 50°N/S. (4) the structures of S. The structures in Fig. 2b of Liu (2017) have much finer scales than those in Fig. 4. The different spatial scale coverages, which will be discussed in Sect. 5, might be responsible for the smaller values of wind shears derived from observations.

In general, the GW-induced shears derived here can reproduce the latitude-height pattern and 60-70% of the simulated shear magnitudes in the zonal mean sense.

3.2 Comparisons with Observational Results

To compare the GW-induced shears derived here and those observed by ground-based lidar and sounding rockets (Larsen, 2002; Yue et al., 2010), we show in Fig. 5 the profiles of S and their zonal means as well as the top 10% and 1% largest S during January and July at around 40°N and Equator. The January and July are representative months for winter and summer, respectively. The latitudes of Equator and 40°N may be representative for low and middle latitudes, where sounding rocket measurements were performed (Fig. 1 of Larsen, 2002; Larsen & Fesen, 2009). The 40°N is near the latitude of 41°N, where the Colorado State University (CSU) Na lidar observations were performed (Yue et al., 2010).

Figure 5 shows that the magnitudes of the GW-induced S profiles increase with height and can be larger than 40 ms^{-1}km^{-1} above 90 km (80 km) during January (July). The height variations and magnitudes of GW-induced S profiles derived here compare well with the over 400 chemical tracer measurements by sounding rocket (Fig. 10 of Larsen (2002)) below 100 km. Moreover, the height variations and magnitudes of GW-induced S profiles derived here compare well with the CSU lidar observations below 100 km. Specifically, the magnitudes of S profiles observed by CSU lidar increase with height and have maxima of ~40 ms^{-1}km^{-1} (Fig. 1c-d of Yue et al. (2010)). This agrees well with the S profiles shown in Fig. 5. After averaging the shears observed by the CSU lidar during summer and winter months, the zonal mean shears are ~12-17 ms^{-1}km^{-1} with stds of ~10 ms^{-1}km^{-1} (Fig. 11c of Yue et al. (2010)). They are slight larger than the magnitudes of 10-13 ms^{-1}km^{-1} derived here (the right column of Fig. 5). The zonal mean shears (the right column and upper row of Fig. 5) derived here have similar magnitudes during January and July above 90 km. However, the mean shears observed by the CSU lidar the have similar magnitudes in winter and summer at ~z=80-105 km. We note that the magnitudes of S derived here are larger in July than in January at Equator. This might be related to the intra-annual variations of S and will be studied in Sect. 4.

A short summary of the above comparisons is below. The GW-induced shears derived from SABER observations agree with the previous observations and model results in general. This provides a global climatology of large shears around the mesopause region partially based on observations. The magnitudes of S derived from SABER observations are similar to those observed by lidar and sounding rocket but are about 60-70% of the high resolution WACCM results in the zonal mean sense. The difference probably comes from (1) the coarse horizontal samplings ~250-350 km of satellite observations and (2) only GWs with $\lambda_z \geq 5$ km and $\lambda_h \geq 2\Delta r$ (Δr is the distance between the two GW profiles in a pair) used to derived shears. This will be further discussed in Section 5.

4 Climatology of GW-induced Shears

With the advantage of 18-year SABER observations, the climatology of the GW-induced shears can be explored on the aspects of their latitudinal variations and intra-annual variations. The four seasons in the northern hemisphere (NH) are: spring (MAM: March, April, and May), summer (JJA: June, July, and August), autumn (SON: September, October, and November), winter (DJF: December, January, and February).

4.1 Latitudes Variations of GW-induced Shears

Figure 6 shows the latitude-height contours of the zonal mean and stds of the GW-induced shears and the top 10% largest shears during four composite seasons. Each composite season is made up by the superpositions of the corresponding seasons from 2002 to 2019. The numbers of profiles used to derive GW-induced wind shears in each season (the fourth row of Fig. 6)

5   have peaks around 50°N/S due to the changes of ascending and descending nodes. The sharp changes of the profile numbers around 50°N/S might induce the discontinuity of the latitudinal variations of GW-induced shears. By further examination of the discontinuities in Fig. 6, we find that the zonal means exhibit more obvious discontinuities at around 50°N (50°S) than those at around 50°S (50°N) during spring and summer (autumn and winter). This is because there are fewer samplings (the fourth row of Fig. 6) at around 50°N (50°S) than those at around 50°S (50°N) during spring and summer (autumn and winter).

10   The hemispheric asymmetry of the sampling is induced by the inconsistency of the date coverages of yaw cycle and season. Consequently, we show in Fig. 7 the zonal means and stds of GW-induced shears and the top 10% largest shears during six composite yaw cycles. The composite yaw cycle is the superposition of all the yaw cycles, which have nearly identical date coverage relative to the beginning of each calendar year. For example, the first yaw cycle of each year covers 0125-0318 in 2002, 0116-0318 in 2003, …, and 20181228-20190226. These dates are mainly in January and February, with a few extending

15   to March and December. We label "1228-0318" on the top of the first column of Fig. 7 to note the all the dates covered by the first yaw cycle. The results in the other five composite yaw cycles are shown in a same manner. The continuous two composite yaw cycles may have overlaps, with the longest overlap time of about 20 days. Thus, the composite yaw cycle can represent the results during two months around the center date of each composite yaw cycle.

       From Fig. 6, we can see that the zonal means of the GW-induced shears (the first row) increase with the increasing height

20   and latitude in general. The peaks are ~10-15 ms^{-1}km^{-1} above 90 km at latitudes of 82.5°S-50°N (50°S-82.5°N) during spring and summer (autumn and winter). Moreover, the wind shears have peaks at a lower height (z~80-90 km) and at latitudes of 82.5°S-50°S (50°N-82.5°N) during autumn and winter (spring and summer). These lower height peaks during spring and autumn (highlighted by blue rectangles) are weaker than those during summer and winter (highlighted by red rectangles). Comparing with Fig. 7 (the second and third columns, 0228-0512, 0502-0715), we find that the weak peak at z~80-90 km

25   during spring is contributed from the wind shears during May (highlighted by a red rectangle in Fig. 7 during the yaw cycle of 0502-0715) since there is no peak at similar location during the yaw cycle of 0228-0512. The same is true during autumn, when the weak peak at z~80-90 km is contributed from the wind shears during November (highlighted by a red rectangle in Fig. 7 during the yaw cycle 1031-114) since there is no peak at similar location during the yaw cycle of 1228-0318. The stronger peaks during summer and winter in Fig. 6 are contributed from those during the yaw cycles of 0502-0715 and 1031-

30   0114, respectively. The stronger peaks above 90 km and at ~z=80-90 km (marked by red rectangles) are both at around the mesopause as referred to the zonal mean temperature (contour lines in the second rows of Figs. 6 and 7).

       The std and the top 10% largest shears, which are shown in the second and third rows of Figs. 6 and 7, respectively, have similar patterns as that of zonal mean shears. The maxima of the std and the top 10% largest shears are, respectively, ~12 ms$^-$

^{1}km^{-1} and ~30 ms^{-1}km^{-1}, which are slightly less than that shown in Fig. 4. This is because the sampling profiles in Figs. 6 and 7 (composite season or yaw cycle over 18-year) are much larger than those in Fig. 4 (only one yaw cycle in one year).

Since the patterns of zonal mean and stds of the GW-induced shears and the top 10% largest shears are similar to each other (as shown in Figs. 4, 6, 7), only the zonal mean shears during each summer from 2002 to 2019 are shown in Fig. 8. It

5   can be seen that the latitude-height distributions of GW-induced shears, including the peaks at lower heights (around the mesopause region) of high latitudes, are similar to the 18-year's mean results shown in Figs. 6 and 7. However, the GW-induced shear magnitudes (shown in Fig. 8) exhibit year-to-year variations. For example, at the SH high latitudes, the wind shears above 90 km are strongest during 2008 and 2019 and weakest during 2002. At the NH high latitudes, the GW-induced shears at ~z=85-95 km vary with year more greatly and have smaller values, as compared to those at around 80 km.

10   **4.2 Intra-annual Oscillations of GW-induced Shears**

Since the GW-induced shears are prominent around the mesopause region, their intra-annual oscillations will be studied at ~z=60-100 km. Figure 9 shows the monthly zonal mean GW-induced shears at four latitudes bands of the NH and SH from 2002 to 2019. A general feature of time-height variations GW-induced shears are the annual (AO) and semiannual oscillations (SAO). To quantify the exact amplitudes and phases of AO and SAO, harmonic fitting is applied on the GW-induced shears.

15   The fitting function has periods both AO and SAO. Figure 10 shows the amplitudes and phases of both AO and SAO at four latitude bands of northern and southern hemispheres (SH).

At 50°N/S (the first row of Fig. 9 and the first column of Fig. 10), the GW-induced shears exhibit different height dependencies of AO and SAO. At 50°N, both AO and SAO reach their maxima at 80 km, while SAO has another peak at 97 km. At z=75-92 km, the AO is dominant and has peak in June. Below 75 km and above 92 km, the AO and SAO are almost

20   equal partitioned. At 50°S, both AO and SAO reach their maxima at ~81 km, while AO has another peak at 98 km. Above 92 km and below 68 km, the AO is dominant and has phase in June. At z=80-90 km, the AO and SAO are almost equal partitioned and have peaks in December and June, respectively. The amplitudes of SAO at 50°N/S have similar amplitudes and height variations. However, the amplitude of AO at 50°N is smaller than that at 50°S. This makes the GW-induced shears hemispherical asymmetric.

25   It should be noted that the phase of AO at 50°N shifts from December at ~65 km to June at ~75 km and then shifts from June at ~88 km to December at ~100 km. Whereas, the phase of AO at 50°S shifts from June at ~70 km to December at ~77 km and then shifts from December at ~85 km to June at ~65 km. In summary, in each hemisphere, the phase of AO shifts from winter below ~65 km (~70 km) to summer at ~z=75-88 km (~z=77-85 km) and then shift to winter again above 95 km at 50°N (50°S), respectively.

30   At 35°N/S (the second row of Fig. 9 and the second column of Fig. 10), the GW-induced shears exhibit both AO and SAO. At 35°N, the amplitudes of AO and SAO vary with height in a similar pattern as those at 50°N but have smaller values. The phases of AO and SAO are also in June when their amplitudes are prominent at z=75-92 km and then shift to winter above

~92 km. At 35°S, the amplitude and phase of AO vary with height in a similar pattern as those at 50°S. The amplitude of SAO is dominant below 90 km with peak in June.

At 20°N (the third row of Fig. 9 and the third column of Fig. 10), the amplitudes of AO and SAO exhibit similar height variations as those at 50°N and 35°N but have smaller values. The AO and SAO reach their peaks at around 81 km in June and have values of ~0.7 ms⁻¹km⁻¹ and ~0.5 ms⁻¹km⁻¹, respectively. At 20°S, the SAO is in the dominant position and has peaks in June at ~92 km and ~67 km. At 5°N/S and at z=85-98 km, the AO is in the dominant position and has peak shifting from July to March. At ~z=71-80, the SAO is in the dominant position and has peak shifting from March to January.

The AO and SAO of the GW-induced shears are summaries as below. The amplitudes of AO have peaks at around 80 km and decrease with the decreasing latitudes. The phases of AO shift from winter to summer and then to winter again with the increasing height. The amplitudes of SAO decrease with the decreasing latitudes. The phases of SAO are in May and June when the SAOs reach their peaks at 50°N/S, 35°N/S and 20°N/S. At 5°N/S, the SAOs shift their phase from March to January in their peak height. The AO and SAO are hemispheric asymmetry. At ~z=75-90 km, the AOs (SAOs) are in the dominant position at latitudes higher than 20°N (20°S). Above ~90 km, the AO and SAO are almost equal partitioned at 50°N and 35°N, whereas, the AO is in the dominant position at 50°S and 35°S. Comparing with the AO and SAO in the GW square temperature amplitude (GWSTA) and absolute momentum flux (GWMF) presented by Chen et al. (2019), we find that the AO and SAO of GW-induced shears agree with GWSTA and GWMF on the aspects of phase shifts and hemispheric asymmetry (Fig. 2 and 3 of Chen et al., 2019). However, the heights at which phase shifts occur are different due to the AO and SAO in the background temperature and static stabilities (Liu et al., 2020).

5 Discussions

To determine the horizontal wavenumbers in the zonal and meridional directions, at least three profiles should be sampled at different locations of the same wave (Wang & Alexander, 2010, Alexander, 2015, Alexander et al., 2018). For the SABER measurement, there are 15 orbits in the ascending and descending nodes, respectively. The nearest distance between two orbits is about 24°, which is much longer than the horizontal wavelengths of most of GWs. This limits our ability to deduce the zonal and meridional horizontal wavenumbers and leads to the uncertainties in deriving the GW-induced shears. The horizontal wavenumber derived from a GW profiles pair is in the along-track direction. It is in general smaller than the horizontal wavenumbers of GWs in reality. The angle (α) between the along-track direction and real GW propagation direction is the dominant source of the uncertainties. This will overestimate the GW-induced shears as shown by Eq. (14) and Fig. 3. According to Eq. (14), the influences of α on S_e increase with the increasing latitudes due to increasing inertial frequency f. For the extreme case, $S_e = 1$ for any α since $f = 0$ over Equator. On the other hand, at the high latitudes, GWs propagate mostly in the zonal direction since their sources are mainly jet/front, topography (Fritts & Alexander, 2003; Plougonven & Zhang, 2014). Fortunately, the SABER orbit track intersects with zonal direction at a smaller angle at high latitudes than that at lower latitudes due to the changes of ascending/descending nodes. This reduces the uncertainties of the GW-induced shears for the zonally propagating waves. Thus, the uncertainties might be smaller than 1.2 as shown in Fig. 3c.

Even with an over-estimation of 1.2, the GW-induced shears derived here are smaller than those of high-resolution model simulations by a factor of 60-70% (Liu, 2017). The smaller GW-induced shears might be induced by the following two reasons: (1) the coarse horizontal samplings of satellite observations and (2) only GWs with $\lambda_h \geq 2\Delta r$ (Nyquist limit) and $\lambda_z \geq 5$ km used to derived shears. The reason for (1) is that the latitude-height variations of stds in Figs. 4, 6, 7 are smoother than those in Fig. 2b of Liu (2017). The small-scale variations in Fig. 2b of Liu (2017) might be smoothed out due to the observational filter of SABER limb sounding pattern (Preusse et al., 2002; Ern et al., 2018).

According to the SABER sampling (Fig. 1 of Ern et al. 2011), the sampling distance of a GW profiles pair $\Delta r \sim 250 - 350$ km limits the resolved GWs with $\lambda_h \geq 500 - 700$ km. Whereas, the horizontal resolution of WACCM is about 25 km (Liu, 2017), this can resolve GWs with $\lambda_h \geq 50$ km according to Nyquist limit, though waves with $\lambda_h \leq 200$ km are excessively damped by numerical diffusion in WACCM (Liu et al., 2014c). The longer sampling distance eliminates the small-scale variations in GW-induced shears and thus reduces the magnitudes of GW-induced shears. The influence of the horizontal sampling distances on wind shears can be further confirmed by the simulation results presented by Shinagawa et al. (2017), who showed that the longitude-latitude distributions of the zonal wind shears have peak values of 16-18 ms⁻¹km⁻¹ at 100 km during summer and winter (Figs. 6 and 7 of their paper). Certainly, the zonal mean of the zonal wind shears should be much smaller than 16-18 ms⁻¹km⁻¹ at 100 km. This magnitude is also smaller than the simulation results presented by Liu (2017). The smaller magnitude of the wind shears might result from the different resolution used by their models. The Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) used by Shinagawa et al. (2017) has a grid size of 2.8° longitude by 2.8° latitude horizontally and 0.2 scale height vertically. Whereas, the WACCAM used by Liu et al. (2014c) and Liu (2017) has a quasi-uniform horizontal resolution of ~25 km, and a 0.1 scale height vertically.

For reason (2), the cutoff criterion of $\lambda_z \geq 5$ km is used here to get more reliable GW profile through DFT. This cutoff criterion is related to the vertical resolution of the SABER measurement and is the same as that used by Ern et al. (2018) to remove the artificial oscillations. To test the influences of the cutoff criterions on the GW-induced shears, we perform a same procedure as that described in Sect. 2 and 3 but relax the cutoff criterion to $\lambda_z \geq 3$ km. The GW-induced shears derived with cutoff criterion of $\lambda_z \geq 3$ km are shown in Fig. 11. It can be seen that the latitude-height patterns of the GW-induced shears are the same as those shown in Fig. 4. However, the maxima of the zonal mean GW-induced shears increase from 12-17 ms⁻¹km⁻¹ for $\lambda_z \geq 5$ km to 15-21 ms⁻¹km⁻¹ for $\lambda_z \geq 3$ km. This illustrates that magnitudes of the GW-induced shears increase with the decreasing cutoff vertical wavelengths.

6 Summary

Due to the importance roles of the large shears in the MLT region on the atmospheric dynamics and electrodynamics, a method of deriving GW-induced shears is proposed in the work. The theorical basis of the method is the dispersion and polarization relations of a linear GW. The data are the SABER temperature profiles measured over the past 18-year. Based on the method and the data, the global GW-induced shears are studied over a time span of 18-year.

The GW-induced shears derived here agree with previous lidar and sounding rocket observations in the aspects of height structures and magnitudes on the climatology sense. Moreover, the GW-induced shears derived here agree with the high-resolution model simulation results in the aspects of latitude-height patterns but have smaller magnitudes in the zonal mean sense. The GW-induced shears reach their maxima around the mesopause region and increase with the increasing latitudes. At most latitudes and during all seasons, the maxima of GW-induced shears are at $\sim z$=90-100 km. At high latitudes of the summer hemisphere, the maxima of GW-induced shears at a lower height ($\sim z$=80-90 km). This latitude-height pattern of GW-induced shears is independent on years. The magnitudes of the GW-induced shears exhibit year-to-year variations.

The GW-induced shears exhibit more prominent AO and SAO at high latitudes than those at lower latitudes. The height variations of the amplitudes AO and SAO are hemispheric asymmetric. The strong AO occurs at around 80 km in the NH and above 92 km in the SH. At middle to high latitudes, the phases of AO shift from winter to summer and then to winter again with the increasing height. The amplitudes of SAO decrease with the decreasing latitudes. The phases of SAO are in May and June when the SAO reach its peak at middle to high latitudes.

The main limitation of the method is the overestimation of the GW-induced shears due to the unresolved GW propagation direction by the method. The other limitations, such as the observational filter, long sampling distance and cutoff criterion of the vertical wavelength, will underestimate the GW-induced shears. To overcome these limitations, it is necessary to develop new techniques and/or more dense satellites to observe the atmosphere with higher horizontal and vertical resolutions.

Data availability. The SABER data were downloaded from ftp://saber.gats-inc.com/Version2_0/Level2A/

Author contribution. XL and JX designed the study and wrote the manuscript. JY and HL contributed to the discussion of the results and the preparation of the manuscript. All authors discussed the results and commented on the manuscript at all stages.

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

Acknowledgments. The SABER data were obtained from ftp://saber.gats-inc.com/Version2_0/Level2A/. This work was supported by the National Natural Science Foundation of China (41831073, 41874182). This work was also supported in part by the Specialized Research Fund and the Open Research Program of the State Key Laboratory of Space Weather. National Center for Atmospheric Research is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

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Figures and Captions
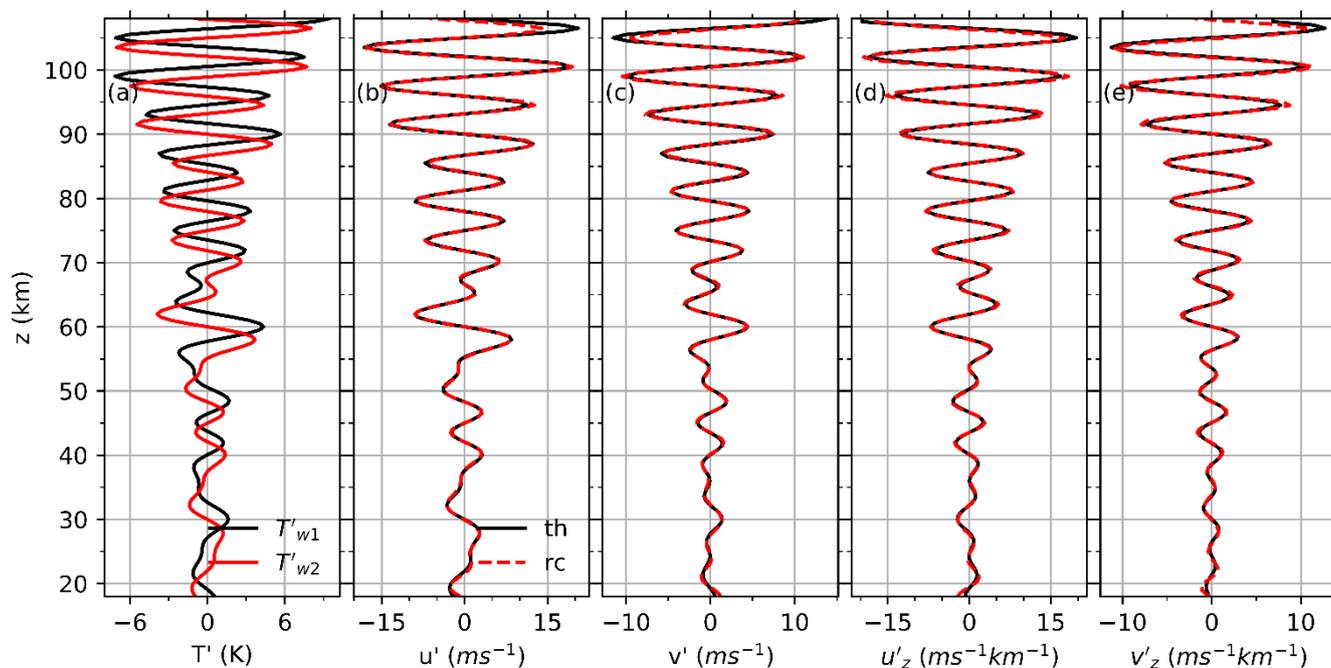
Figure 1: Synthetic temperature perturbation profiles (a, $T'_{w1}(z)$ and $T'_{w2}(z)$ are represented by black and red lines, respectively) and the
corresponding winds (b, zonal; c, meridional) and shears (d, zonal; e, meridional). The winds and shears are, respectively, calculated from
the prescribed amplitudes and wavenumbers (black line, labelled as "th") and reconstructed by spectral decomposition method (red dashed
line, labelled as "rc"). All panels have the same y-axis scale.
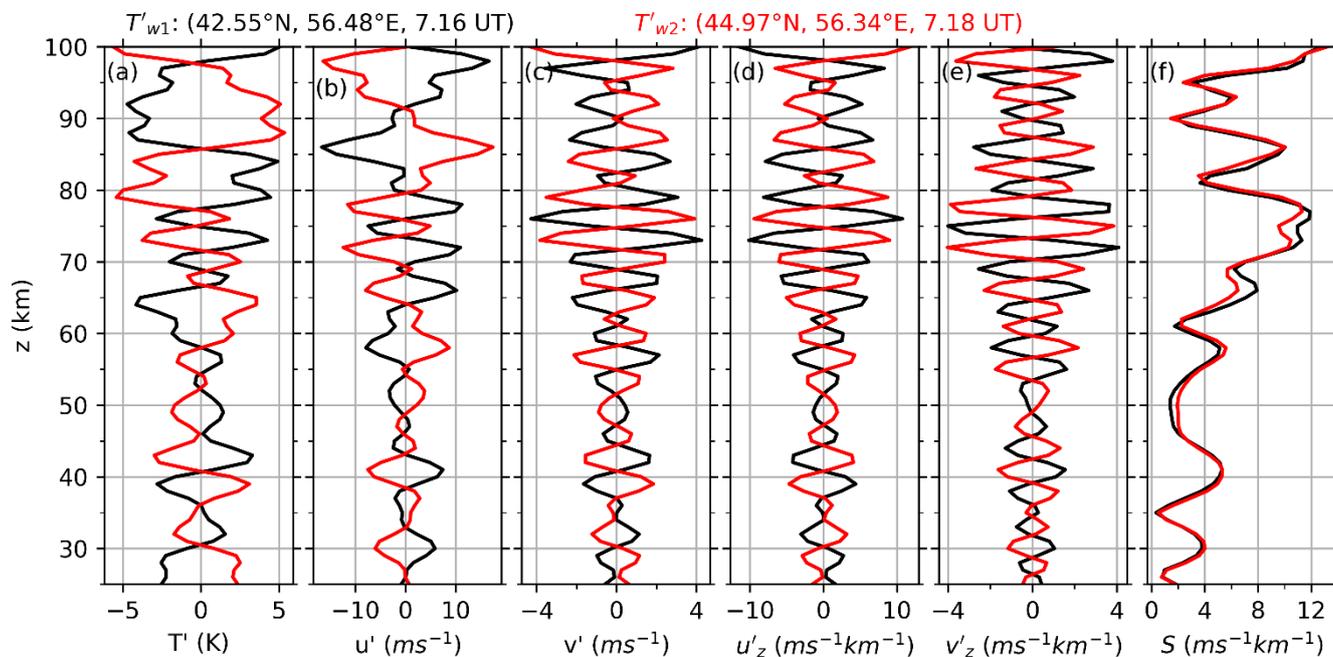
Figure 2: Flow chart of derivation winds and shears induced by GW profiles pair (red and black lines indicate the results from T'_{w1} and T'_{w2}, respectively). (a): T'_{w1} and T'_{w2} were measured at (42.55ºN, 56.48ºE, 7.16 UT) and (44.97ºN, 56.34ºE, 7.18 UT), respectively, on 1st January 2018. The distance between the two adjacent profiles is 269.8 km. (b) and (c): the GW induced winds in the along and cross track directions, respectively; (d) and (e): the GW induced shears in the along and cross track directions, respectively; (f): the GW-induced shear (S). All panels have the same y-axis scale.
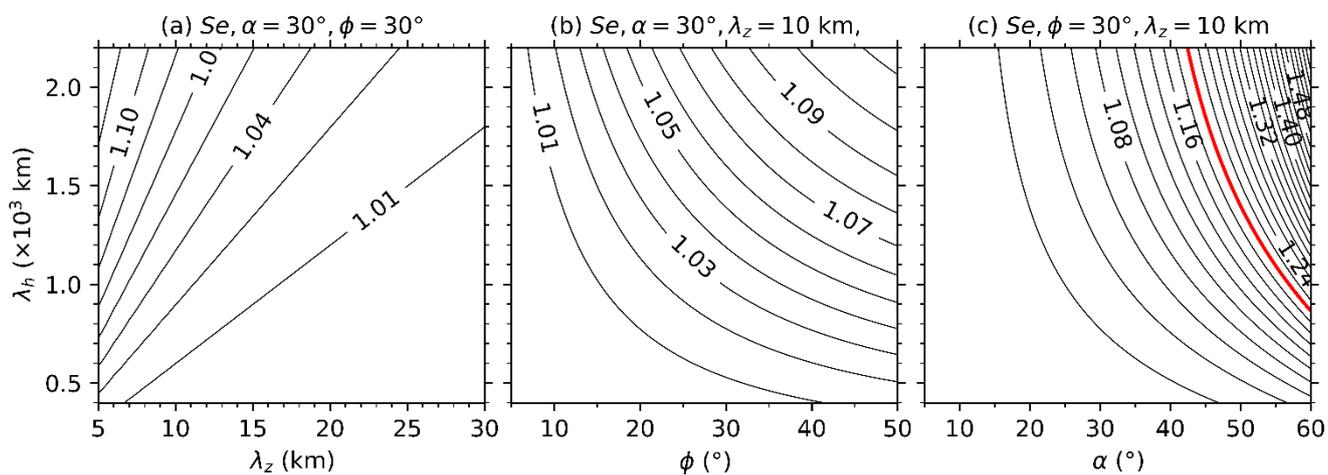
Figure 3: Dependencies of S_e on the horizontal and vertical wavelengths for $\alpha = 30°$ and $\phi = 30°$ (a), on the latitude ϕ for $\alpha = 30°$ and $\lambda_z = 10$ km (b) and on the angle α for $\phi = 30°$ (c). The red contour line in (c) indicates $S_e = 1.2$. All panels have the same y-axis scale.
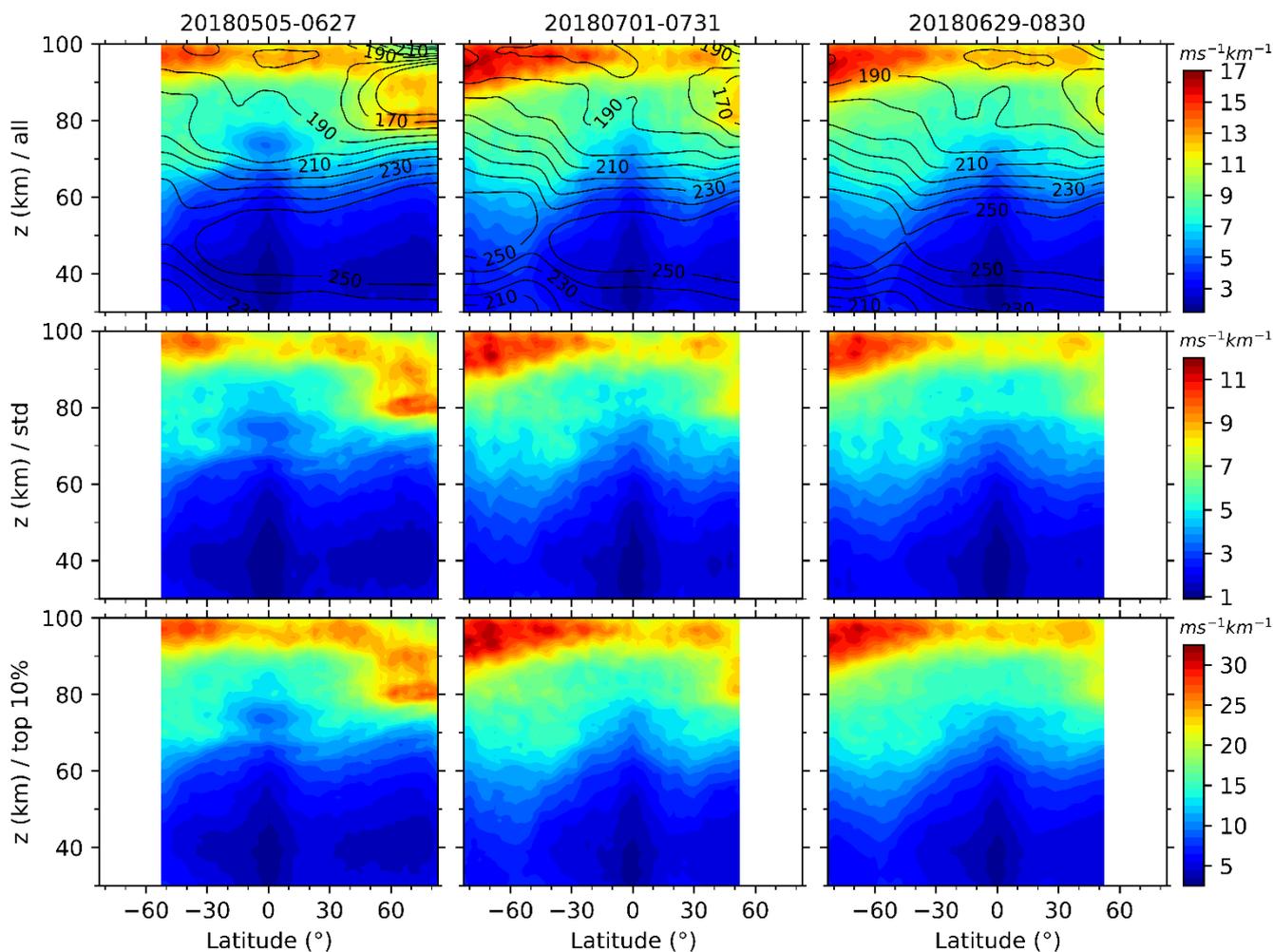
Figure 4: Latitude-height contours of the zonal means (upper row) and standard deviations (std, middle row) of GW-induced shears and the top 10% largest shears (bottom row) during three periods (left column: 0506-0627; middle column: 0701-0731; right column: 0629-0830, the four numbers mean mmdd). The contour lines shown in the upper row are the corresponding zonal mean temperature. Same color scale is used in each row with unit of ms⁻¹km⁻¹. All panels have the same scales in both x-axis and y-axis.
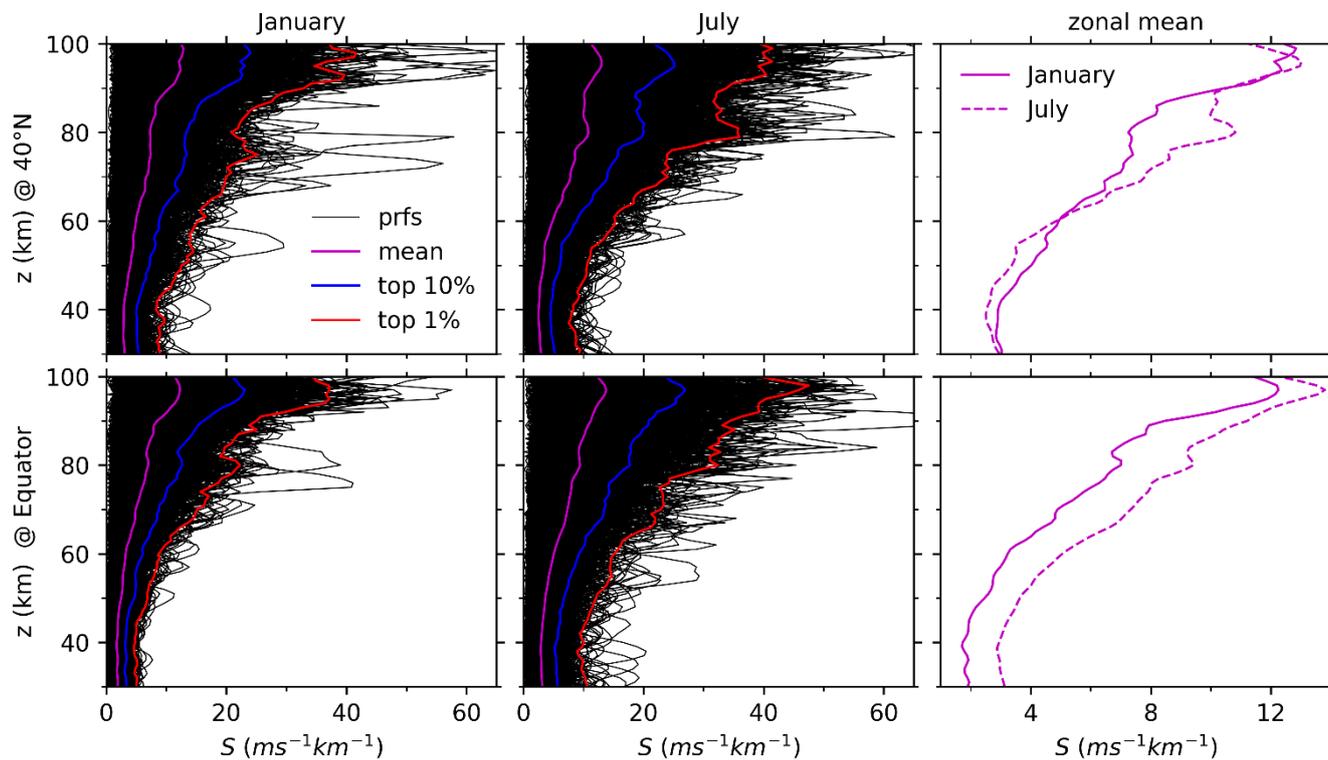
Figure 5: Profiles of S (black) and their mean (magenta) as well as the top 10% (blue) and 1% (red) largest S during January (left column)
and July (middle) at around 40°N (upper) and Equator (below). The zonal means of S during January (solid) and July (dashed line) at the
two latitudes are also shown in the right column for comparison. Same x-axis (y-axis) scale is used in each row (column).
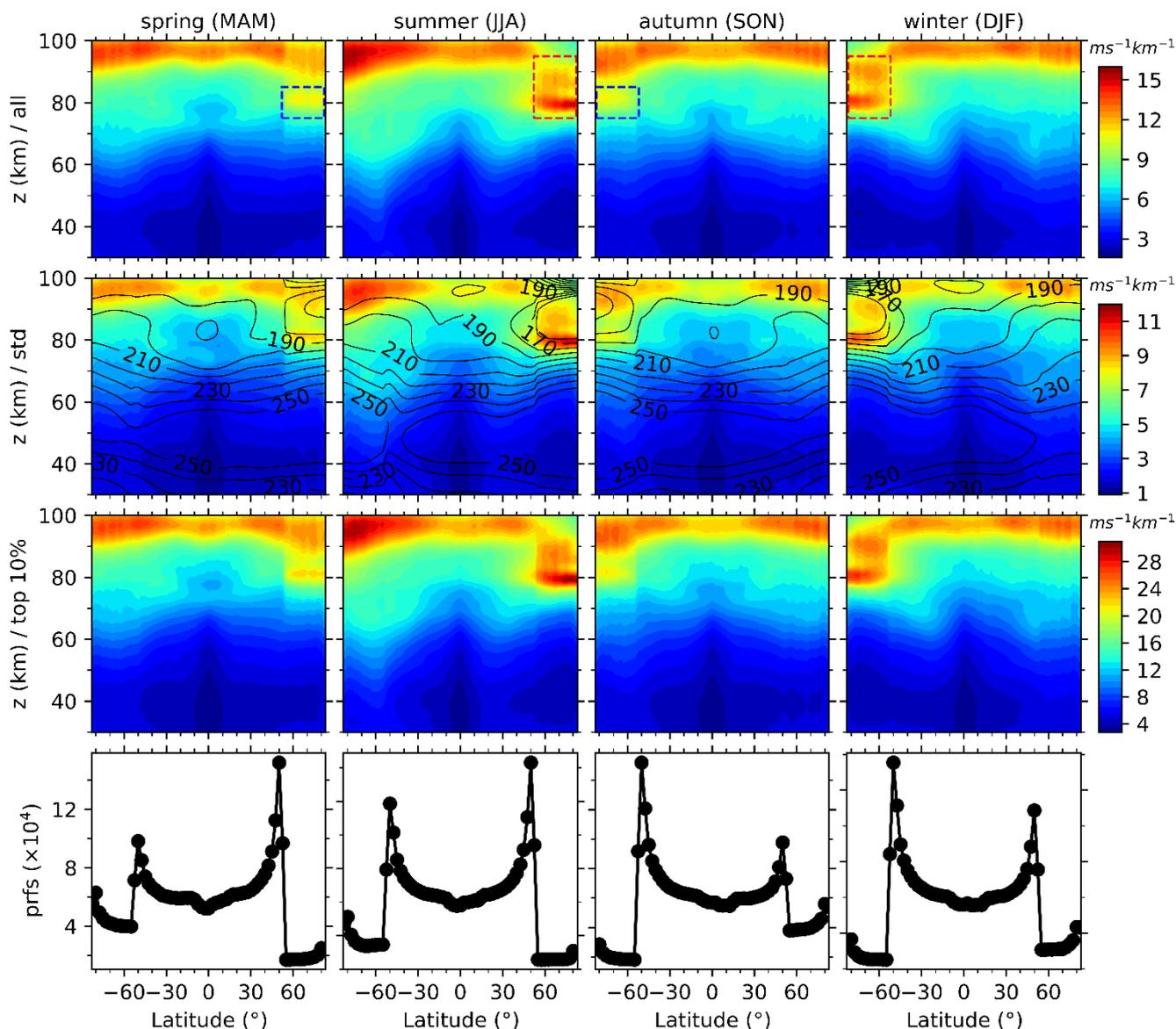
Figure 6: Latitude-height contours of the zonal means (the first row) and standard deviations (std, the second row) of GW-induced wind shears and the top 10% largest shears (the third row) during four composite seasons (noted on the top of each column). The composite season is the superposition of the corresponding season from 2002 to 2019. For more readable, the zonal mean temperatures are shown as contour lines only in the second row. The rectangles are to highlight the peak at a lower height. The numbers of profiles used to derive GW-induced wind shears in each season are shown in the fourth row. Same color scale is used in each row with unit of ms^{-1}km^{-1}. Each row has the same y-axis scale. All panels have the same x-axis scale.
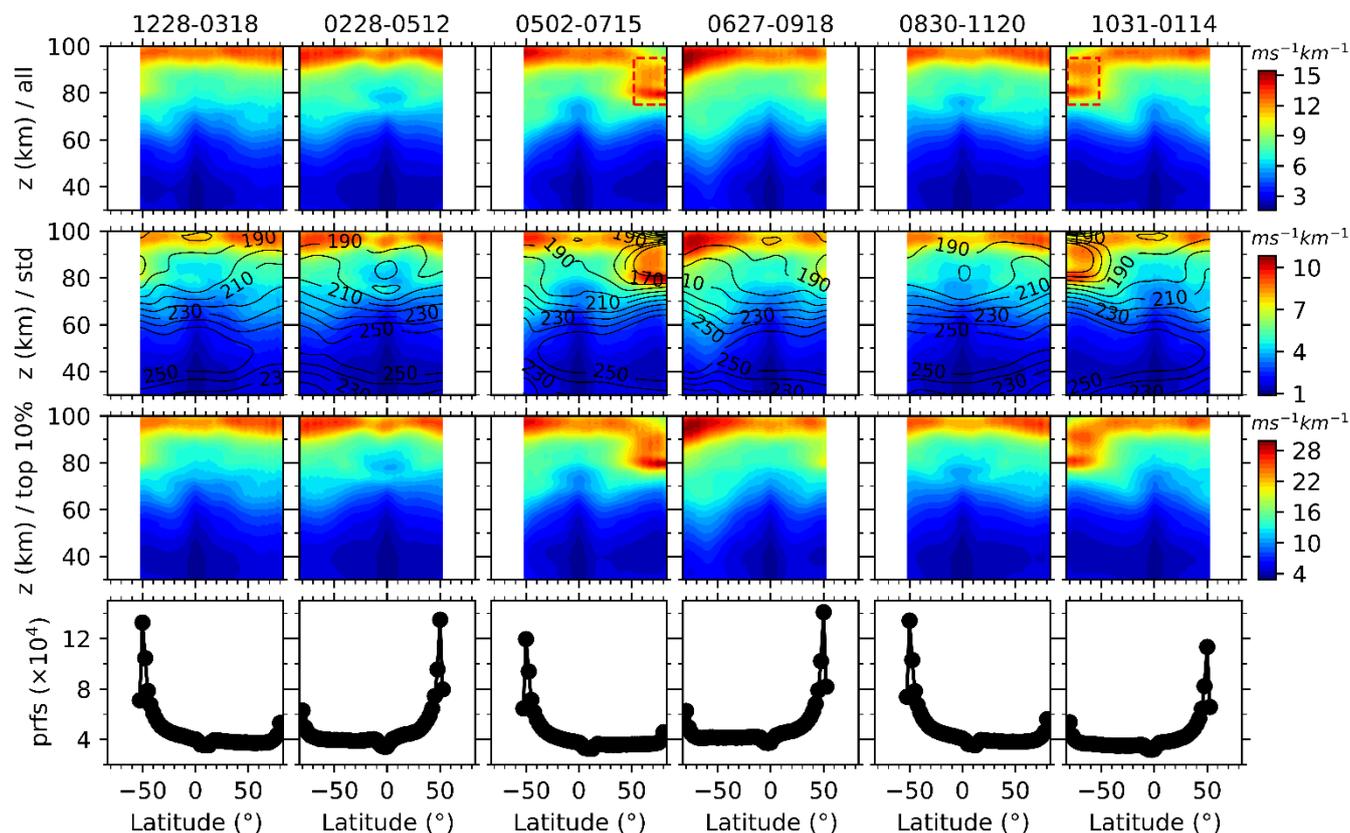
Figure 7: Same caption as Fig. 6 but during six composite yaw cycles from 2002 to 2019. The composite yaw cycle is the superposition of all the yaw cycles, which have nearly identical date coverage relative to the beginning of each calendar year, from 2002 to 2019. The date coverage of each yaw cycle is labelled on the top of each column (see text for detail). For more readable, the zonal mean temperatures are shown as contour lines only in the second row. The rectangles are to highlight the peak at a lower height.
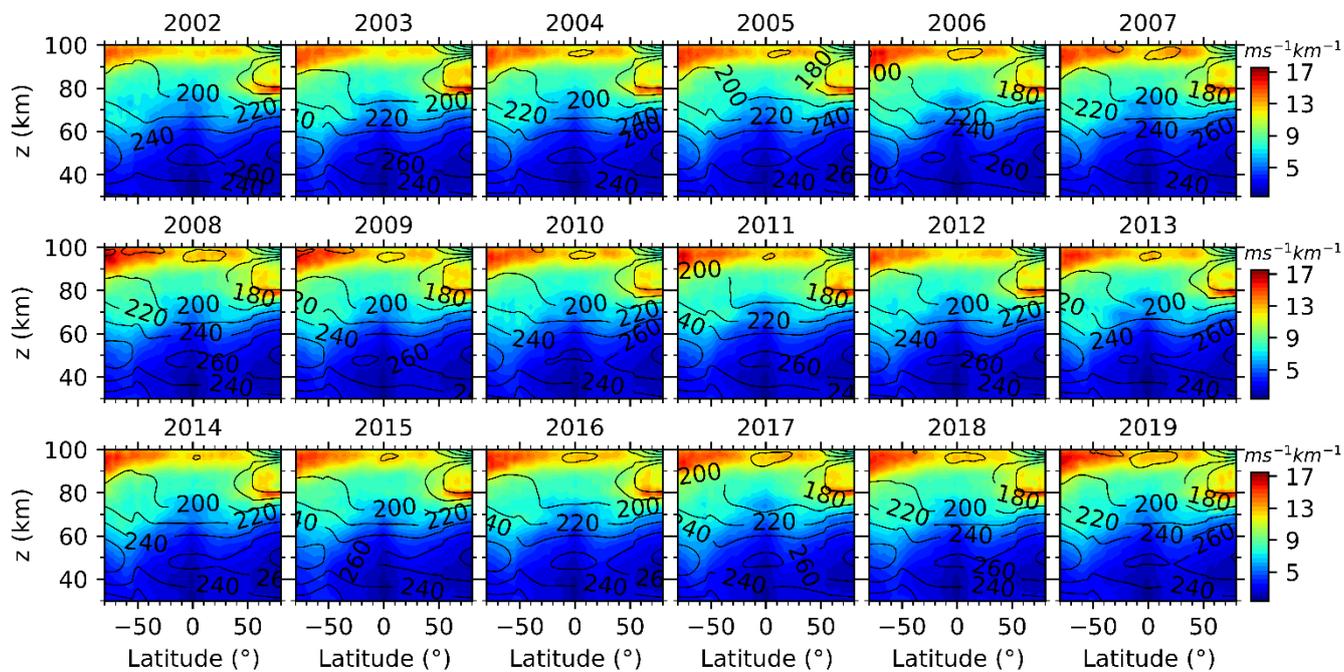
Figure 8: Latitude-height contours of the zonal mean GW-induced wind shears (color filled contour) and temperature (contour lines) during each summer from 2002 to 2019. All panels have the same color scales with unit of ms⁻¹km⁻¹. All panels have the same x-axis and y-axis scales.
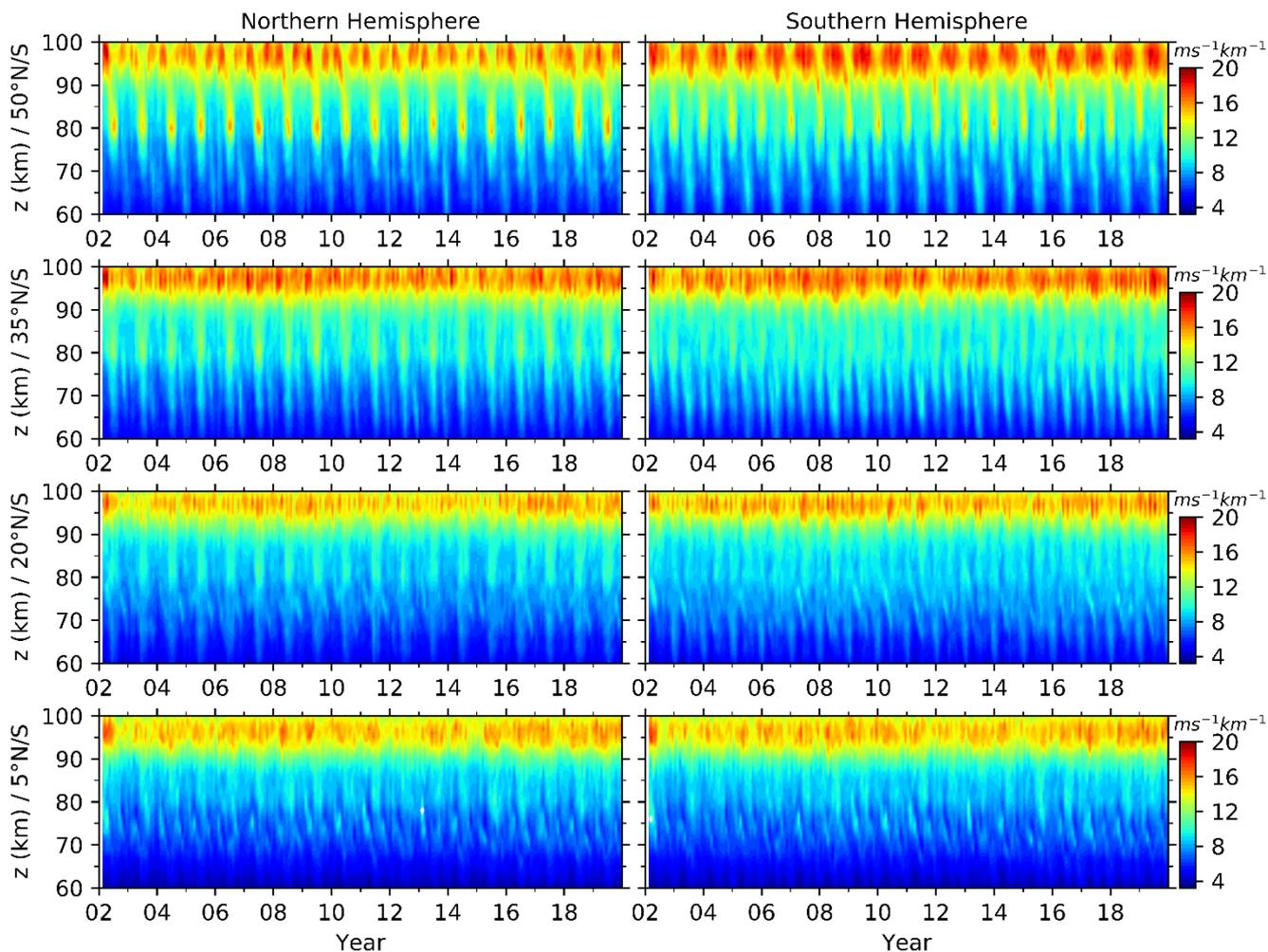
Figure 9: Time-height contours of the monthly zonal mean GW-induced shears (S) at four latitudes (50°N/S, 35°N/S, 20°N/S, 5°N/S, see the y-label of each row) of the NH (left column) and SH (right column) from 2002 to 2019. All panels have the same color scales with unit of ms^{-1}km^{-1}. All panels have the same x-axis and y-axis scales.
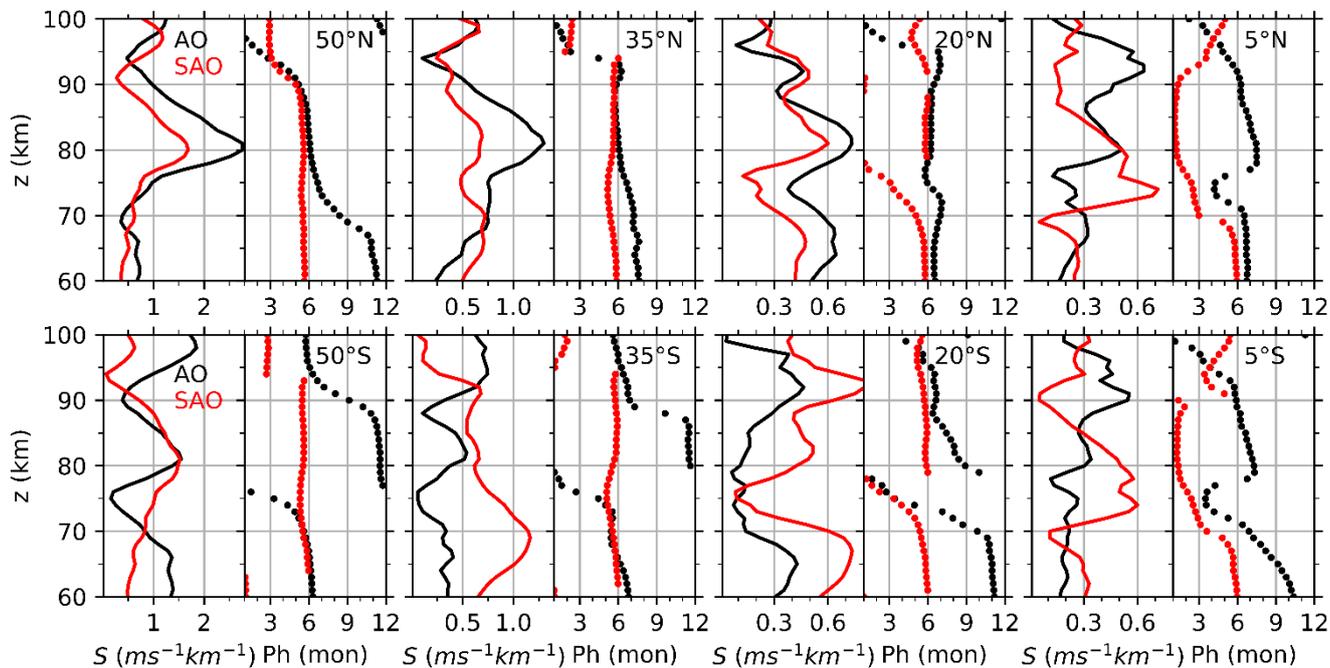
Figure 10: Amplitudes (left column of each panel) and phases (right column of each panel) of AO (black) and SAO (red) of the GW-
induced wind shears at four latitude bands of NH (upper row) and SH (lower row). The phase is defined as the month when the oscillation
reaches its peak. Same x-axis is used at each latitude band. Same y-axis scale is used for all panels.
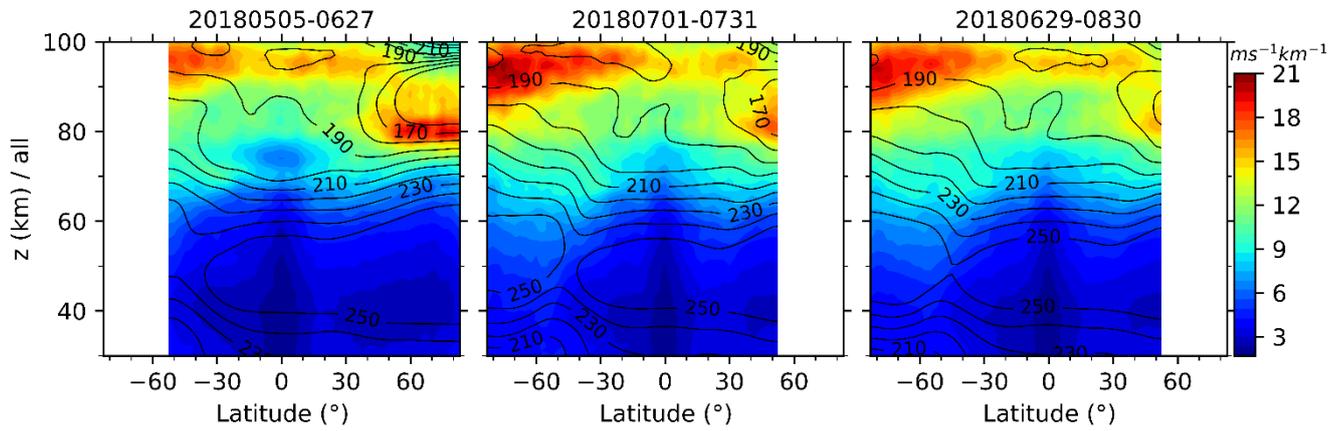
Figure 11. Same caption as Fig. 4 but for the zonal mean GW-induced shears with cutoff criterion of 3 km.