Eastward-propagating planetary wave in the polar

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middle atmosphere

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Abstract. We presented the global variations of the eastward propagating wavenumber 1 (E1), 2 (E2), 3 (E3), and 4 (E4) planetary waves (PWs) and their diagnostic results in the polar middle atmosphere, using MERRA-2 temperature and wind datasets in 2019. It is clearly shown that the eastward wave modes exist during winter periods with westward background wind in both hemispheres. The maximum wave amplitudes in the southern hemisphere (SH) are slightly larger and lie lower than those in the northern hemisphere (NH). It is also found that the wave perturbations peak at lower latitudes with smaller amplitude as the wavenumber increases. The period of the E1 mode varies from 3 to 5 days in both hemispheres, while the period of E2 mode is slightly longer in the NH (~48 h) than in the SH (~40 h). The periods of the E3 are ~30 h in both SH and NH, and the period of E4 is ~24 h. Though the wave periods become shorter as the wavenumber increases, their mean phase speeds are relatively stable, which are ~ 53 , ~ 58 , ~55, and ~52 m/s at 70° latitudes for W1, W2, W3, and W4, respectively. The eastward PWs occur earlier with increasing zonal wavenumber, which agrees well with the seasonal variations of the critical layers generated by the background windseasonal variations of the background zonal wind through the generation of critical layers. Diagnostic analysis also shows that the mean flow instability in the upper stratosphere and upper mesosphere may both contribute to the amplification of the eastward PWs.

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1 Introduction

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Large amplitude planetary waves are dominant in the stratosphere, 31 mesosphere, and lower thermosphere region and their interaction with 32 zonal mean winds is the primary driving force of atmospheric dynamics. 33 In addition, sudden stratospheric warmings (SSWs) and quasi-biennial 34 oscillation (QBO) events can dynamically couple the entire atmosphere 35 from the lower atmosphere to the ionosphere ((Li et al., 2020; Yamazaki et 36 al., 2020; Yadav et al., 2019; Matthias and Ern, 2018; Stray et al., 2015)Li 37 et al., 2020; Yamazaki et al., 2020; Yadav et al., 2019; Matthias and Ern, 38 2018; Stray et al., 2015). Westward propagating planetary wave is one of 39 the prominent features during austral and boreal summer periods. 40 Westward quasi-2-day waves 41 (Q2DWs) are the most obvious representative waves and one of the most investigated phenomena by 42 planetary wave observations. Most previous studies focused on westward 43 propagating Q2DWs, including zonal wavenumbers of 2 (W2), 3 (W3), 44 and 4 (W4) modes (Lainer et al., 2018; Gu et al., 2018b; Wang et al., 2017; 45 Pancheva et al., 2016; Gu et al., 2016a; Gu et al., 2016b; Lilienthal and 46 Jacobi, 2015; Gu et al., 2013; Limpasuvan and Wu, 2009; Salby, 47 1981)(Lainer et al., 2018; Gu et al., 2018c; Wang et al., 2017; Pancheva et 48 al., 2017; Gu et al., 2016a; Gu et al., 2016b; Lilienthal and Jacobi, 2015; 49 Gu et al., 2013; Limpasuvan and Wu, 2009; Salby, 1981). The sSeasonal 50 variations of the occurrence date, peak amplitude, and wave period for 51

eastward Q2DWs are rarely studied (Gu et al., 2017; Lu et al., 2013; 52 Alexander and Shepherd, 2010; Sandford et al., 2008; Palo et al., 2007; 53 Merzlyakov and Pancheva, 2007; Manney and Randel, 1993; Venne and 54 Stanford, 1979)(Gu et al., 2017; Lu et al., 2013; Alexander and Shepherd, 55 2010; Venne and Stanford, 2010; Merzlyakov and Pancheva, 2007; Palo et 56 al., 2007; Sandford et al., 2007; Manney et al., 1993).

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Q2DWs usually maximize after the summer solstice in middle 58 latitudes. The largest wave amplitudes are observed near the mesopause in 59 January–February in the Southern Hemisphere (SH), while in the Northern 60 Hemisphere (NH) in July–August (Tunbridge et al., 2011) (Tunbridge et al., 61 2011). The W3 and W4 Q2DWs reach a maximum amplitudes during 62 austral and boreal summer periods in the mesosphere and lower 63 thermosphere, respectively. The westward Q2DWs activity has an obvious 64 seasonal variation (Liu et al., 2019; Gu et al., 2018b; Rao et al., 2017)(Liu 65 et al., 2019; Gu et al., 2018d; Rao et al., 2016). Tunbridge et al. 66 (2011) Tunbridge et al. (2011) have long-term observed long-term Q2DW 67 in the NH and SH, and found that the W3 is generally stronger than those 68 of the other two modes in the SH, reaching anthe amplitude of ~12-K, 69 while the W4 is stronger than W3 in the NH, and can reaching ~4-K. In 70 addition, W4 is generally longer lived than W3, and W4 is still observed 71 after W3 has ended. The results of Liu et al. (2004)Liu and H.-L. (2004) 72 show that the wave source, instability, critical layer, and mean zonal wind 73

structure are the primary reasons for the seasonal variation of Q2DWs. Gu et al. (2019) Gu et al. (2018d) have the long-term observation of satellite datasets in the SH and found that the strongest events of W2, W3, and W4 are delayed with increasing the zonal wavenumber and would be indistinguishable confused during the SSWs period. Then wave periods of W4, W3 and W2 vary between $\sim 41-56$ h, $\sim 45-52$ h, and $\sim 45-48$ h, respectively. Then the wave period of W3 primarily fluctuated in 45-52 h, while the W4 varies is concentrated between 41-56 h, and the W2 is primarily distributed in 45-48 h. In addition, W2 can be observed in global satellite datasets, showing weaker amplitude than W3 and W4 in the NH and SH (Meek et al., 1996)(Meek et al., 1996). The propagation and amplification of Q2DWs are primarily modulated dominated by instability, refractive index, and critical layer, while the variation of background wind may cause different zonal wavenumber events (Gu et al., 2016a; Gu et al., 2016b)(Gu et al., 2016a; Gu et al., 2016b). Xiong et al. (2018)Xiong et al. (2018) studied variations in Q2DWs activity during the SSWs period and found that W1 iswas generated by the nonlinear interaction between SPW2 and W3. Gu et al. (2018c) Gu et al. (2018b) found that the coupling between the NH and SH enhanced the summer easterly during SSWs and promoted the nonlinear interaction between W3 and SPW1 during the SSWs period. Recent studies have found significant eastward planetary waves activity in the polar stratosphere and mesosphere regions, with periods of

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nearly 2 and 4 days with near 2 and 4 days in the wave periods (Gu et al., 96 2017; Sandford et al., 2008; Merzlyakov and Pancheva, 2007; Coy et al., 97 2003; Manney and Randel, 1993)(Gu et al., 2017; Venne and Stanford, 98 2010; Merzlyakov and Pancheva, 2007; Sandford et al., 2007; Coy et al., 99 2003; Manney et al., 1993). Planetary waves with zonal wavenumbers -1 100 (E1) and -2 (E2) correspond to 4- and 2-day waves, respectively. In 101 addition, planetary waves of 1.2-day with wavenumber -3 (E3) and 0.8-day 102 with wavenumber -4 (E4) have been found to have the same phase speeds 103 as E1 and E2In addition, the planetary waves of 1.2-day with wavenumber 104 -3 (E3) and 0.8-day with wavenumber -4 (E4) have been found same phase 105 speeds as the 2- and 4-day waves (Manney and Randel, 1993)(Manney et 106 107 al., 1993). This series of eastward propagating planetary waves hasve a significant effect on the thermal and dynamic structure of the polar 108 stratosphere, resulting in significant changes in the wind and temperature 109 variations in of the polar stratosphere (Coy et al., 2003; Venne and Stanford, 110 1979)(Venne and Stanford, 2010; Coy et al., 2003). Palo et al. (1999)Palo 111 et al. (1999) demonstrated a series of nonlinear interactions between the 112 migrating tides and Q2DWs. Further research, Palo et al. (2007) Palo et al. 113 (2007) presented evidence that the eastward E2 Q2DW iswas coupled by 114 the nonlinear planetary wave and the tides in the mesosphere and lower 115 thermosphere. 116

Merzlyakov & Pancheva. (2007) Merzlyakov and Pancheva. (2007)

analyzed and studied satellite datasets and they observed found that the wave periods of the eastward propagating wave with the zonal wave numbers -1 and -2 in February 2004, while E1 and E2 events is with wave periods within 1.5-5 days. They found that the direction of EP fluxes for eastward planetary waves is from the upper layer to the lower atmosphere, suggesting that the upper atmosphere has a dynamic influence on the lower atmosphere. Sandford et al. (2008)Sandford et al. (2007) reported a significant —Q2DW—fluctuations of E2 Q2DW in the polar mesosphere with a zonal wavenumber of -2 (E2). They found that changes variations of in mean zonal winds during a major SSW-period can influenced the propagation of polar E2affect the propagation of polar E2. In addition, they believe that E2 fluctuation is representative in the mesosphere and caused by the instabilities in the polar night jet. Gu et al. (2017) Gu et al. (2017) foundproposed that the amplitude of E2 can reach ~10K, ~20 m/s, and ~30 m/s in temperature, zonal wind, and meridional wind in the austral winter period, while the amplitude of E2 decreases by near two-thirds in the boreal winter period. Lu et al. (2013) Lu et al. (2013) found that the propagation height of eastward planetary wave propagations was limited to the winter high latitudes, which may be because negative refractive indices equatorward of ~45°S result in evanescent wave characteristicscaused by the negative refractive index of 45°S at the equator, thus preventing the propagation of planetary wave propagation to the low latitudes. They

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believe that the instability region at ~50-60°S may be induced by the stratospheric polar night jet and/or the "double-jet" structure.

The second modern retrospective research and application analysis (MERRA-2) datasets used investigate the eastward are to propagating propagation wave characteristics in the polar stratospheric and mesospheric region during 2019 in the polar stratospheric and mesospheric region, including zonal wavenumbers -1 (E1), -2 (E2), -3 (E3) and -4 (E4). Particularly, weour investigate study is to explore the variation of the occurrence date, peak amplitude, and wave period for of eastward waves, and as well as the role of instability, background wind structure, and critical layer for in the propagation and amplification of eastward waves propagation and amplification. The remaining parts of this paper are organized as follows. In Section 2, the data and methods used in our study are described. In Section 3 analyzes the global latitude-temporal variation structure of eastward waves in the 2019 winter-of 2019. The amplification and propagation features of the eastward planetary waves different wavenumber events for eastward planetary waves in the NH and SH with different wavenumber events are investigated in Section 3.1 and 3.2, respectively. In Section 3.3 compares and analyzeswill compare and analyze eastward waves in the NH and SH. In Section 4 summarizes our research results.

2 Data and Analysis

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The least-square method is applied to each time window to extract the
E1-, E2-, E3-, and E4-wave, with 10-day, 6-day, 4-day, and 4-day, and is
used by us to determine the amplitude (Gu et al., 2013)(Gu et al., 2013).

This method has previously been used successfully to identify planetary
waves from satellite measurements (Gu et al., 2019; Gu et al., 2018a; Gu
et al., 2018b; Gu et al., 2018c; Gu et al., 2013)(Gu et al., 2018a; Gu et al., 2018b; Gu et al., 2018c; Gu et al., 2018d).

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$$y = A\cos[2\pi(\sigma \cdot t + s \cdot \lambda)] + B\sin[2\pi(\sigma \cdot t + s \cdot \lambda)] + C \tag{1}$$

The least-squares method is used to fit the parameters of (A, B, and C). Where $(\sigma, t, s, and \lambda)$ are the frequency, <u>UT time</u>, zonal wavenumber, <u>The squares of wave and longitudes</u>. The amplitude of wave R of wavenumber could be expressed as $R = \sqrt{A^2 + B^2}$.

The second modern retrospective research and application analysis (MERRA-2) data is a set of long-term atmospheric reanalysis datasets started by NASA in 1980, and now using an upgraded version of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. MERRA-2 includes updates to the model (Molod et al., 2014; Molod et al., 2012)(Molod et al., 2015; Molod et al., 2012) and the Global Statistical Interpolation (GSI) analysis scheme of Wu et al. (2002)Wu et al. (2002). The MERRA-2 data includes various meteorological variables such as net radiation, temperature, relative humidity, wind speed, etc. The MERRA-2 data covers the world, with a

spatial resolution of $0.5^{\circ}*0.625^{\circ}$ and a temporal resolution of 1 hour. This kind of meteorological data is widely used to detect the middle atmosphere such as the planetary wave in the polar atmosphere, global thermal tides, climate variability, and aerosol (Ukhov et al., 2020; Sun et al., 2020; Bali et al., 2019; Lu et al., 2013)(Sun et al., 2020; Ukhov et al., 2020; Bali et al., 2019; Lu et al., 2013). These studies indicate that MERRA-2 data can be used in our research with high authenticity. The MERRA-2 datasets are used to obtain the variation in background wind, instability, refractive index, and critical layer, and explore the rules of eastward planetary waves propagation and amplification through diagnostic analysis.

The critical layer will absorb or reflect planetary waves during upward propagation from the lower atmosphere. Planetary waves that gain sufficient energy in the instability region will be amplified during reflection. The planetary wave will be amplified from the reflection process after gaining sufficient energy in the instability region. This shows that the critical layer plays an important role in regulating the amplification and propagation of planetary waves (Gu et al., 2016a; Gu et al., 2016b; Liu et al., 2004)(Gu et al., 2016a; Gu et al., 2016b; Liu and H. L., 2004). The baroclinic/barotropic instability in the atmospheric space structure is caused by the simultaneous equalization of the negative latitude gradient and the quasi-geostrophic potential vorticity ($\overline{q_{\varphi}}$). Where (Ω) denote the angular speed of the Earth's rotation, and the latitude and zonal mean zonal

wind are represented by $(\varphi \text{ and } \overline{u})$, in the second part, the (a) represents the Earth radius, in the last part, $(\rho, f, and N)$ denote the background air density, Coriolis parameter, and buoyaney frequency, respectively. The vertical and latitudinal gradients are represented by subscripts $(z \text{ and } \varphi)$.

$$\overline{q_{\varphi}} = 2\Omega \cos \varphi - \left(\frac{\left(\overline{u}\cos\varphi\right)_{\varphi}}{a\cos\varphi}\right)_{\varphi} - \frac{a}{\rho}\left(\frac{f^2}{N^2}\rho\overline{u}_z\right)_z$$
(2)

The baroclinic/barotropic instability in the atmospheric space structure is caused by the simultaneous equalization of the negative latitude gradient and the quasi-geostrophic potential vorticity $(\overline{q_{\varphi}})$. wWhere (Ω) denote the angular speed of the Earth's rotation, and the latitude and zonal mean zonal wind are represented by $(\underline{\varphi} \text{ and } \underline{u})$, in the second part, the (\underline{a}) represents the Earth radius, in the last part, $(\underline{\rho}, f)$, and \underline{N} denote the background air density, Coriolis parameter, and buoyancy frequency, respectively. The vertical and latitudinal gradients are represented by subscripts $(\underline{z} \text{ and } \underline{\varphi})$.

Andrews et al. (1987) Andrews et al. (1987) define the Eliassen-Palm (EP) flux vectors (F) to show the properties of planetary wave propagation, calculated as follows:

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$$F = \rho a \cos \varphi \left[\frac{\overline{u_z} \overline{v \theta}}{\overline{\theta_z}} - \overline{v u} \right] \left[f - \frac{(\overline{u} \cos \varphi)_{\varphi}}{a \cos \varphi} \right] \frac{\overline{v \theta}}{\overline{\theta_z}} - \overline{w u}$$
 (3)

24 <u>w</u>Where u' and v' are the planetary wave perturbations in the zonal and

meridional wind, θ and w represent potential temperature and vertical wind, respectively. The planetary wave propagation is only favorable where the square of refractive index m^2 was positive:

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$$m^{2} = \frac{\overline{q_{\varphi}}}{a(\overline{u} - c)} - \frac{s^{2}}{(a\cos\varphi)^{2}} - \frac{f^{2}}{4N^{2}H^{2}}$$
 (4)

www.here (s) denote the zonal wavenumber, the phase speed is represented by (c), and the (H) represents the scale height. The square of the refractive index is taken as the waveguide of planetary waves.

$$c = -\nu_0 \cos\left(\frac{\varphi\pi}{180}\right) / sT$$
 (5)

where (\underline{c}) denote the phase speed, the equatorial linear velocity is represented by (\underline{v}_0) , and the $(\underline{\varphi})$ represents the latitude, \underline{s} and \underline{T} represent zonal wavenumber and wave period, respectively.

3 Results and Discussion

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The global temporal-latitude variation structures of E1, E2, E3, and E4 extracted from the 2019 MERRA-2 temperature datasets using time windows of 10-, 6-, 4- and 4-days respectively are shown in Figure 1. The mean temperature amplitudes of E1, E2, E3, and E4 at 55.4km during periods of 3~5-, 1.5~2.5-, 1~1.5-, and 0.9~1.1-days are shown in Figure 1a, 1b, 1c, and 1d. Eastward waves are characterized by obvious seasonal variations in the SH and NH. The eastward wave modes during winter periods in the SH and NH are characterized by obvious seasonal variations. In addition, the E1, E2 (E3), and E4 reach the ir maximum amplitudes at

50-80°(S/N). In the SH, the strongest E1 and E2 events of E1 and E2 occur 246 on days 209-218 and 167-172, while those of E3 and E4 events occur on 247 days 151-154 and 139-142 days. This shows that their occurrence date of 248 maximum amplitude occurs earlier with increasing zonal wavenumber. In 249 addition, the maximum amplitudes of E1, E2, E3, and E4 are ~6.0K, ~4.2K, 250 ~3.6K, and ~2.4K, indicating that their peak amplitudes decrease with 251 increasing zonal wavenumber. In the NH, the strongest E1, E2, E3 and E4 252 events occur on days 41-50, 69-74, 35-38 and 63-66, and the corresponding 253 peak amplitudes are ~ 5.5 K, ~ 3.8 K, ~ 2.8 K and ~ 1.2 K. the occurrence dates 254 of the strongest events of E1, E2, E3, and E4 are days 41-50, 69-74, 35-38, 255 and 63-66, and the corresponding peak amplitudes are 5.5K, 3.8K, 2.8K, 256 and 1.2K. The results showIt is found that the peak amplitude also 257 decreases with increasing zonal wavenumber in the NH, but the occurrence 258 date is irregulartheir occurrence dates vary irregularly. In addition, the E4 259 is weak in the NH and almost impossible to find, so W4 is out of the 260 discussion in the NH. Figure 2 shows the changes in zonal mean zonal wind 261 at 70°S and 70°N in 2019that the 2019 zonal mean zonal wind variations 262 at 70°S and 70°N. It is found that the background wind on days 90-240 263 (70°S) is dominated by westward wind, and reached $\sim 80 \text{ m/s}$ at $\sim 50 \text{km}$ on 264 days 210, while it is dominated by eastward wind in late and early 2019, 265 and reaches ~-40 m/s at ~60km. Meanwhile, the background wind is 266 primarily westerly wind in late and early 2019 (70°N), and reaches ~90 m/s 267

at ~ 60km on days 50, while on days 120-240, the background wind is primarily easterly wind, and the amplitude reaches -40 m/s on days 200.

Compared with Figure 1, the results show that the eastward wave modes exist during winter periods with westward background wind in both hemispheres. It is clearly shown that the eastward wave modes exist during winter periods with westward background wind in both hemispheres.

3.1 In the Southern Hemisphere

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Figure 3 shows that maximum amplitude is observed to be ~48.2km and \sim 70-80°S for E1, and E2 and E3 at \sim 48.2km and \sim 60-70°S, while E4 at ~48.2km and ~50-60°Sthe E1, E2 (E3), and E4 are distributed in ~70-80°S, ~60-70°S, and ~50-60°S at ~48.2km, respectively. The maximum perturbation observed for E1 occur on days 211-220 with an amplitude of ~8.5K, and the remaining fluctuations occur on days 161-170, 187-196 and 231-240, while the E2 maximizes at days 219-224 with an amplitude of \sim 7.8K, and also shows three peaks at days 139-144, 173-178, and 187-192. Besides, the strongest E3 occurs on days 151-154 with an amplitude of ~5.2K, and the rest are distributed on days 141-144, 201-204, 209-202. E4 perturbations are distributed on days 127-130, 145-148, 161-164, 213-216, with weak amplitude of ~3K. According to previous studies, the wave period of the eastward wave varies. Therefore, periodic variability of E1, E2, E3, and E4 has also been investigated. The results show that the period corresponding to the maximum perturbation of E1 falls between ~106

(days 187-196) and ~69 h (days 211-220), and their wave periods vary greatly. However, the wave period of E2 gradually changes from ~42 h (days 139-144) to \sim 38 h (days 219-224), and its stability is stronger than that of E1. In addition, the wave periods of E3 and E4 are about ~39 h and ~24 h, respectively. Thus, E2, E3, and E4 wave periods are more stable than E1. E1 events occur on days 161-170, 187-196, 211-220, and 231-240, respectively, and the maximum fluctuation on days 211-220 is ~8.5K, as shown in Figure 3a. In addition, the wave period of E1 decreased from the maximum ~106 h (days 187-196) to ~69 h (days 211-220), indicating the instability of the E1 wave period. E2 events occur on days 139-144, 173-178, 187-192, and 219-224, and the maximum amplitude of ~7.8K occurs on days 219-224, and the wave period of E2 is stable approximate 40 h (Figure 3b). The strongest E3 event occurs on days 151-154, and the rest are distributed on days 141-144, 201-204, 209-202, and shows E3 wave period approximate 29 h, as shown in Figure 3c. From Figure 3d, E4 events are distributed on days 127-130, 145-148, 161-164, 213-216, with a weak amplitude of about ~3K, while the wave period is stable at near 24 h. In addition, we found that the planetary waves E1, E2, E3, and E4 have similar phase speeds.

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The spectra, spatial <u>(vertical and latitudinal)</u> structures of temperature, zonal and meridional wind, and diagnostic analysis of E1 are extracted from the corresponding two representative events, as shown in Figure 4.

312	Figure 4a, 4b shows the least-squares fitting spectra for MERRA-2
313	temperature on days 187-196, 211-220 at ~48.2km and ~70-80°S, when
314	and where the E1 maximizes. An eastward wavenumber -1 signal with the
315	period of ~106 h and ~69 h clearly dominates the whole spectrum. The
316	temperature spatial structure corresponding to these E1 is shown in Figure
317	4c, 4d. The temperature spatial structure of E1 presents an obvious
318	amplitude bimodal structure at ~70-80°S and ~50km, and ~70-80°S and
319	~60km, with the maximum at ~70-80°S and ~50km. The strongest
320	temperature amplitude of E1 occurs at ~50km and ~70-80°S with an
321	amplitude of ~10K on the days 211-220, and the other peak is ~9K (~70-
322	80°S and ~60km). The temperature amplitude of ~9K occurs at ~50km and
323	\sim 70-80°S during days 187-196, and the rest is \sim 7K (\sim 70-80°S and \sim 60km).
324	The corresponding spatial structures of zonal wind and meridional wind of
325	these E1 is shown in Figures 4e, 4f, 4g, and 4h. The maximum zonal wind
326	amplitude of E1 occurs at ~60-70°S and ~60km with an amplitude of ~14
327	m/s on days 187-196, and ~20 m/s at ~50-60°S and ~60km on days 211-
328	220. The amplitude of E1 meridional wind reaches ~10 m/s at ~70-80°S
329	and ~55km (days 187-196) and ~17 m/s at ~70-80°S and ~60km (days 211-
330	220), respectively.
331	The E1 planetary wave has a wave period of ~106 h and ~69 h on days
332	187-196 and 211-220 (Figures 4a and 4b). The temperature spatial
333	structure of E1 events presents an obvious dual structure of amplitudes at

~50km and ~60km, as displayed in Figures 4c and 4d. The strongest 334 temperature amplitude of E1 occurs at ~50 km and ~70-80°S with an 335 amplitude of ~10K on the days 211-220, and the other peak is ~9K (60km). 336 The temperature amplitude of ~9K occurs on days 187-196, and the rest is 337 ~7K (60km). The spatial structures of zonal wind and meridional wind of 338 E1 are shown in Figures 4e, 4f, 4g, and 4h. The maximum amplitudes of 339 zonal and meridional winds occur at ~60°S and ~60km, and ~80°S and 340 ~60km. The amplitude of zonal and meridional wind reaches ~14 m/s and 341 ~20 m/s, and ~10m/s and ~17m/s on days 187-196 and 211-220, 342 respectively. Figure 4i, 4j shows the diagnostic analysis results for the E1 343 events during days 187–196, 211–220. It is clear that the EP flux vectors is 344 more favorable to propagate in the SH winter and is dramatically amplified 345 by the mean flow instabilities and appropriate background winds at polar 346 and between ~40 and ~80km, with EP flux propagating into the upper 347 atmosphere (Figure 4i). Meanwhile, there is an EP flux at mid-latitudes and 348 ~60-80km, which propagates into the lower atmosphere. The wave-mean 349 flow interactions near its critical layer (106 h) of the green curve amplifies 350 E1, and the positive refractive index region surrounded by the yellow curve 351 also enhances E1 propagation. In addition, the strong instability and weak 352 background wind at ~70-80°S and ~40-60km provide sufficient energy for 353 the upward EP flux to propagate and amplify. However, the downward 354 propagating EP flux is amplified by weak instability and strong 355

background wind at ~50-60°S and ~60-70km. Besides, both upward and downward EP flux eventually propagate toward the equator at ~50km. Figure 4j shows that EP flux on days 211-220 propagates downward and amplifies after the interaction of the critical layer (~69 h), facilitated by the positive refractive index region, which strong instability and weak background wind at ~50-60°S and ~60-70km provide sufficient energy, and ultimately point towards the equator at ~50km. The results show that the weak background wind and strong instability in the polar promote the upward propagation and amplification of the EP flux. Meanwhile, the appropriate background wind and instability in mid-latitude are also conducive to the downward propagation and amplification of EP flux. From Figure 4i, E1 EP flux presents two directions of propagation. It is clear that the E1 is more favorable to propagate in the winter hemisphere and is dramatically amplified by the mean flow instabilities and appropriate background winds at polar and middle latitudes between ~40 and ~80 km, where the former propagate to the upper atmosphere and the latter to the lower atmosphere. In addition, E1 is amplified by wave-mean flow interactions near its critical layer (106 h). The strong instability and weak background wind and positive refractive index region provide sufficient energy for the upward EP flux to propagate and amplify. However, the downward EP flux is propagated and amplified by the interaction of the critical layer in the positive refractive index region, where the strong

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background wind and weak instability provide sufficient energy. In addition, both upward and downward EP fluxes eventually propagate toward the equator at ~50km. Figure 4j shows that EP flux propagates downward and amplifies after the interaction of the critical layer (~69 h), which strong instability and strong background wind provide energy, and ultimately point towards the equator. We believe that the weak background wind and strong instability in the polar region promote the upward propagation and amplification of the EP flux. In addition, the strong background wind and weak instability in the middle latitudes are not conducive to the downward propagation and amplification of the EP flux. In other words, instability and appropriate background wind play a dominant role in the propagation and amplification of the E1.

The spectra are observed at ~48.2km and ~60-70°S on days 173-178, 219-224 for E2, when the eastward wavenumber -2 becomes the primary wave mode with the wave period of ~38 h and ~39 h, as shown in Figure 5a, 5b. The temperature spatial structure corresponding to these E2 is shown in Figure 5c, 5d. The temperature spatial structure of E2 shows an obvious amplitude bimodal structure at ~60-70°S and ~50km, and ~60-70°S and ~60km, with the maximum at ~60-70°S and ~50km. The maximum temperature amplitude of E1 occurs at ~50km and ~60-70°S with an amplitude of ~7.5K on the days 173-178, and the other peak is ~6K (~70°S and ~60km). The temperature amplitude of ~10K occurs at ~50km

and $\sim 60-70^{\circ}$ S during days 219-224, and the rest is $\sim 6K$ ($\sim 70^{\circ}$ S and $\sim 60km$). 400 The corresponding spatial structures of zonal wind and meridional wind of 401 these E2 is shown in Figures 5e, 5f, 5g, and 5h. The zonal wind spatial 402 structure of E2 shows an obvious amplitude bimodal structure at ~50-60°S 403 and \sim 60km, and \sim 70-80°S and \sim 60km, with the maximum at \sim 50-60°S and 404 ~60km. The maximum zonal wind amplitudes of E2 occur at ~50-60°S and 405 \sim 60km with an amplitude of \sim 10 m/s on days 173-178, and the other peak 406 is ~ 9 m/s ($\sim 70-80$ °S and ~ 60 km). The zonal wind amplitude of ~ 20 m/s 407 occurs at ~50-60°S and ~60km on days 219-224, and the rest is ~15 m/s 408 $(\sim 70-80^{\circ} \text{S} \text{ and } \sim 60 \text{ km})$. The amplitude of E2 meridional wind reaches ~ 13 409 m/s at $\sim 70-80^{\circ}$ S and ~ 60 km (days 173-178) and ~ 27 m/s at $\sim 70-80^{\circ}$ S and 410 \sim 60km (days 219-224), respectively. 411 From Figures 5a and 5b, the wave periods of E2 planetary waves are 412 38 h and 39 h on days 173-178 and 219-224. The temperature spatial 413 structure of E2 events shows an obvious amplitude dual structure (Figures 414 5c and 5d). The maximum temperature amplitude of the E2 event on days 415 219-224 and 173-178 is ~9K (~50km) and ~7K (~50km). The spatial 416 structures of zonal wind and meridional wind of E2 are shown in Figures 417 5e, 5f, 5g, and 5h. The maximum amplitudes of zonal and meridional winds 418 occur at ~60°S and ~60km, and ~80°S and ~60km. The maximum 419 amplitude of zonal wind reaches ~10 m/s and ~20 m/s, while the 420 meridional wind is slightly stronger than the zonal wind, which reaches 421

~13 m/s and ~27 m/s on days 173-178 and 219-224. The results in Figures 5i and 5j show diagnostic analysis during days 173-178, 219-224 for E2. It is clear that E2 is more favorable to propagate in the SH winter and is dramatically amplified by the mean flow instabilities at middle-high latitudes between ~40km and ~80km, with EP flux propagating into the lower atmosphere, and EP flux eventually propagate toward the equator at ~50km. Besides, E2 is amplified and propagated by the wave-mean flow interactions near its critical layer (~38 h) of the green curve, and the promoting effect of the positive refractive index region surrounded by the yellow curve. Meanwhile, the weak instability and strong background wind at ~50-60°S and ~50-70km provide energy for the propagation and amplification of EP flux into the lower atmosphere during days173-178 (Figure 5i). In the diagnostic analysis of days 219-224, it is found that E2 obtains sufficient energy from strong instability and strong background wind at ~50-60°S and ~60-70km, and is amplified and propagated into the lower atmosphere through the critical layer and positive refractive index action, as shown in Figure 5j. The results show that the background wind at \sim 50-60°S and \sim 50-70km is weaker on days 173-178 than on days 219-224, and the instability at \sim 50-60°S and \sim 60-70km is stronger on days 219-224 than on days 173-178. According to Figure 5a, 5b results shows that E2 has absorbed sufficient energy to be amplified under the background conditions during days 219-224. From Figures 5i and 5j, it is clear that the

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E2 is more favorable to propagate in the SH winter and is dramatically amplified by the mean flow instabilities at middle-high latitudes between ~40km and ~80km. Then turns to the equator at ~50km. We find that the background wind in Figure 5i is weaker than that in Figure 5i, but the instability is stronger. This finding indicates that E2 has absorbed sufficient energy to be amplified under the background conditions during days 219-224 (Figure 5j). Figures 6a and 6b show the observed spectra of E3 at ~48.2km and ~60-70°S on days 151-154 and 201-204, and the wave period of locked wavenumber -3 is ~29 h and ~29 h, respectively. The corresponding temperature spatial structures of these E3 is shown in Figure 6c, 6d. The temperature spatial structure of E3 shows an obvious amplitude bimodal structure at ~60-70°S and ~50km, and ~60-70°S and ~60km, with the maximum at ~60-70°S and ~50km. Besides, E3 also has a weak peak at ~60-70°S and ~70km. The strongest temperature amplitude of E3 occurs at \sim 50km and \sim 60-70°S with an amplitude of \sim 6K on the days 151-154, and the other peak is $\sim 5 \text{K}$ ($\sim 60-70^{\circ} \text{S}$ and $\sim 60 \text{km}$). The temperature amplitude of \sim 5K occurs at \sim 50km (\sim 60km) and \sim 60-70°S during days 201-204. The corresponding spatial structures of zonal wind and meridional wind of these E3 is shown in Figures 6e, 6f, 6g, and 6h. The zonal wind spatial structure of E3 shows an obvious amplitude bimodal structure at ~70-80°S and ~60km, and ~50-60°S and ~60km. The zonal wind amplitudes of E3

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occur at ~70-80°S and ~60km (~50-60°S and ~60km) with an amplitude of ~9 m/s on days 151-154, and ~9 m/s at ~70-80°S and ~60km (~50-60°S and ~60km) on days 201-204. The amplitude of E3 meridional wind reaches ~13 m/s at ~60-70°S and ~55km (days 151-154) and ~16 m/s at ~60-70°S and ~55km (days 201-204), respectively.

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EP flux of E3 is similar to that of E2. The instability and appropriate background wind at mid-high latitudes between ~50 and ~70km dramatically amplify the propagation of E3, which is enhanced by the interaction near the critical layer (~29 h) and the positive refractive index region. (Figures 6i and 6j). It is worth noting that the strong instability and weak background wind at ~50-60°S and ~60-70km on days 151-154 provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere, and ultimately point towards the equator at 50km. The EP flux propagate to the lower atmosphere during days 201-204, and is amplified by interaction at the critical layer (\sim 29 h). In addition, weak instability and weak background wind at ~50-60°S and ~60-70km provide the energy to amplify E3 propagation. Combine with Figure 6c, 6d, the stronger the instability at ~50-60°S and ~60-70km, the stronger the temperature amplitude of E3. We believe that the background wind and instability at ~50-60°S and ~60-70km are the primary reasons for the propagation and amplification of EP flux into the lower atmosphere.

The spectra are observed to be at ~48.2 km and ~50-60°S on days

127-130, 213-216 for E4, when the eastward wavenumber -4 signal with 488 the wave period of ~25 h and ~21 h, as shown in Figure 7a, 7b. The 489 corresponding temperature spatial structures of these E4 is shown in Figure 490 7c, 7d. The temperature spatial structure of E4 shows an obvious amplitude 491 bimodal structure at ~50-60°S and ~50km, and ~50-60°S and ~60km, with 492 the maximum at ~50-60°S and ~50km. The maximum temperature 493 amplitude of E4 occurs at ~50km and ~50-60°S with an amplitude of ~4K 494 on the days 127-130, and the other peak is $\sim 3 \text{K}$ ($\sim 60-70^{\circ} \text{S}$ and $\sim 60 \text{km}$). 495 The temperature amplitude of ~3K occurs at ~50km (~60km) during days 496 213-216. The corresponding spatial structures of zonal wind and 497 meridional wind of these E4 is shown in Figures 7e, 7f, 7g, and 7h. The 498 zonal wind spatial structure of E4 shows an obvious amplitude bimodal 499 structure at ~50-60°S and ~55km, and ~60-70°S and ~55km, with the 500 maximum at ~50-60°S and ~55km. The maximum zonal wind amplitude 501 of E4 occurs at ~50-60°S and ~55km with an amplitude of ~9 m/s on days 502 127-130, and the other peak is $\sim 5 \text{K}$ ($\sim 60-70^{\circ} \text{S}$ and $\sim 55 \text{km}$). The zonal wind 503 amplitude of ~ 5 m/s occurs at $\sim 50-60$ °S ($\sim 60-70$ °S) and ~ 55 km on days 504 213-216. The amplitude of E4 meridional wind reaches ~ 8 m/s at $\sim 60-70$ °S 505 and \sim 55km (days 127-130) and \sim 10 m/s at \sim 60-70°S and \sim 55km (days 213-506 216), respectively. Figures 6a and 6b show that the E3 planetary waves 507 have wave periods of ~29 h on days 151-154 and 201-204. The temperature 508 spatial structure of E3 events presents a dual structure, as shown in Figures 509

6c and 6d. The maximum temperature amplitude of E3 is ~7K (~50km) on days 151-154, and the other peak is ~5K (~60km). The temperature amplitude of E3 is ~5K (~50, ~60km) on days 201-204. The spatial structures of zonal wind and meridional wind of E3 are shown in Figures 6e, 6f, 6g, and 6h. The maximum amplitudes of zonal and meridional winds occur at ~50°S and ~60km, and ~60°S and ~60km. The maximum zonal wind is ~10 m/s, while the meridional wind is slightly stronger than the zonal wind at ~15 m/s. The EP flux of E3 is similar to that of E2. We find that instability at mid-high latitudes between ~50 and ~70km dramatically amplifies the E3 propagation and that the interaction near the critical layer enhances the process (Figures 6i and 6j). It is worth noting that the region of background wind at ~50-60°S and ~60-70km is similar during days 151-154 and 201-204, while the former is strong instability and the latter is weak instability. This finding indicates that the strong instability provides sufficient energy for the amplification for E3 propagation on days 151-154. Figures 7i and 7j show diagnostic analysis on days 127-130, 213-216 for E4. The results show that E4 is dramatically amplified by the mean flow instabilities at middle-high latitudes between ~50km and ~70km, with EP flux propagating into the lower atmosphere, and EP flux eventually propagate toward the equator at ~50km. E4 is amplified and propagated by the wave-mean flow interaction near the critical layer (~25 h, ~21 h), and the positive refractive index region provides the promoting effect. The

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strong instability and weak background wind at ~50-60°S and ~60-70km provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere during days127-130. Besides, E4 obtains energy from weak instability and weak background wind at ~50-60°S and ~60-70km on days 213-216, and is amplified and propagated into the lower atmosphere. The background wind at ~50-60°S and ~60-70km on days 127-130 is similar to on days 213-216, and the instability at ~50-60°S and ~60-70km is stronger on days 127-30 than on days 213-216. According to Figure 7a, 7b results shows that E4 has absorbed sufficient energy to be amplified under the background conditions on days 127-130. The temperature amplitude on 127-130 days is stronger.

The wave period of E4 reaches ~25 h and ~21h during days 127-130 and 213-216 in Figures 7a and 7b. The maximum temperature amplitude of E4 occurs on days 127-130, reaching ~4K (~50km), the other peak is ~3K (~60km). The temperature amplitude is ~3K (~50, ~60 km) on days 213-216, as displayed in Figure 7d. The spatial structures of zonal wind and meridional wind of E4 are shown in Figures 7e, 7f, 7g, and 7h. The maximum amplitudes of zonal and meridional winds occur at ~50°S and ~60km, and ~60°S and ~60km. The maximum zonal wind is ~8 m/s, while the meridional wind is slightly stronger than the zonal wind at ~10 m/s. We find that the instability in the mid-high latitudes between ~50 and ~70km

and the interaction near the critical layer greatly enhance the propagation and amplification of E4 EP flux, as shown in Figures 7i and 7j. The weak background wind and strong instability appear on days 127-130, while the strong background wind and weak instability appear on days 213-216. This finding indicates that E4 is difficult to obtain sufficient energy to be amplified under background conditions during days 213-216. The amplitude on 127-130 days is stronger.

3.2 In the Northern Hemisphere

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Figure 8 shows that maximum amplitude is observed to be ~59.2 km and \sim 70-80°N for E1, and the E2 and E3 peaks at \sim 59.2 km and \sim 60-70°N. The maximum perturbation of E1 is observed to be at days 41-50 with an amplitude of ~8K, and the remaining fluctuation occur on days 25-34, 339-348. Besides, the strongest E2 occurs on days 69-74 with an amplitude of \sim 7K, and the rest are distributed on days 25-30, 317-322, and 341-346, while the E3 maximizes at days 35-38 with an amplitude of ~3K, and also shows one peaks at days 53-56. Based on the study of the wave period in the SH for eastward wave, the periodic variability in the NH for E1, E2, and E3 is also investigated. The wave periods of E1 decreased from a maximum of \sim 118 h (days 25-34) to \sim 80 h (days 41-50), indicating that the wave period of E1 is unstable in the NH. The E2 events occur on days 25-30, 69-74, 317-322, and 341-346, of which the corresponding wave periods are ~36, ~53, ~52, and ~48 h, which are stronger stable than E1. Besides,

the wave period of E3 is relatively stable at ~29 h and ~27 h. Thus, E2 and 576 E3 wave periods are more stable than E1. 577 Figure 8 shows that the E1 and E2 (E3) are distributed at ~70-80°N, 578 and ~60-70°N at ~59.2km, respectively. E1 events occur on days 25-34, 579 41-50, and 339-348 respectively, in which the maximum temperature 580 amplitude of days 41-50 reaches ~8K, as shown in Figure 8a. In addition, 581 the wave periods of E1 decreased from a maximum of ~118 h (days 25-34) 582 to ~80 h (days 41-50), indicating that the wave period of E1 is unstable in 583 the NH. Clearly, the E2 events occur on days 25-30, 69-74, 317-322, and 584 341-346, of which the corresponding wave periods are ~36, ~53, ~52, and 585 ~48 h, and the maximum temperature amplitude reaches ~7K on days 69-586 74, as shown in Figure 8b. Figure 8c shows two E3 events. The strongest 587 temperature amplitude of E3 occurs on days 35-38 and reaches ~3K, and 588 the other one occurs on days 53-56. The wave period of E3 is relatively 589 stable at ~29 h and ~27 h. We did not study the E4 event in the NH, because 590 E4 is weak. 591 The spectra, spatial (vertical and latitudinal) structures of temperature, 592 zonal and meridional wind, and diagnostic analysis of E1 are extracted 593 from the corresponding representative events, as shown in Figure 9. 594 Figures 9a and 9b show the observed spectra of E1 at ~59.2km and ~70-595 80°N on days 25-34 and 41-50, and the wave period of locked wavenumber 596 -1 is \sim 118 h and \sim 80 h, respectively. The corresponding temperature spatial 597

structures of these E1 is shown in Figure 9c, 9d. The temperature spatial 598 structure of E1 shows an obvious amplitude bimodal structure during days 599 25-34 at $\sim 60-70$ °N and ~ 60 km, and $\sim 40-50$ °N and ~ 70 km, with the 600 maximum at ~60-70°N and ~60km. Besides, E1 also has bimodal structure 601 on days 41-50 at \sim 60-70°N and \sim 60km, and \sim 60-70°N and \sim 70km. The 602 strongest temperature amplitude of E1 occurs at ~60-70°N and ~60km with 603 an amplitude of \sim 7K on the days 25-34, and the other peak is \sim 4K (\sim 40-604 50°N and ~70km). The temperature amplitude of ~10K occurs at ~60km 605 and ~60-70°N during days 41-50, and the rest is ~8K (~60-70°N and 606 ~70km). The corresponding spatial structures of zonal wind and meridional 607 wind of these E1 is shown in Figures 9e, 9f, 9g, and 9h. The zonal wind 608 spatial structure of E1 shows an obvious amplitude bimodal structure at 609 \sim 70-80°N and \sim 70km, and \sim 50-60°N and \sim 70km. The zonal wind 610 amplitude of ~13 m/s occurs at ~70-80°N and ~70km on days 25-34, and 611 the rest is ~ 10 m/s ($\sim 50-60$ °N and ~ 70 km). In addition, there is a weak 612 peak of 9K during days 25-34 (~30-40°N and ~70 km). The maximum 613 zonal wind amplitude of E1 occurs at ~70-80°N and ~70km with an 614 amplitude of \sim 19 m/s on days 41-50, and the other peak is \sim 13K (\sim 50-60°N 615 and \sim 70km). The amplitude of E1 meridional wind reaches \sim 14 m/s at \sim 70-616 80° N and \sim 70km (days 25-34) and \sim 22 m/s at \sim 70-80°N and \sim 70km (days 617 41-50), respectively. From Figures 9a and 9b, the wave periods of planetary 618 E1 waves on days 25-34 and 41-50 are ~118 h and ~80 h, respectively. The 619

temperature spatial structure of the E1 event presents an obvious dual amplitude structure (~60km, ~70km). From Figure 9d, the strongest temperature amplitude of E1 appears at ~60km on days 41-50, with an amplitude of ~10K, and the rest peak is ~8K (~70km). The temperature amplitude of ~7K appears on days 25-34, and the rest is ~4K (~70km), as shown in Figure 9c. The spatial structures of zonal wind and meridional wind of E1 are shown in Figures 9e, 9f, 9g, and 9h. The maximum amplitudes of zonal and meridional winds occur at ~50°N and ~70km, and ~80°N and ~70km. The maximum zonal wind is ~14 m/s, while the meridional wind is slightly stronger than the zonal wind at ~18 m/s.

The diagnostic analysis results for E1 in Figures 9i and 9j show that E1 is dramatically amplified by the mean flow instabilities at middle-high latitudes between ~50km and ~70km, with EP flux propagating into the polar lower atmosphere, and EP flux eventually propagate toward the equator at ~50km. The wave-mean flow interaction near the critical layers (~118 h, ~80 h) amplifies and propagates E1, and the promoting effect of the positive refractive index region amplifies E1. Besides, the weak instability and strong background wind at ~40-50°N and ~60-70km provide energy for the propagation and amplification of EP flux into the polar lower atmosphere during days 25-34. The E1 obtains sufficient energy from weak instability and suitable background wind on days 41-50 at ~40-50°N and ~60-70km, and is amplified and propagated into the polar lower

atmosphere through the critical layer and positive refractive index action. The background wind at ~40-50°N and ~60-70km is stronger on days 25-34 than on days 41-50, but their instability is similar, indicating that stronger background winds may be unfavorable to E1 propagation and amplification at mid-northern latitudes. According to Figure 9a, 9b results shows that E1 has absorbed sufficient energy to be amplified under the background conditions during days 41-50, showing a stronger temperature amplitude. The results show that E1 is more conducive to the propagation in winter in the NH, and the instability at mid-latitude between ~60 and ~80 km and the interaction near the critical layer dramatically amplify the propagation of E1, which eventually turns toward the equator in the Arctic (Figures 9i and 9j). Obviously, the instability on days 25-34 and 41-50 is relatively weak, but the former has stronger background winds. This finding indicates that the background condition on days 41-50 is conducive to the propagation and amplification for E1. The spectra are observed to be at \sim 59.2 km and \sim 60-70°N on days 25-30, 69-74 for E2, when the eastward wavenumber -2 signal with the period of ~36 h and ~53 h, as shown in Figure 10a, 10b. The corresponding temperature spatial structures of these E2 is shown in Figure 10c, 10d. The temperature spatial structure of E2 shows an obvious amplitude bimodal structure at ~60-70°N and ~60km, and ~60-70°N and ~70km, with the maximum at ~60-70°N and ~60km. The maximum temperature amplitude

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of E2 occurs at ~60-70°N and ~60km with an amplitude of ~5K on days 25-30, and the other peak is \sim 4K (\sim 60-70°N and \sim 70km). The temperature amplitude of ~9K occurs on days 69-74 at ~60°S and ~60km, and the other peaks are \sim 7K (\sim 60-70°N and \sim 70km), \sim 5K (\sim 60-70°N and \sim 50km). The corresponding spatial structures of zonal wind and meridional wind of these E2 is shown in Figures 10e, 10f, 10g, and 10h. The zonal wind spatial structure of E2 shows an obvious amplitude bimodal structure at ~60-70°N and ~ 60 km, and $\sim 40-50$ °N and ~ 60 km, with the maximum at $\sim 40-50$ °N and ~60km. The maximum zonal wind amplitude of E2 occurs at ~60-70°N and $\sim 60 \text{km}$ ($\sim 40-50^{\circ} \text{N}$ and $\sim 60 \text{km}$) with an amplitude of $\sim 6 \text{ m/s}$ on days 25-30. Zonal wind amplitude occurs at ~40-50°N and ~60km with an amplitude of \sim 18 m/s on days 41-50, and the other peak is \sim 16K (\sim 60-70°N and ~60km). The amplitude of E2 meridional wind reaches ~7 m/s at ~60- 70° N and \sim 70km (days 25-30) and \sim 18 m/s at \sim 60-70°N and \sim 60km (days 41-50), respectively. Figures 10i and 10j show diagnostic analysis on days 25-30, 69-74 for E2. It is clear that E2 is dramatically amplified by the mean flow instabilities at middle-high latitudes between ~40km and ~70km, with EP flux propagating into the polar lower atmosphere, and EP flux eventually propagate toward the equator at ~50km. E2 is amplified and propagated by the wave-mean flow interaction near the critical layers (~36 h, ~53 h), and the positive refractive index region provides the promoting effect. The

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weak instability and strong background wind at ~50-60°N and ~60-70km provide energy for the propagation and amplification of EP flux into the polar lower atmosphere during days 25-30. Besides, E2 obtains sufficient energy from strong instability and suitable background wind at ~50-60°N and ~60-70km on days 69-74, and is amplified and propagated into the polar lower atmosphere. The background wind at ~50-60°N and ~60-70km on days 127-130 is similar to on days 213-216, and the instability at ~50-60°S and ~60-70km is stronger on days 127-30 than on days 213-216. The background wind at ~50-60°N and ~60-70km is stronger on days 25-30 than on days 69-74, but the instability at ~50-60°N and ~60-70km is stronger on days 69-74 than on days 25-30. According to Figure 10a, 10b temperature amplitude results shows that E2 has absorbed sufficient energy to be amplified under the background conditions on days 69-74, with the temperature amplitude on days 69-74 is stronger.

Figures 11a and 11b show the observed spectra of E3 at ~59.2km and ~60-70°N on days 35-38 and 53-56, and the wave period of locked wavenumber -3 is ~29h and ~27h, respectively. The corresponding temperature spatial structures of these E3 is shown in Figure 11c, 11d. The temperature spatial structure of E3 shows an obvious amplitude bimodal structure at ~50-60°N and ~60km, and ~50-60°N and ~70km, with the maximum at ~50-60°N and ~60km. The strongest temperature amplitude

of E3 occurs at \sim 60km and \sim 50-60°N with an amplitude of \sim 6K on the days 708 35-38, and the other peak is \sim 5K (\sim 50-60°N and \sim 70km). The temperature 709 amplitude of ~4K occurs at ~60km (~70km) and ~50-60°N during days 53-710 56. The corresponding spatial structures of zonal wind and meridional wind 711 of these E3 is shown in Figures 6e, 6f, 6g, and 6h. The zonal wind spatial 712 structure of E3 shows an obvious amplitude bimodal structure at ~40-50°N 713 and \sim 70km, and \sim 60-70°N and \sim 70km. The zonal wind amplitudes of E3 714 occur at ~40-50°N and ~70km with an amplitude of ~15 m/s on days 35-715 38, and ~ 12 m/s at $\sim 60-70$ °N and ~ 70 km. The maximum zonal wind 716 amplitude of E3 occurs at ~40-50°N and ~70km (~60-70°N and ~70km) 717 with an amplitude of \sim 7 m/s (\sim 6 m/s) on days 53-56. The amplitude of E3 718 719 meridional wind reaches \sim 22 m/s at \sim 50-60°N and \sim 70km (days 35-38) and \sim 12 m/s at \sim 60-70°N and \sim 70km (days 53-56), respectively. 720 Obviously, the instability and appropriate background wind at mid-721 latitude between \sim 50 and \sim 70 km and the interaction near the critical layers 722 (~29 h, ~27 h) dramatically amplify the propagation of E3, as shown in 723 Figures 11i and 11j. The background wind is similar on days 35-38 and 53-724 56, and the former is more unstable. This finding indicates that the E3 in 725 propagation is more likely to get sufficient energy to be amplified on days 726 35-38. The instability and appropriate background wind at mid-high 727 latitudes between ~50 and ~70km dramatically amplify the propagation of 728 E3, which is enhanced by the interaction near the critical layers (\sim 29 h, \sim 27 729

h) and the positive refractive index region. (Figure 11i, 11j). It is worth noting that the strong instability and weak background wind at ~50-60°N and ~60-70km on days 35-38 provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere, and ultimately point towards the equator at 50km. The EP flux propagate to the lower atmosphere during days 35-38, and is amplified by interactions at the critical layer (~29 h). In addition, weak instability and weak background winds on days 53-56 at ~50-60°N and ~60-70km provide the energy to amplify E3 propagation. Combine with Figure 11c, 11d, the stronger the instability at ~50-60°N and ~60-70km, the stronger the temperature amplitude of E3. The results show that the instability on days 35-38 at ~ 50 -60°N and ~60-70km are the primary reasons for the propagation and amplification of EP flux into the lower atmosphere. From Figures 10a and 10b, the wave period of E2 on days 25-30 and 69-74 reaches ~36h and ~53h. The maximum temperature amplitude of E2 appears on days 69-74, reaches ~10K (~60km), and the other peak is ~7K (~70km). The maximum temperature amplitude is ~5K (~60km) during days 25-30, and another peak is ~4K (~70km). The spatial structures of zonal wind and meridional wind of E2 are shown in Figures 10e, 10f, 10g, and 10h. The maximum amplitudes of zonal and meridional winds occur at ~50°N and ~70km, and ~60°N and ~70km. The maximum zonal and meridional winds are ~7 (~18) m/s on days 35-30 (69-74). Clearly, the instability at a mid-high latitude

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between ~40 and ~80 km and the interaction near the critical layer dramatically amplify the propagation of E2, which eventually turns toward the equator, as displayed in Figures 10i and 10j. Obviously, the temperature amplitude is stronger on days 69-74, which indicates that E2 obtains sufficient energy for amplification under the background condition.

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The E3 planetary waves have wave periods of ~29h and ~27h on days 35-38 and 53-56, as shown in Figures 11a, and 11b. Clearly, from Figures 11c, and 11d, the maximum temperature amplitude of E3 is ~6K (~70km) on days 35-38, and another peak is ~5K (~60km). The peak temperature amplitude is ~4K (~60, ~70 km) on days 53-56. The spatial structures of zonal wind and meridional wind of E3 are shown in Figures 11e, 11f, 11g, and 11h. The maximum amplitudes of zonal and meridional winds occur at ~40°N and ~70km, and ~50°N and ~70km. The maximum zonal and meridional winds are ~15 (~7) and ~22 (~13) m/s on days 35-38 (53-56). Obviously, the instability at mid-latitude between ~60 and ~70 km and the interaction near the critical layer dramatically amplify the propagation of E3, as shown in Figures 11i and 11j. The background wind is similar on days 35-38 and 53-56, and the former is more unstable. This finding indicates that the E3 in propagation is more likely to get sufficient energy to be amplified on days 35-38.

3.3 Comparison between SH and NH

We find that tThe observed latitude and maximum amplitude for

774 eastward planetary waves (E1, E2, E3, E4) decreasee and weaken with increasing zonal wavenumber in the SH, reaching ~70-80°S, ~60-70°S, 775 $\sim 60-70^{\circ}$ S, and $\sim 50-60^{\circ}$ S, and ~ 10 K, ~ 9 K, ~ 6 K, and ~ 3 K, respectively. In 776 addition, the occurrence date is earlier with increasing zonal wavenumber. 777 The temperature spatial structure shows a bimodaldual-peak structure (~50) 778 and ~60km), primarily located at ~50km. The maximum zonal wind 779 amplitudes of E1 and E2, E3 and E4 are almost the equivalents, which are 780 ~20 m/s and ~10 m/s respectively. The maximum meridional wind 781 amplitudes of E1, E2, E3 and E4 are \sim 17 m/s, \sim 27 m/s, \sim 16 m/s, and \sim 11 782 m/s respectively. The wave period of E1 tends to get shorter from 5 to 3 783 days, while E2 and E3 are close to ~40 h and ~30 h, while E4 remains at 784 785 ~24 h. E1, E2, E3, and E4 are more favorable to propagation in the SH winter and are dramatically amplified by the mean flow instabilities at 786 middle latitudes between ~40 and ~70-km, with EP flux propagating into 787 the lower atmosphere, and EP flux eventually propagate toward the equator 788 at ~50km. In addition, the propagation of EP flux for E1 to the upper 789 atmosphereE1 upward propagating EP flux may be influenced by the 790 instability and background wind at the Antarctic ~50km. 791

The observed latitudes of E1, E2 (E3) decrease with increasing wavenumber in the NH, which are ~70-80°N, ~60-70°N, and ~60-70°N. The temperature spatial structure of E1, E2, and E3 presents a <u>bimodal dual</u> peak structure, primarily located at ~70km, reaches ~10K, ~9K, and ~6K.

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The maximum zonal wind amplitude for E1, E2 and E3 occurs at ~50-80°N and ~70km, and their amplitude is almost equal to ~18 m/s. The maximum zonal wind amplitude appears at ~50-80°N and ~60km. E1, E2, E3, and E4 are almost the equivalent, which is ~18 m/s respectively. The maximum meridional wind of E1, E2 and E3 occur at ~50-80°N and ~70km, with amplitudes of ~22 m/s, ~18 m/s and ~22 m/s, respectively. The maximum meridional wind amplitude appears at ~50-80°N and ~60km. The maximum amplitudes of E1, E2, and E3 are ~22 m/s, ~18 m/s, and ~22 m/s respectively. The wave period of E1 tends to be shorter from 5-3 days, and E2 and E3 are close to ~48 h and ~30 h. In addition, E1, E2, and E3 are more favorable to propagation in the NH winter and are dramatically amplified by the mean flow instabilities at middle latitudes between ~40 and ~70-km, with EP flux propagating into the lower atmosphere, and EP flux eventually propagate toward the equator at ~50km.

4 Summary and Conclusions

We present for the first time an extensive study of the global variation for eastward planetary wave activity, including zonal wave numbers of -1 (E1), -2 (E2), -3 (E3), -4 (E4), in the stratosphere and mesosphere using the MERRA-2 temperature and wind observations in 2019. The temperature and wind amplitudes and wave periods of each event were determined by 2-D least-squares fitting. Our study includes the spatial and temporal behaviors of the eastward planetary waves in both hemispheres

- 818 with a comprehensive diagnostic analysis on their propagation and
- amplification. The key findings of the study are summarized as follows:
- 1. The latitudes for the maximum (temperature, zonal and meridional
- wind) amplitudes of E1, E2, E3, and E4 decrease with increasing
- wavenumber in the SH and NH. The E1, E2, E3, and E4 events occur
- earlier with increasing zonal wavenumber in the SH. In addition, eastward
- wave modes exist during summer periods with westward background wind
- in both hemispheres.
- 2. The temperature spatial structures of E1, E2, E3, and E4 present a
- 827 double-peak structure, which is located at ~50km and ~60km in SH,
- \sim 60km, and \sim 70km in SH. In addition, the lower peak is usually larger than
- the higher one.
- 3. The maximum (temperature, zonal and meridional wind) amplitudes of
- E1, E2, and E3 decrease with increasing zonal wavenumber in the SH and
- NH. The maximum temperature amplitudes in the SH are slightly larger
- and lie lower than those in the NH. In addition, the meridional wind
- amplitudes are slightly larger than the zonal wind in the SH and NH.
- 835 4. The wave period of the E1 mode varies from 3 to 5 days in both
- hemispheres, while the period of E2 mode is slightly longer in the NH (\sim 48
- h) than in the SH (\sim 40 h). The periods of E3 are \sim 30 h in both SH and NH,
- and the period of E4 is \sim 24 h.
- 5. The eastward planetary wave is more favorable to propagate in the

winter hemisphere and is dramatically amplified by the mean flow instabilities and appropriate background winds at polar and middle latitudes between $\sim\!40$ and $\sim\!80$ –km. Furthermore, the amplification of planetary waves through wave-mean flow interaction most easily occurs near its critical layer. In addition, the direction of EP flux ultimately points towards the equator.

6. The strong instability and appropriate background wind in the lower layer of the Antarctic region may provide sufficient energy to promote the E1 propagation and amplification to the upper atmospherelayer.

This study demonstrates how the background zonal wind in the polar middle atmosphere affects the dynamics of eastward planetary waves in the polar middle atmosphere.

853	Data availability. MERRA-2 data are available at http://disc.gsfc.nasa.gov .
854	
855	Author contributions. LT carried out the data processing and analysis and
856	wrote the manuscript. SYG and XKD contributed to reviewing the article.
857	
858	Competing interests. The authors declare that they have no conflict of
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860	
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864	
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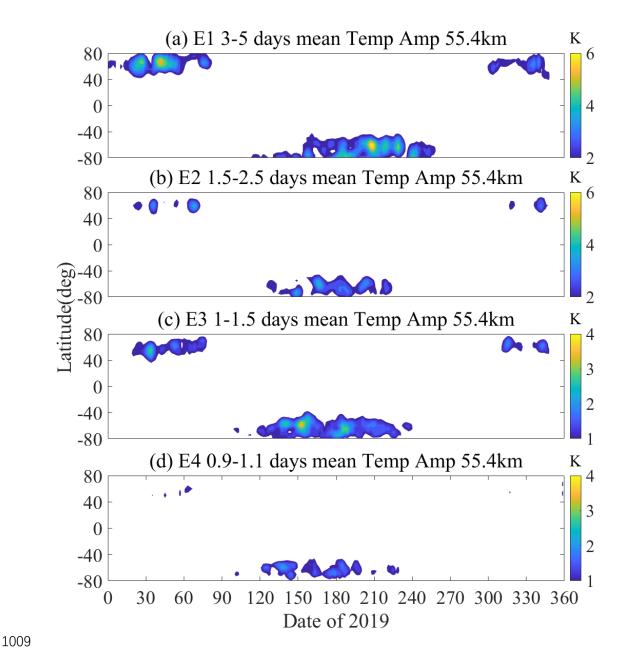


Figure 1. The global latitude-temporal variation structures of the (a) E1, (b) E2, (c) E3, (d) E4 planetary waves during 2019. White areas represent small amplitude data (corresponds to the right color bar). The confidence interval is 0.95.

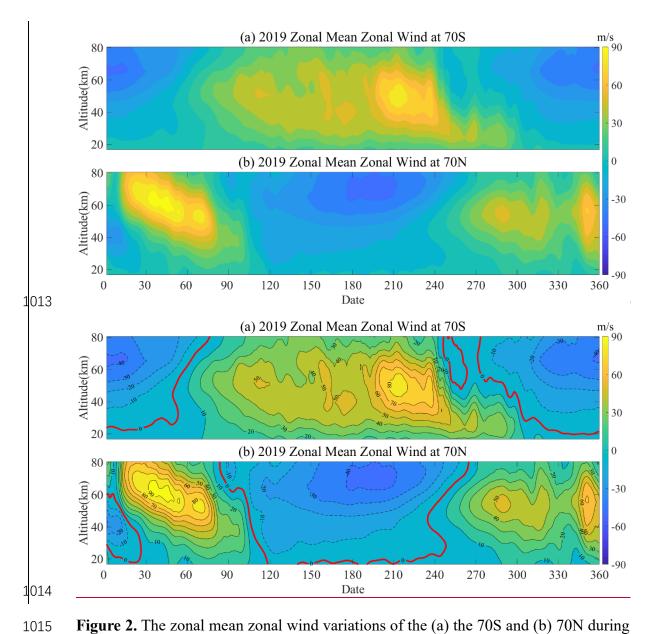


Figure 2. The zonal mean zonal wind variations of the (a) the 70S and (b) 70N during 2019. The dotted line represents east wind, the solid line represents west wind, and the red solid line is 0m/s.

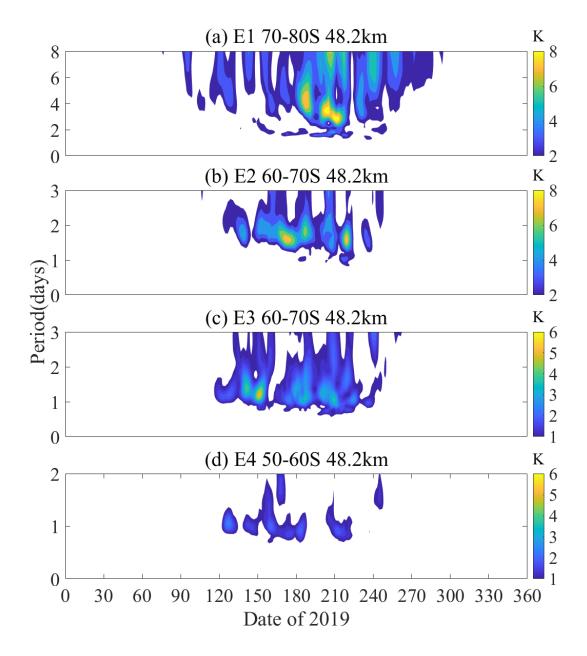
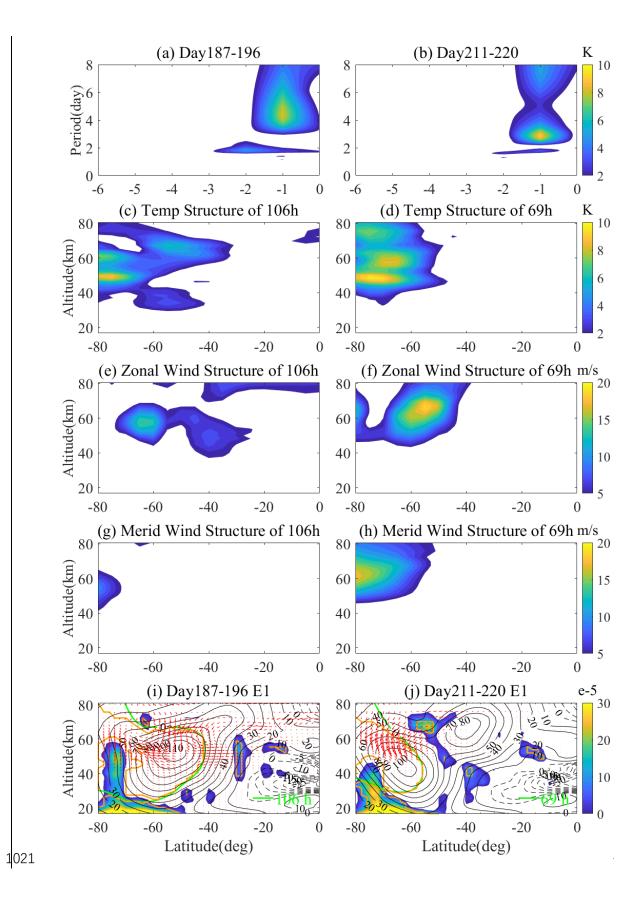


Figure 3. The temporal variations of the (a) E1, (b) E2, (c) E3, (d) E4 QTDWs during 2019 austral winter period.



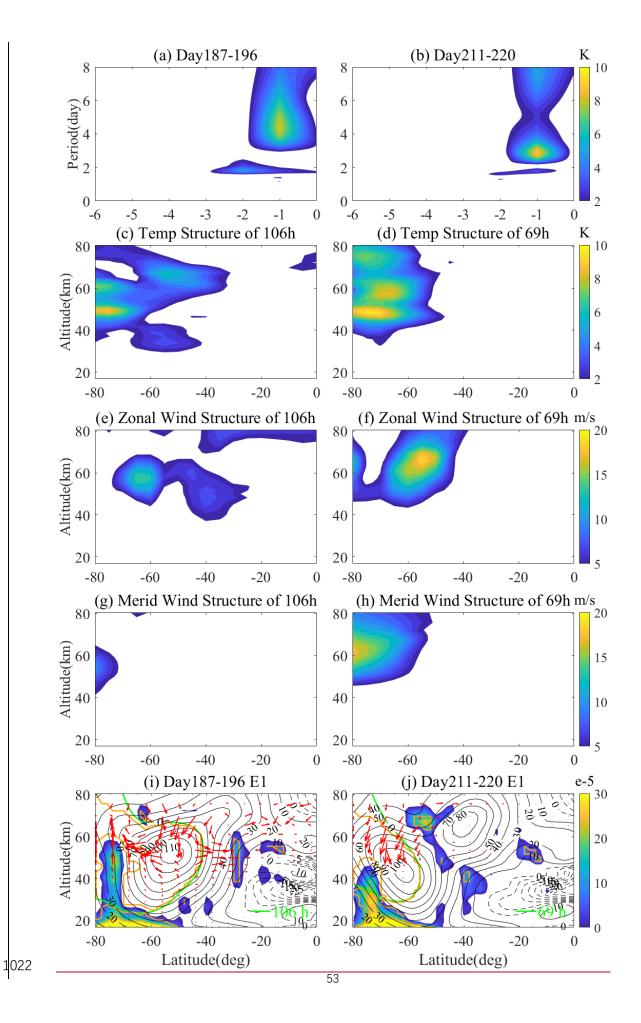
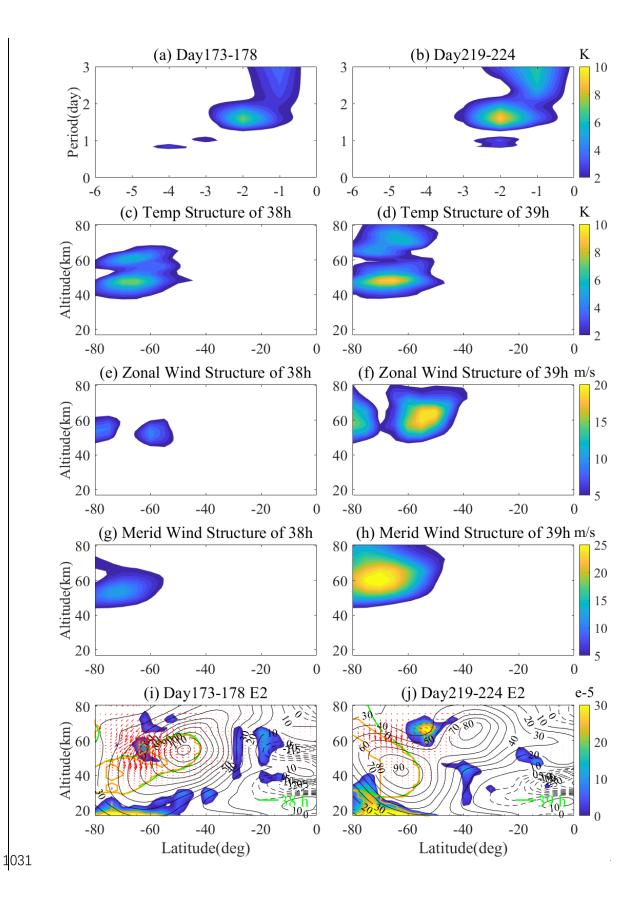


Figure 4. The (a, b) spectra, (c, d) temperature spatial structures, (e, f) zonal wind spatial structures, (g, h) meridional wind spatial structures, and (i, j) diagnostic analysis of the E1 typical events during 2019 austral winter period. The MERRA-2 temperature data observations at 48.2km and 70-80°S during days 187–196 (Figure 4a), 211–220 (Figure 4d) are utilized, respectively. The instability (blue shaded region), EP fluxes (red arrow), and critical layers (green line) for E1 typical event. The green line represents critical layers of the E1 with the natural period. Regions enclosed by orange solid lines are characterized by the positive refractive index for the E1.



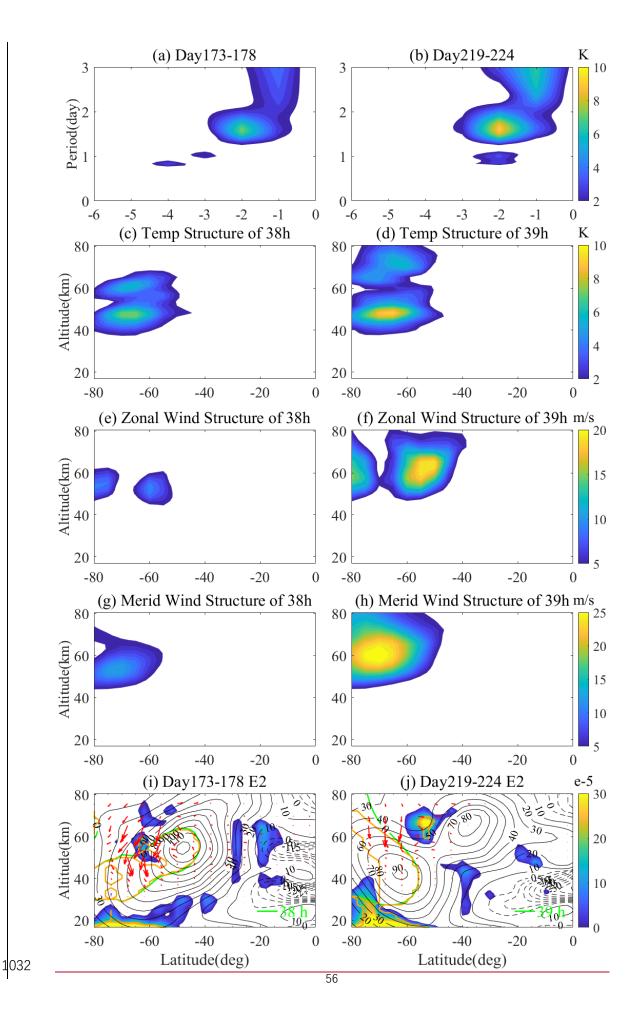
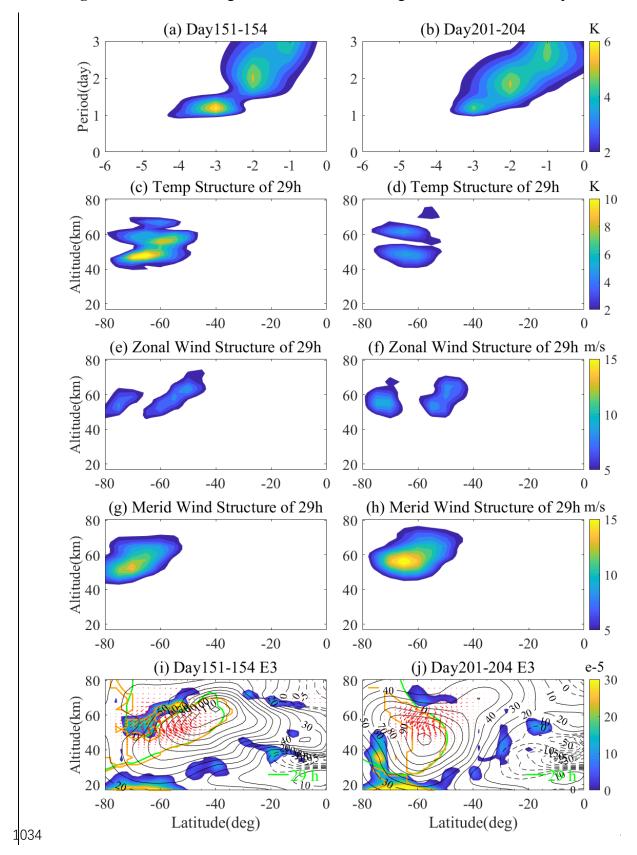


Figure 5. The same as Figure 4 but for the E2 during the 2019 austral winter period.



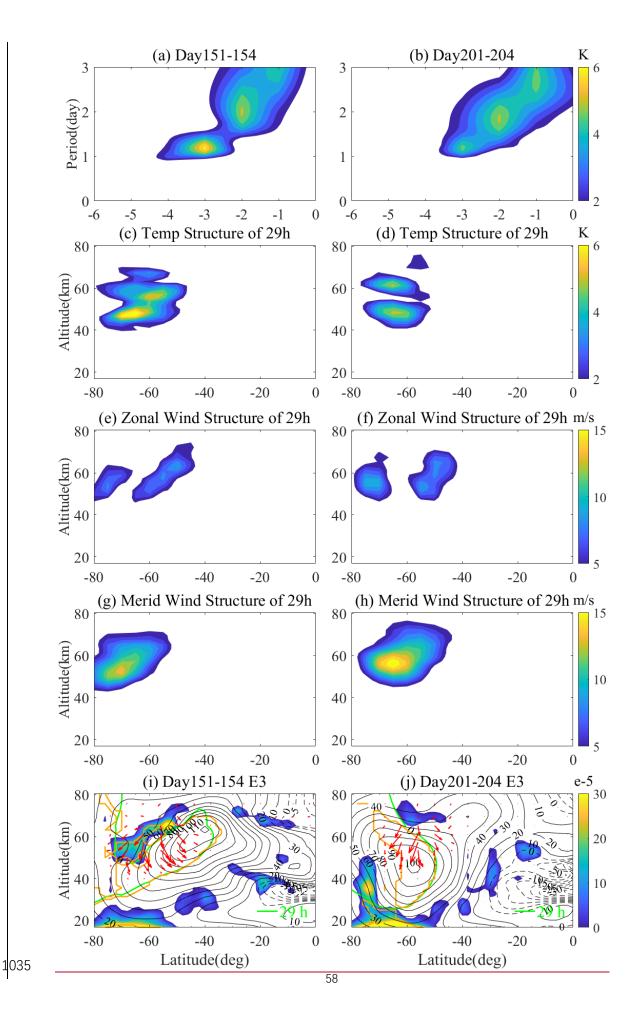
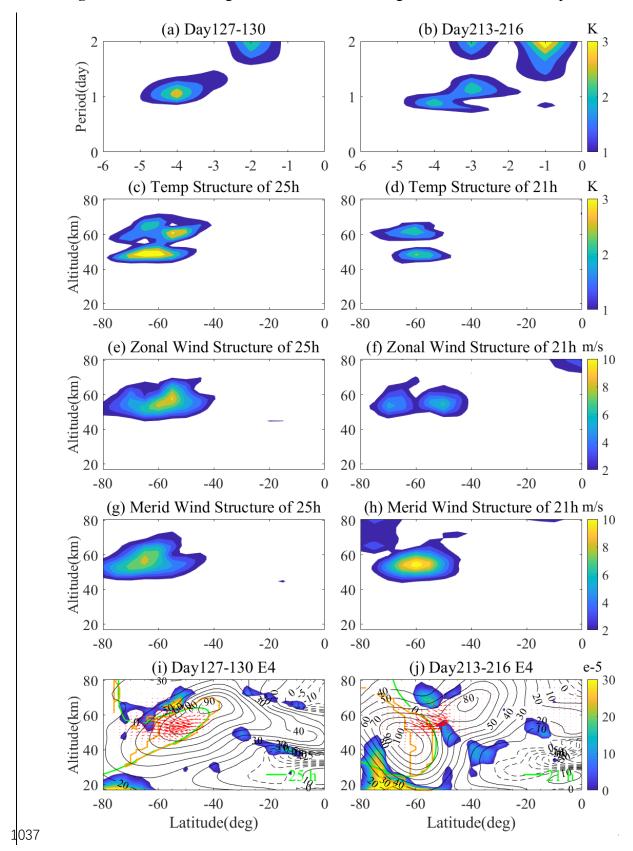
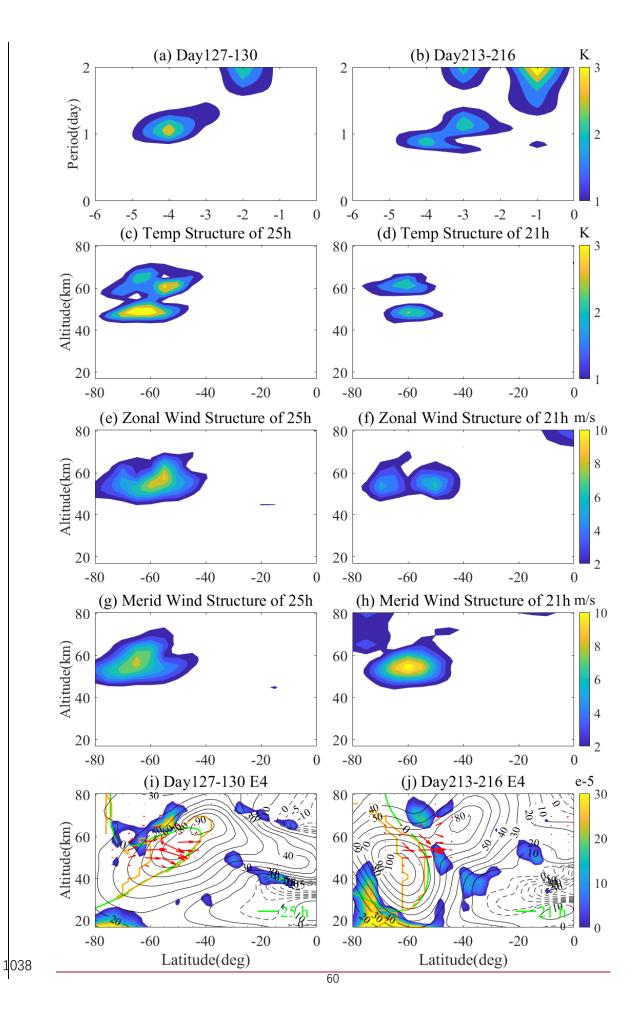


Figure 6. The same as Figure 4 but for the E3 during the 2019 austral winter period.





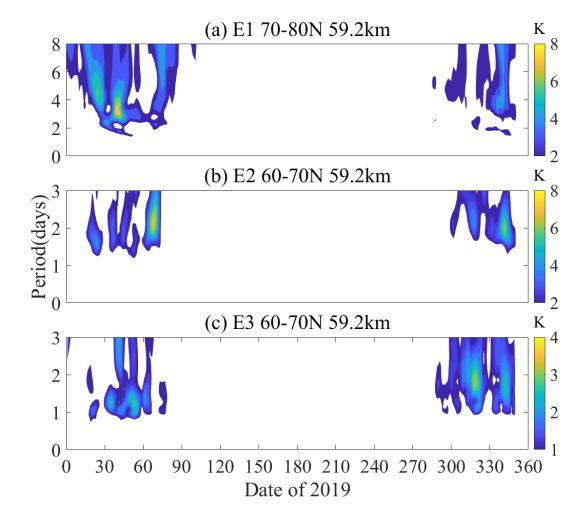
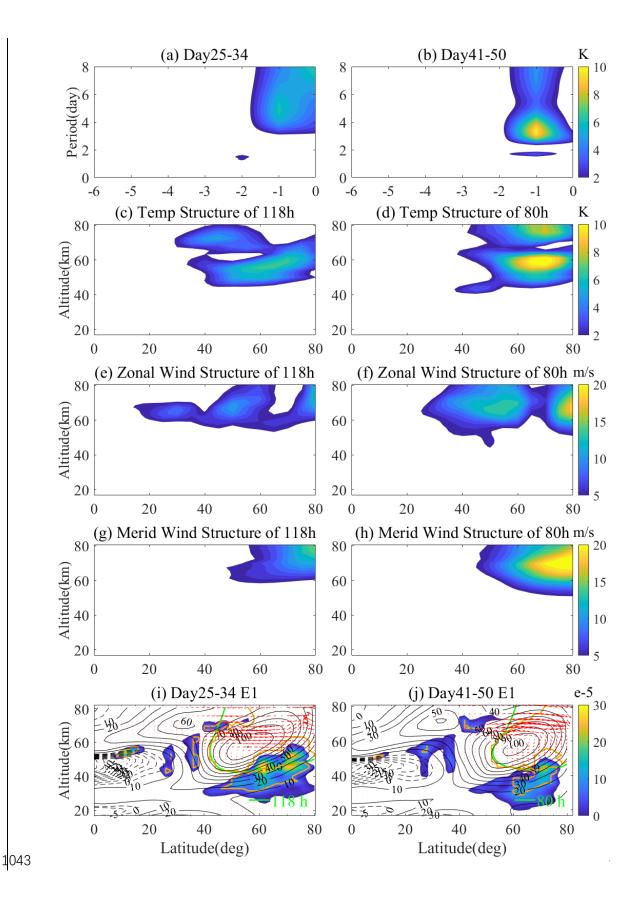


Figure 8. The temporal variations of the (a) E1, (b) E2, and (c) E3 QTDWs during the 2019 boreal winter period.



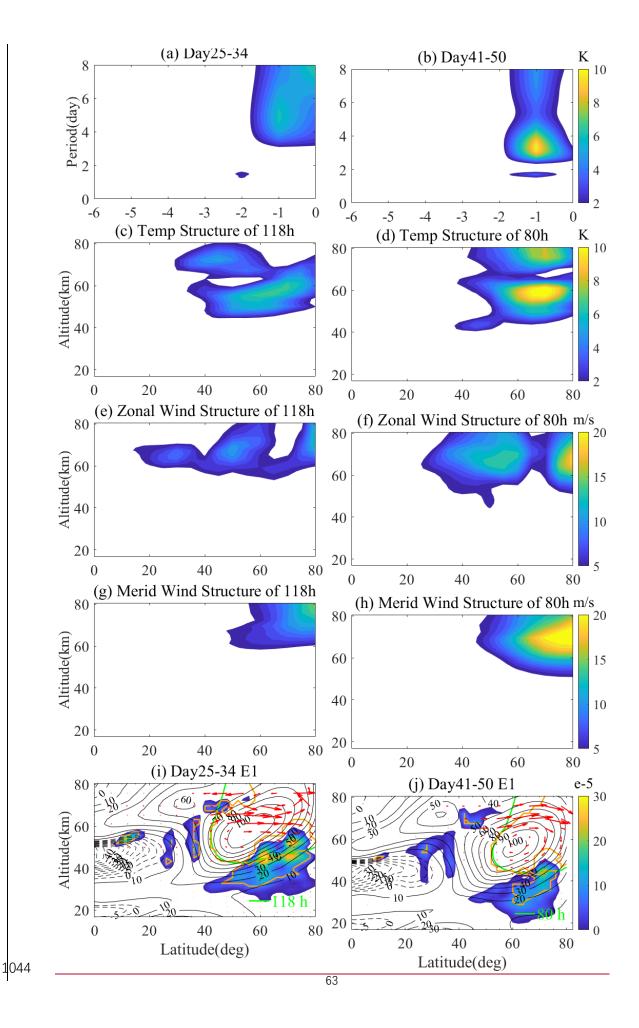
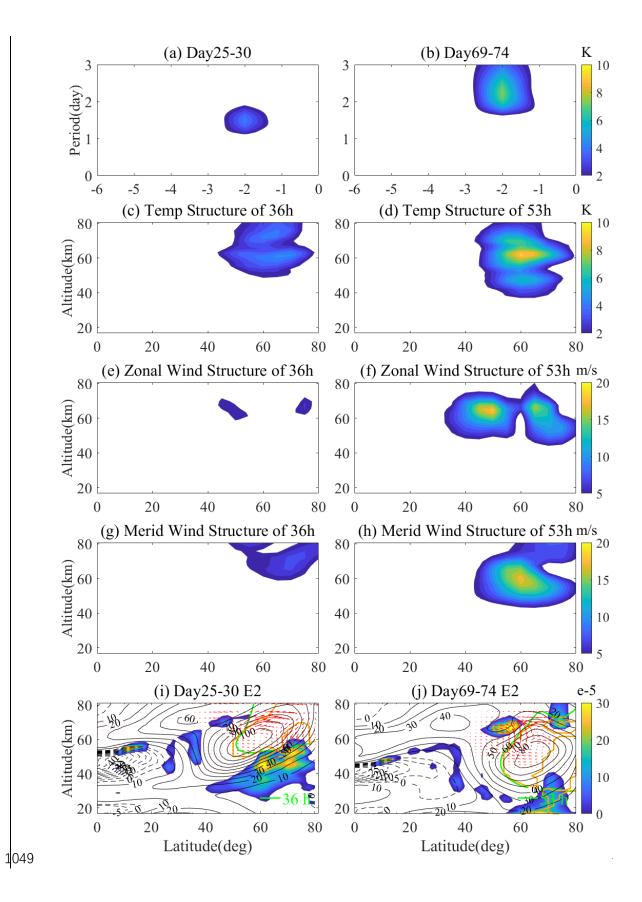


Figure 9. he (a, b) spectra, (c, d) temperature spatial structures, (e, f) zonal wind spatial structures, (g, h) meridional wind spatial structures, and (i, j) diagnostic analysis of the E1 typical events during 2019 boreal winter period. The E1 events at 48.2km and 70-1048 80°N were obtained from the MERRA-2 reanalysis.



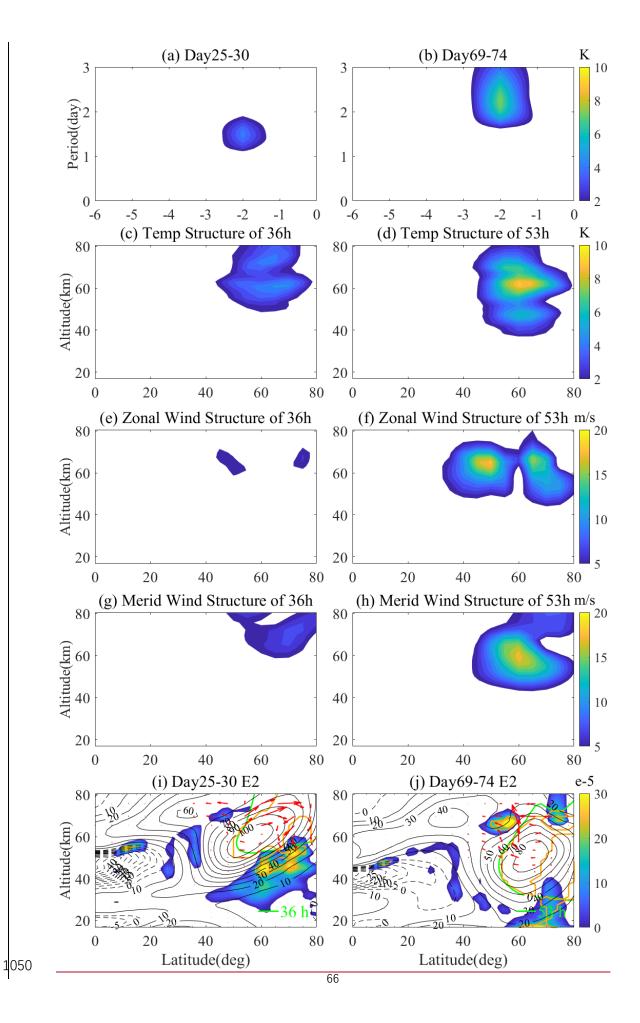
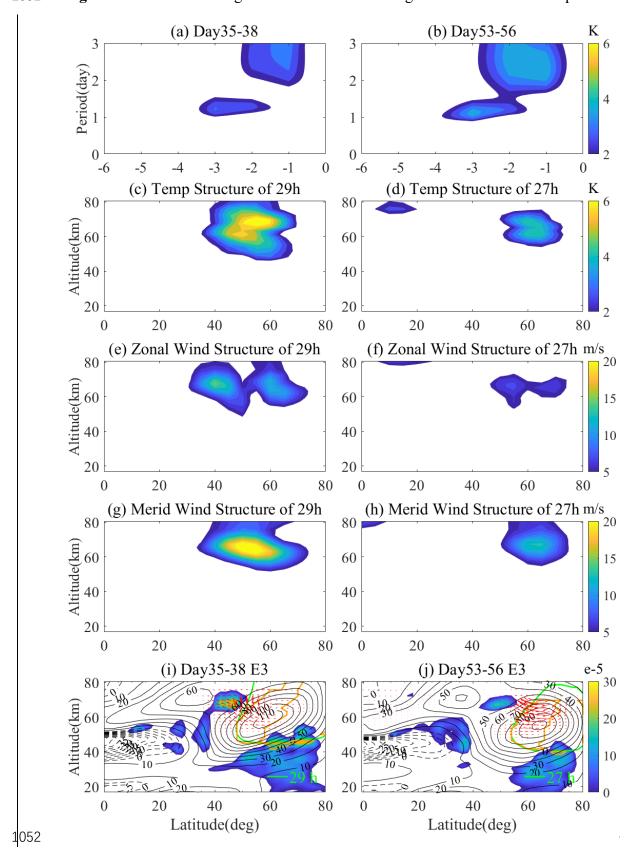


Figure 10. The same as Figure 9 but for the E2 during the 2019 boreal winter period.



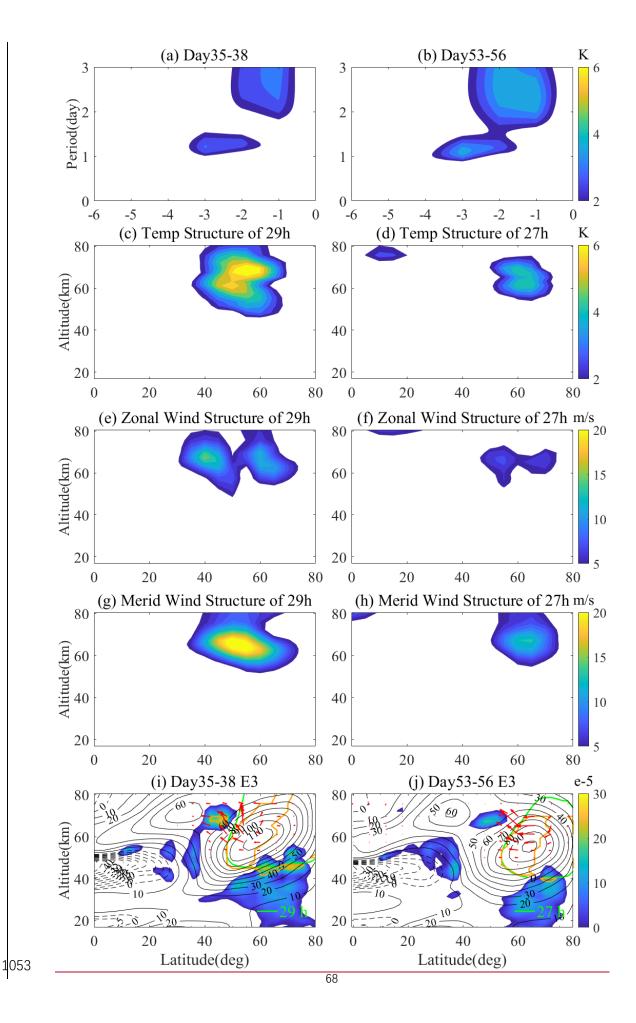


Figure 11. The same as Figure 9 but for the E3 during the 2019 boreal winter period.

Eastward-propagating planetary wave in the polar middle atmosphere

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Abstract. According to MERRA-2 temperature and wind datasets in 5 2019, this study we presented the global variations of the eastward 6 propagating wavenumber 1 (E1), 2 (E2), 3 (E3), and 4 (E4) planetary 7 waves (PWs) and their diagnostic results in the polar middle atmosphere, 8 using MERRA-2 temperature and wind datasets in 2019. It is clearly shown that. We clearly demonstrated the eastward wave modes exist 10 during winter periods with westward background wind in both 11 hemispheres. The maximum wave amplitudes in the southern hemisphere 12 (SH) are slightly larger and lie lower than those in the northern 13 hemisphere (NH). Moreover, It is also found that the wave perturbations 14 peak at lower latitudes with smaller amplitude as the wavenumber 15 increases. The period of the E1 mode varies from 3 to 3-5 days in both 16 hemispheres, while the period of E2 mode is slightly longer in the NH 17 (\sim 48 h) than in the SH (\sim 40 h). The periods of the E3 are \sim 30 h in both 18 SH and NH, and the period of E4 is ~24 h. Despite the shortening 19 of Though the wave periods with the increase of become shorter as the 20 wavenumber increases, their mean phase speeds are relatively stable, 21 which are ~ 53 m/s, ~ 58 m/s, ~ 55 m/s, and ~ 52 m/s at 70° latitudes for W1, 22

W2, W3, and W4, respectively. The eastward PWs occur earlier with increasing zonal wavenumber, which agrees well with the seasonal variations of the critical layers generated by the background wind. Our diagnostic Diagnostic analysis also indicated shows that the mean flow instability in the upper stratosphere and upper mesosphere might both contribute to the amplification of the eastward PWs.

1 Introduction

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The dominance of large Large amplitude planetary waves are 30 dominant in the stratosphere, mesosphere, and lower thermosphere 31 regionsregion and their interactionsinteraction with zonal mean winds 32 isare the primary driving force of atmospheric dynamics. In addition, 33 sudden stratospheric warmings (SSWs) and quasi-biennial oscillation 34 (QBO) events can dynamically couple the entire atmosphere from the 35 lower atmosphere to the ionosphere (Li et al., 2020; Yamazaki et al., 2020; 36 Yadav et al., 2019; Matthias and Ern, 2018; Stray et al., 2015). Westward 37 propagating planetary wave is one of the prominent features during 38 austral and boreal summer. Westward quasi-2-day waves (Q2DWs) are 39 the most obvious representative waves and one of the most investigated 40 phenomena using by planetary wave observations. Most of the previous 41 studies focused on the westward propagating Q2DWs, i.e., including zonal 42 wavenumbers of 2 (W2), 3 (W3), and 4 (W4) modes (Lainer et al., 2018; 43 Gu et al., 2018b; Wang et al., 2017; Pancheva et al., 2016; Gu et al., 44 2016a; Gu et al., 2016b; Lilienthal and Jacobi, 2015; Gu et al., 2013; 45 Limpasuvan and Wu, 2009; Salby, 1981). However, limited studies were 46 conducted to understand the seasonal Seasonal variations of the 47 occurrence date, peak amplitude, and wave period for the eastward 48 Q2DWs are rarely studied (Gu et al., 2017; Lu et al., 2013; Alexander and 49 Shepherd, 2010; Sandford et al., 2008; Palo et al., 2007; Merzlyakov and 50

Pancheva, 2007; Manney and Randel, 1993; Venne and Stanford, 1979).

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Typically, Q2DWs usually maximize after the summer solstice in the 52 middle 53 latitudes. The largest wave amplitudes are generally appearobserved near the mesopause in January–February in the Southern 54 Hemisphere (SH), while in the Northern Hemisphere (NH) in July-55 August (Tunbridge et al., 2011). W3 and W4 Q2DWs reach amplitudes 56 during austral and boreal summer in the mesosphere and lower 57 thermosphere, respectively. The seasonal variation of westward Q2DWs 58 activity has anis obvious seasonal variation (Liu et al., 2019; Gu et al., 59 2018b; Rao et al., 2017). By observing the long-term Q2DW in the NH 60 and SH, Tunbridge et al. (2011) have observed long-term Q2DW in the 61 NH and SH, and foundreported that W3 is generally stronger than the 62 other two modes in the SH, reaching the amplitude of ~12K; while W4 is 63 stronger than W3 in the NH, reaching ~4K. MoreoverIn addition, W4 is 64 generally lives longer lived than W3, and W4 canis still be observed after 65 the ending of W3 has ended. A previous study has demonstrated The 66 results of Liu et al. (2004) show that wave source, instability, critical 67 layer, and mean zonal wind are the primary reasons for the seasonal 68 variation of Q2DWs (Liu et al., 2004). By studying the long-term satellite 69 datasets in the SH, Gu et al. (2019) have the long-term observation of 70 satellite datasets in the SH and foundsuggested that the strongest events 71 of W2, W3, and W4 could beare delayed with increasing the zonal 72

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wavenumber, and these events would be indistinguishable during SSWs.
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    Then The wave periods of W4, W3 and W2 vary between around ~41-56 h,
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    ~45-52 h, and ~45-48 h, respectively. Furthermore In addition, W2 can be
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    observed usingin global satellite datasets, but it has anshowing weaker
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    amplitude weaker than W3 and W4 in the NH and SH (Meek et al., 1996).
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    The propagation and amplification of Q2DWs are primarily modulated by
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    instability, refractive index, and critical layer, while the variation of
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    background wind may cause different zonal wavenumber events (Gu et
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    al., 2016a; Gu et al., 2016b). By analyzing the variation of Q2DWs
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    activity during SSWs, Xiong et al. (2018) studied variations in Q2DWs
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    activity during SSWs and foundnoticed that W1 is generated by the
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    nonlinear interaction between SPW2 and W3. During SSWs, Gu et al.
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    (2018b) found that the coupling between the NH and SH can
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    enhance<del>enhanced</del>
                        the
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    promote<del>promoted</del> the nonlinear interaction between W3 and SPW1
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    during SSWs(Gu et al., 2018b).
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         Some recentRecent studies have discoveredfound
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    eastward planetary waves in the polar stratosphere and mesosphere
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    regions, with periods of nearly 2two and 4four days (Gu et al., 2017;
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    Sandford et al., 2008; Merzlyakov and Pancheva, 2007; Coy et al., 2003;
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    Manney and Randel, 1993). Planetary waves with zonal wavenumbers -1
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    (E1) and -2 (E2) correspond to 4- and 2-day waves, respectively. In
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additionFurthermore, planetary waves of 1.2-day with wavenumber -3 (E3) and 0.8-day with wavenumber -4 (E4) have been reported to containfound to have the same phase speeds as E1 and E2 (Manney and Randel, 1993). This series of eastward planetary wave can significantly affecthas a significant effect on the thermal and dynamic structure of the polar stratosphere, resulting in profoundsignificant changes in the wind and temperature of the polar stratosphere (Coy et al., 2003; Venne and Stanford, 1979). Beyond the knowledge about Palo et al. (1999) demonstrated a series of nonlinear interactions between migrating tides and Q2DWs (Palo et al., 1999), further investigation has confirmed-Further research, Palo et al. (2007) presented evidence that E2 Q2DW is coupled by nonlinear planetary wave and tides in the mesosphere and lower thermosphere (Palo et al., 2007). By studying and analyzing satellite datasets, Merzlyakov and Pancheva. (2007) indicated analyzed and studied satellite datasets and found that the wave periods of E1 and E2 events rangeis within 1.5-5 days. They reported found that EP flux travels is from the upper layer to the lower atmosphere, meaningsuggesting that the upper atmosphere has a dynamic influence on the lower atmosphere. Sandford et al. (2008) reported about significant fluctuations of E2 Q2DW in the polar mesosphere. They found indicated the influence of that changes in mean zonal winds during a major SSW oninfluenced the propagation of polar

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E2. In addition, they proposed believe that the significance of E2 fluctuation is representative in the mesosphere and caused driven by the instabilities in the polar night jet. Gu et al. (2017) found that the For E2, amplitude of E2 temperature, zonal wind and meridional wind during the austral winter can reach ~10_K, ~20 m/s, and ~30 m/s, respectively; in temperature, zonal wind, and meridional wind in the austral winter, while those during the boreal winter can drop by almost the amplitude of E2 decreases by near two-thirds in the boreal winter. Lu et al. (2013) found that eastward planetary wave propagation iswas limited to the winter high latitudes, which may be probably because the negative refractive indices equatorward of ~45°S result in evanescent wave characteristics, thus preventing the propagation of planetary wave to low latitudes. That study suggested that They believe that the instability region at ~50-60°S mightmay be induced by the stratospheric polar night jet and/or the "double-jet" structure. In this study, we use the The second modern retrospective research

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In this study, we use the The second modern retrospective research and application analysis (MERRA-2) datasets are used to investigate the eastward propagating wave characteristics in the polar stratospheric and mesospheric region during 2019, including E1, E2, E3 and E4. Specifically Particularly, we investigate the variation of the occurrence date, peak amplitude, and wave period of eastward waves; as well as the role of instability, background wind structure, and critical layer in the

propagation and amplification of eastward waves. The remaining parts of this paper are organized as follows. Im-Section 2 describes; the data and methods used in thisour study—are described. Im-Section 3 analyzes the global latitude-temporal variation structure of eastward waves induring winterthe in 2019—winter. The amplification and propagation features of the eastward planetary waves in the NH and SH with different wavenumber events are examined investigated in Sections Section 3.1 and 3.2, respectively. Im-Section 3.3 compares and analyzes the eastward waves in the NH and SH. In Section 4 summarizes our All research results are summarized in Section 4.

2 Data and Analysis

The least-square method is applied to each time window to extract the E1-, E2-, E3-, and E4-wave, with 10-day, 6-day, 4-day, and 4-day, and is used by us to determine the amplitude (Gu et al., 2013). This method has been shown topreviously been used successfully to-identify planetary waves from satellite measurements (Gu et al., 2019; Gu et al., 2018a; Gu et al., 2018b; Gu et al., 2018c; Gu et al., 2013).

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$$y = A\cos[2\pi(\sigma \cdot t + s \cdot \lambda)] + B\sin[2\pi(\sigma \cdot t + s \cdot \lambda)] + C \tag{1}$$

The least-squares method is used to fit the <u>a set of parameters of</u>

(A, B, A, B and C). Where where $(\sigma, t, s, \underline{\sigma}, t, s)$ and λ) are the frequency,

UT time, zonal wavenumber, and longitudes. The amplitude of wave R

cancould be expressed as $-R = \sqrt{A^2 + B^2}$.

The second modern retrospective research and application analysis 161 (MERRA-2) covers the data is a set of long-term atmospheric reanalysis 162 datasets started initiated by NASA in 1980, and now using an. It has been 163 upgraded recently using version of the Goddard Earth Observing System 164 Model, Version 5 (GEOS-5) data assimilation system. Briefly, MERRA-2 165 includes some updates to the model (Molod et al., 2014; Molod et al., 166 2012) and the Global Statistical Interpolation (GSI) analysis scheme of 167 Wu et al. (2002). The MERRA-2 data consist of includes various 168 meteorological variables, such ase.g., net radiation, temperature, relative 169 humidity, and wind speed, etc. The spatial coverage of MERRA-2 data is 170 the globecovers the world, with a (spatial resolution: of 0.5°*×0.625°; 171 and a temporal resolution: of 1 hhour). This kind of meteorological data 172 isare widely used to detect the middle atmosphere such as the planetary 173 wave in the polar atmosphere, global thermal tides, climate variability, 174 and aerosol (Ukhov et al., 2020; Sun et al., 2020; Bali et al., 2019; Lu et 175 al., 2013). These Many recent studies indicated indicate that the feasibility 176 of using MERRA-2 data for the kind of research in present studycan be 177 used in our research with high authenticity. Therefore, we apply the The 178 MERRA-2 datasets are used to obtain the variation in background wind, 179 instability, refractive index, and critical layer; and explore the rules of 180 eastward planetary waves propagation and amplification through 181 diagnostic analysis. 182

The critical layer will absorb or reflect planetary waves during upward propagation—from the lower atmosphere during upward propagation. Planetary waves that gain sufficient energy in the instability region will be amplified during reflection. In a sense, This shows that the critical layer plays an important role in regulating the amplification and propagation of planetary waves (Gu et al., 2016a; Gu et al., 2016b; Liu et al., 2004).

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$$\overline{q_{\varphi}} = 2\Omega \cos \varphi - \left(\frac{\left(\overline{u}\cos\varphi\right)_{\varphi}}{a\cos\varphi}\right)_{\varphi} - \frac{a}{\rho}\left(\frac{f^2}{N^2}\rho\overline{u}_z\right)_z$$
 (2)

The baroclinic/barotropic instability in the atmospheric space structure is caused by the simultaneous equalization of the negative latitude gradient and the quasi-geostrophic potential vorticity $(\overline{q_{\varphi}})$. In Equation (2), where (Ω) denote is the angular speed of the Earth's rotation; $\overline{\varphi}$ is the latitude; \overline{u} is the angular speed of the Earth's rotation; $\overline{\varphi}$ is the latitude; \overline{u} is the latitude and zonal mean zonal wind; are represented by $(\varphi \text{ and } \overline{u})$, in the second part, the (\underline{u}) is the represents the Earth radius; in the last part, $(\rho, f, \text{ and } N)$ denote the background ρ is the air density; f is the Coriolis parameter; f and f is the buoyancy frequency; f respectively, subscripts f and f are the vertical and latitudinal gradients, are represented by subscripts f and f are the vertical According to Andrews et al. (1987), the properties of planetary wave

propagation can be calculated using define the Eliassen-Palm (EP) flux vectors (F), i.e., to show the properties of planetary wave propagation,

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$$F = \rho a \cos \varphi \left[\frac{\overline{u_z} \overline{v'\theta}}{\overline{\theta_z}} - \overline{v'u} \right] \left[f - \frac{(\overline{u} \cos \varphi)_{\varphi}}{a \cos \varphi} \right] \frac{\overline{v'\theta}}{\overline{\theta_z}} - \overline{w'u}$$
 (3)

where u' and v' are the planetary wave perturbations in the zonal and meridional wind, respectively; θ' and w' are represent the potential temperature and vertical wind, respectively. The planetary wave propagation is only favorable where the square of refractive index m^2 is was positive:

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$$m^{2} = \frac{\overline{q_{\varphi}}}{a(\overline{u} - c)} - \frac{s^{2}}{(a\cos\varphi)^{2}} - \frac{f^{2}}{4N^{2}H^{2}}$$
 (4)

where (s) denote is the zonal wavenumber, c is the phase speed is represented by (c), and the (H) represents the scale height. The square of the refractive index is taken as the waveguide of planetary waves, i.e., c

$$c = -v_0 \cos\left(\frac{\varphi \pi}{180}\right) / sT \tag{5}$$

where (c) denote the phase speed, o_0 is the equatorial linear velocity is

represented by (o_0) , and the (ϕ) represents the latitude, o_0 is the zonal

wavenumber and o_0 represent zonal wavenumber and is the wave

219 period<u>.</u>, respectively.

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3 Results and Discussion

Figure 1 shows the The global temporal-latitude variation structures of E1, E2, E3, and E4 extracted from the 2019 MERRA-2 temperature

datasets using time windows of 10-, 6-, 4- and 4-days, respectively are 223 shown in Figure 1. The mean temperature amplitude amplitudes of E1, E2, 224 E3, and E4 at 55.4 km during the periods of $3\sim5$, $1.5\sim2.5$, $1\sim1.5$, and 225 0.9~1.1-days are displayedshown in Figure 1a, 1b, 1c, and 1d, 226 respectively. Eastward waves are characterized by obvious seasonal 227 variations in the SH and NH. In addition, E1, E2 (E3), and E4 reach their 228 maximum amplitudeamplitudes at 50-80°(S/N). In the SH, the strongest 229 E1 and E2 events occur on days 209-218 and 167-172; while E3 and E4 230 events occur on days 151-154 and 139-142. This means that their 231 occurrence date of maximum amplitude getsoccurs earlier with increasing 232 zonal wavenumber. In addition, the maximum amplitudeamplitudes of 233 234 E1, E2, E3, and E4 are ~ 6.0 K, ~ 4.2 K, ~ 3.6 K, and ~ 2.4 K, respectively, indicating that their peak amplitude amplitudes drop with rising decrease 235 with increasing zonal wavenumber. In the NH, the strongest E1, E2, E3 236 and E4 events occur on days 41-50, 69-74, 35-38 and 63-66, respectively; 237 and the corresponding peak amplitudeamplitudes are ~5.5_K, ~3.8_K, 238 ~2.8 K and ~1.2 K, respectively. Whilst the The results demonstrates how 239 the decline ofthat the peak amplitude decreases with increasing zonal 240 wavenumber in the NH, but the occurrence date is irregular. Moreover In 241 addition, E4 is relatively weak in the NH and difficultalmost impossible 242 to find, so W4 is insignificantout of the discussion in the NH. Figure 2 243 presentsshows the changes in zonal mean zonal wind at 70°S and 70°N in 244

2019. It <u>can be seen is found</u> that the background wind on days 90-240 (70°S) is dominated by westward wind, and <u>reachesreached</u> ~80 m/s at ~50_km on days 210; while it is dominated by eastward wind in late and early 2019, and reaches ~-40 m/s at ~60_km. Meanwhile, the background wind is primarily westerly wind in late and early 2019 (70°N), and reaches ~90 m/s at ~-60_km on days 50; while on days 120-240, the background wind is primarily easterly wind, and the amplitude reaches -40 m/s on days 200. Compared with Figure 1, the results show that the eastward wave modes exist during winter periods with westward background wind in both hemispheres.

3.1 In the Southern Hemisphere

Figure 3 shows that observed maximum amplitude is at observed to be ~48.2 km and ~70-80°S for E1; and E2 and E3 at __~48.2 km and ~60-70°S for E2 and E3; while E4 at ~48.2 km and ~50-60°S for E4.

The For E1, the observed maximum perturbation observed for E1 occur occurs on days 211-220 (with an amplitude of ~8.5 K), and the remaining fluctuations occur on days 161-170, 187-196 and 231-240, while the For E2, the observed maximum perturbation happens—maximizes at days 219-224 (with an amplitude of ~7.8 K), and also shows three peaks appear onat days 139-144, 173-178, and 187-192. Regarding E3Besides, the strongest perturbation E3—occurs on days 151-154 (with an amplitude of ~5.2 K), while and the rest are distributed on days 141-144, 201-204,

and 209-202. E4 perturbations are distributed on days 127-130, 145-148, 267 161-164, 213-216, with weak amplitude of ~3 K. Since According to 268 earlierprevious studies mentioned that, the wave period of the eastward 269 wave can vary, varies. Therefore, we also investigate the periodic 270 variabilities variability of E1, E2, E3, and E4 has also been investigated. 271 The results show that the period corresponding to the maximum 272 perturbation of E1 falls between ~106 (days 187-196) and ~69 h (days 273 211-220), and their periods vary significantly greatly. 274 wave Nonetheless However, the wave period of E2 gradually changes from ~42 275 h (days 139-144) to ~38 h (days 219-224), and its stability is stronger 276 than that of E1. In addition, the The wave periods of E3 and E4 are about 277 ~39 h and ~24 h, respectively. These results reflect that Thus, E2, E3, and 278 E4 wave periods are more stable compared tothan E1. 279 The spectra, spatial (vertical and latitudinal) structures of 280 temperature, zonal and meridional wind, and diagnostic analysis of E1 are 281 extracted from the two corresponding two representative events, (refer 282 toas shown in Figure 4). Figures Figure 4a, 4b showshows the 283 least-squares fitting spectra for MERRA-2 temperature on days 187–196, 284 211-220 at ~48.2 km and ~70-80°S, when and where the E1 maximizes. 285 An eastward wavenumber -1 signal with the periodsperiod of ~106 h and 286 ~69 h clearly dominates the whole spectrum. The temperature spatial 287 structures structure corresponding to these E1 (i.e., ~106 h and ~69 h) are 288

displayedis shown in FiguresFigure 4c, 4d. The temperature spatial structure of E1 exhibitspresents an obvious amplitude bimodal structure at $\sim 70-80^{\circ}$ S and ~ 50 km, and $\sim 70-80^{\circ}$ S and ~ 60 km, with the maximum at ~70-80°S and ~50 km. The strongest temperature amplitude of E1 occurs at ~ 50 km and $\sim 70-80$ °S with an amplitude of ~ 10 K on the days 211-220, and the other peak is \sim 9K (\sim 70-80°S and \sim 60_km). The temperature amplitude of ~9K occurs at ~50 km and ~70-80°S during days 187-196, and the rest is $\sim 7K$ ($\sim 70-80^{\circ}S$ and ~ 60 km). The corresponding spatial structures of zonal wind and meridional wind of these E1 areis shown in Figures 4e, 4f, 4g, and 4h. The maximum zonal wind amplitude of E1 occurs at ~60-70°S and ~60 km with an amplitude of \sim 14 m/s on days 187-196, and \sim 20 m/s at \sim 50-60°S and \sim 60 km on days 211-220. The amplitude of E1 meridional wind hitsreaches ~10 m/s at $\sim 70-80^{\circ}$ S and ~ 55 km (days 187-196) and ~ 17 m/s at $\sim 70-80^{\circ}$ S and \sim 60 km (days 211-220), respectively. Figures Figure 4i, 4j showshows the diagnostic analysis results for the E1 events during days 187–196, and 211–220, respectively. Apparently, It is clear that the EP flux vectors is more favorable to propagate in the SH winter and is dramatically amplified by the mean flow instabilities and appropriate background winds at polar and between ~40 km and ~80 km, with EP flux propagating into the upper atmosphere (Figure 4i). Meanwhile, there is an EP flux at the mid-latitudes and

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~60-80 km, which propagates into the lower atmosphere. The wave-mean flow interactions near its critical layer (106 h) of the green curve amplifies E1, and the positive refractive index region surrounded by the yellow curve also enhances E1 propagation. In addition, the strong instability and weak background wind at ~70-80°S and ~40-60 km provide sufficient energy for the upward EP flux to propagate and amplify. Nevertheless However, the downward propagating EP flux is amplified by weak instability and strong background wind at ~50-60°S and ~60-70 km. Besides, both upward and downward EP fluxesflux eventually propagate toward the equator at ~50 km. Figure 4j shows that EP flux on days 211-220 propagates downward and amplifies after the interaction of the critical layer (~69 h). Facilitated by the positive refractive index region, which strong instability and weak background wind at ~50-60°S and ~60-70 km provide sufficient energy, and ultimately point towards the equator at ~50 km. The results show that the weak background wind and strong instability in the polar region can promote the upward propagation and amplification of the EP flux. Meanwhile, the appropriate background wind and instability in the mid-latitudes mid-latitude are also conducive to the downward propagation and amplification of EP flux. In other words, instability and appropriate background wind dominateplay a dominant role in the propagation and amplification of the E1.

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For E2, Thethe spectra are observed at ~48.2_km and ~60-70°S on

days 173-178, and 219-224 for E2, when the eastward wavenumber -2 becomes the primary wave mode with the wave periodsperiod of ~38 h and ~39 h, respectively (as shown in Figures Figure 5a, 5b). The temperature spatial structuresstructure corresponding to these E2 (~38 h and ~39 h) areis presentedshown in FiguresFigure 5c, 5d. The temperature spatial structure of E2 shows an obvious amplitude bimodal structure at ~60-70°S and ~50 km, and ~60-70°S and ~60 km, with the maximum at ~60-70°S and ~50_km. The maximum temperature amplitude of E1 occurs at ~50 km and ~60-70°S with an amplitude of \sim 7.5 K on the days 173-178, and the other peak is \sim 6 K (\sim 70°S and \sim 60 km). The temperature amplitude of ~ 10 K happensoccurs at ~ 50 km and \sim 60-70°S during days 219-224, and the rest is \sim 6 K (\sim 70°S and \sim 60 km). The corresponding spatial structures of zonal wind and meridional wind of these E2 areis illustratedshown in Figures 5e, 5f, 5g, and 5h. The zonal wind spatial structure of E2 shows an obvious amplitude bimodal structure at ~50-60°S and ~60 km, and ~70-80°S and ~60 km, with the maximum at ~50-60°S and ~60 km. The maximum zonal wind amplitude amplitudes of E2 appear occur at ~50-60°S and ~60 km with an amplitude of ~ 10 m/s on days 173-178, and the other peak is ~ 9 m/s $(\sim 70-80^{\circ} \text{S} \text{ and } \sim 60 \text{ km})$. The zonal wind amplitude of $\sim 20 \text{ m/s}$ occurs at \sim 50-60°S and \sim 60 km on days 219-224, and the rest is \sim 15 m/s (\sim 70-80°S and ~60 km). The amplitude of E2 meridional wind reaches ~13 m/s at

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 $\sim\!\!70\text{-}80^\circ S$ and $\sim\!\!60_\text{km}$ (days 173-178) and $\sim\!\!27$ m/s at $\sim\!\!70\text{-}80^\circ S$ and $\sim\!\!60$ km (days 219-224), respectively.

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The results in Figures 5i and 5j illustrateshow the diagnostic analysis during days 173-178, and 219-224 for E2, respectively. Obviously, It is clear that E2 is more likelyfavorable to propagate in the SH winter and is dramatically amplified by the mean flow instabilities at the middle-high latitudes between ~40 km and ~80 km., with With EP flux propagating into the lower atmosphere, and EP fluxit eventually propagatespropagate toward the equator at ~50 km. Besides, E2 is amplified and propagated by the wave-mean flow interactions near its critical layer (~38 h) of the green curve, and the promoting effect of the positive refractive index region surrounded by the yellow curve. Meanwhile, the weak instability and strong background wind at ~50-60°S and ~50-70 km provide the energy for the propagation and amplification of EP flux into the lower atmosphere during days 173-178 (Figure 5i). According to In the diagnostic analysis of days 219-224, it is found that E2 obtains sufficient energy from strong instability and strong background wind at ~50-60°S and ~60-70 km, and. It is amplified and propagated into the lower atmosphere through the critical layer and positive refractive index action, (as shown in Figure 5j). The results show that the background wind at \sim 50-60°S and \sim 50-70 km is weaker on days 173-178 than on days 219-224; and the instability at $\sim 50-60^{\circ}$ S and $\sim 60-70$ km is stronger on

days 219-224 than on days 173-178. According to Figure 5a, 5bOur results showshows that E2 has absorbed sufficient energy to be amplified under the background conditions during days 219-224 (Figures 5a, 5b).

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Figures 6a and 6b show the observed spectra of E3 at ~48.2 km and ~60-70°S on days 151-154 and 201-204, and the wave periodsperiod of locked wavenumber -3 areis ~29 h and ~29 h, respectively. The corresponding temperature spatial structures of these E3 (i.e., ~29 h and ~29 h) are displayed is shown in Figures Figure 6c, 6d. The temperature spatial structure of E3 shows an obvious amplitude bimodal structure at $\sim 60-70^{\circ}$ S and ~ 50 km, and $\sim 60-70^{\circ}$ S and ~ 60 km, with the maximum at \sim 60-70°S and \sim 50 km. Besides, E3 also has a weak peak at \sim 60-70°S and \sim 70 km. The strongest temperature amplitude of E3 occurs at \sim 50 km and \sim 60-70°S with an amplitude of \sim 6K on the days 151-154, and the other peak is ~ 5 K ($\sim 60-70$ °S and ~ 60 km). The temperature amplitude of ~ 5 K happensoccurs at ~50 km (~60 km) and ~60-70°S during days 201-204. The corresponding spatial structures of zonal wind and meridional wind of these E3 is are shown in Figures 6e, 6f, 6g, and 6h. The zonal wind spatial structure of E3 shows an obvious amplitude bimodal structure at $\sim 70-80^{\circ}$ S and ~ 60 _km, and $\sim 50-60^{\circ}$ S and ~ 60 _km. The zonal wind amplitudes of E3 occur at \sim 70-80°S and \sim 60 km (\sim 50-60°S and \sim 60 km) with an amplitude of ~9 m/s on days 151-154, and ~9 m/s at ~70-80°S and $\sim 60 \text{ km}$ ($\sim 50\text{-}60^{\circ}\text{S}$ and $\sim 60 \text{ km}$) on days 201-204. The amplitude of E3 meridional wind <u>hitsreaches</u> ~ 13 m/s at $\sim 60-70^{\circ}$ S and ~ 55 _km (days 400 151-154) and ~ 16 m/s at $\sim 60-70^{\circ}$ S and ~ 55 _km (days 201-204), respectively.

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EP flux of E3 is similar to that of E2. The instability and appropriate background wind at the mid-high latitudes between ~50 km and ~70 km dramatically amplify the propagation of E3, which is enhanced by the interaction near the critical layer (~29 h) and the positive refractive index region. (Figures 6i and 6j). Notably, It is worth noting that the strong instability and weak background wind at ~50-60°S and ~60-70 km on days 151-154 provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere, and ultimately point towardtowards the equator at 50 km. During days 201-204, the The EP flux propagatespropagate tointo the lower atmosphere during days $\frac{201-204}{1}$, and isgets amplified by interaction at the critical layer (~29 h). BesidesIn addition, weak instability and weak background wind at ~50-60°S and ~60-70 km provide the energy to amplify the E3 propagation. Combine with Figure Figures 6c, 6d indicate that, the stronger the instability at ~50-60°S and ~60-70 km, the stronger the temperature amplitude of E3. We believe that the background wind and instability at ~50-60°S and ~60-70 km are the mainprimary reasons for the propagation and amplification of EP flux into the lower atmosphere.

The For E4, the spectra appearare observed to be at ~48.2 km and

 \sim 50-60°S on days 127-130, and 213-216 for E4, when the eastward 421 wavenumber -4 signal with the wave period of ~25 h and ~21 h, as shown 422 in Figure (see Figures 7a, 7b). The corresponding temperature spatial 423 structures of these E4 (i.e., ~25 h and ~21 h) are—is shown in 424 Figures Figure 7c, 7d. The temperature spatial structure of E4 shows an 425 obvious amplitude bimodal structure at ~50-60°S and ~50 km, and 426 \sim 50-60°S and \sim 60 km, with the maximum at \sim 50-60°S and \sim 50 km. The 427 maximum temperature amplitude of E4 occurs at ~50 km and ~50-60°S 428 with an amplitude of \sim 4 K on the days 127-130, and the other peak is \sim 3 429 K (\sim 60-70°S and \sim 60 km). The temperature amplitude of \sim 3 K occurs at 430 ~50 km (~60 km) during days 213-216. The corresponding spatial 431 432 structures of zonal wind and meridional wind of these E4 are presentedis shown in Figures 7e, 7f, $7g_7$ and 7h. The zonal wind spatial structure of 433 E4 shows an obvious amplitude bimodal structure at ~50-60°S and ~55 434 km, and $\sim 60-70^{\circ} S$ and ~ 55 _km, with the maximum at $\sim 50-60^{\circ} S$ and ~ 55 435 km. The maximum zonal wind amplitude of E4 happensoccurs at 436 \sim 50-60°S and \sim 55 km with an amplitude of \sim 9 m/s on days 127-130, and 437 the other peak is $\sim 5 \text{K}$ ($\sim 60-70^{\circ} \text{S}$ and $\sim 55 \text{ km}$). The zonal wind amplitude 438 of ~ 5 m/s occurs at $\sim 50-60$ °S ($\sim 60-70$ °S) and ~ 55 km on days 213-216. 439 The amplitude of E4 meridional wind reaches ~8 m/s at ~60-70°S and 440 \sim 55 km (days 127-130) and \sim 10 m/s at \sim 60-70°S and \sim 55 km (days 441 213-216), respectively. 442

Figures 7i and 7i show dDiagnostic analysis for E4 on days 127-130, and 213-216 for E4 are shown in Figures 7i and 7j, respectively. The results demonstrateshow that E4 is dramatically amplified by the mean flow instabilities at the middle-high latitudes between ~50 km and ~70 km, with. With EP flux propagating into the lower atmosphere, and EP fluxit finally propagates eventually propagate toward the equator at ~50 km. E4 is amplified and propagated by the wave-mean flow interaction near the critical layer (\sim 25 h, \sim 21 h), and the positive refractive index region generatesprovides the promoting effect. The strong instability and weak background wind at ~50-60°S and ~60-70 km provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere during days 127-130. Besides, E4 obtains energy from weak instability and weak background wind at ~50-60°S and ~60-70 km on days 213-216, and it is amplified and propagated into the lower atmosphere. The background wind at ~50-60°S and ~60-70 km on days 127-130 is similar to on days 213-216, and the instability at ~50-60°S and ~60-70 km is stronger on days 127-30 than on days 213-216. According to Figures Figure 7a, and 7b, results shows that E4 absorbs has absorbed sufficient energy to be amplified under the background conditions on days 127-130, and. The the temperature amplitude on 127-130 days is stronger.

3.2 In the Northern Hemisphere

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Figure 8 shows that the observed maximum amplitude appears at is observed to be ~59.2 km and ~70-80°N for E1, and the E2 and E3 peaks at ~59.2 km and ~60-70°N. The maximum perturbation of E1 occursis observed to be at on days 41-50 (with an amplitude of ~8K), whileand the remaining fluctuations occurfluctuation occur on days 25-34, and 339-348. Besides, the strongest E2 occurs on days 69-74 (with an amplitude of ~ 7 K), and the rest are distributed on days 25-30, 317-322, and 341-346, while. By contrast, the E3 maximizes onat days 35-38 (with an amplitude of $\sim 3K$), and also shows a peakone peaks at on days 53-56. Based on the study of the wave period in the SH for eastward wave, the periodic variabilities of E1, E2 and E3variability in the NH for E1, E2, and E3 is are also examined investigated. The wave period periods of E1 decreasesdecreased from a maximum of ~118 h (days 25-34) to ~80 h (days 41-50), indicating the instability of that the wave period of E1 is unstable in the NH. The E2 events occur on days 25-30, 69-74, 317-322, and 341-346, of which the corresponding wave periods are ~ 36 , ~ 53 , ~ 52 , and ~48 h, which are stronger and more stable than E1. Besides, the wave period of E3 is relatively stable at ~29 h and ~27 h. Thus, E2 and E3 wave periods are more stable than E1. spectra, spatial (vertical and latitudinal) structures of temperature, zonal and meridional wind, and diagnostic analysis of E1 are extracted from the corresponding representative events (-as shown in

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Figure 9). Figures 9a and 9b show the observed spectra of E1 at ~59.2 km 487 and ~70-80°N on days 25-34 and 41-50, and the wave periodsperiod of 488 locked wavenumber -1 isare ~118 h and ~80 h, respectively. The 489 corresponding temperature spatial structures of these E1 (~118 h and ~80 490 h) areis shown in Figures Figure 9c, 9d. The temperature spatial structure 491 of E1 shows an obvious amplitude bimodal structure during days 25-34 at 492 \sim 60-70°N and \sim 60 km, and \sim 40-50°N and \sim 70 km, with the maximum at 493 ~60-70°N and ~60_km. On top of that Besides, E1 also has bimodal 494 structure on days 41-50 at \sim 60-70°N and \sim 60 km, and \sim 60-70°N and \sim 70 495 km. The strongest temperature amplitude of E1 occurs at ~60-70°N and 496 \sim 60 km with an amplitude of \sim 7 K on the days 25-34, and the other peak 497 is ~ 4 K ($\sim 40-50$ °N and ~ 70 km). The temperature amplitude of ~ 10 K 498 occurs at ~60 km and ~60-70°N during days 41-50, and the rest is ~8 K 499 (~60-70°N and ~70_km). The corresponding spatial structures of zonal 500 wind and meridional wind of these E1 are illustratedis shown in Figures 501 9e, 9f, 9g₇ and 9h. The zonal wind spatial structure of E1 presentsshows 502 an obvious amplitude bimodal structure at ~70-80°N and ~70 km, and 503 \sim 50-60°N and \sim 70 km. The zonal wind amplitude of \sim 13 m/s occurs at 504 \sim 70-80°N and \sim 70_km on days 25-34, and the rest is \sim 10 m/s (\sim 50-60°N 505 and ~70 km). In addition, there is a weak peak of 9K during days 25-34 506 $(\sim 30-40^{\circ} \text{N} \text{ and } \sim 70^{\circ} \text{km})$. The maximum zonal wind amplitude of E1 507 occurs at ~70-80°N and ~70 km with an amplitude of ~19 m/s on days 508

41-50, and the other peak is \sim 13K (\sim 50-60°N and \sim 70_km). The amplitude of E1 meridional wind <u>hitsreaches</u> \sim 14 m/s at \sim 70-80°N and \sim 70_km (days 25-34) and \sim 22 m/s at \sim 70-80°N and \sim 70_km (days 41-50), respectively.

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The diagnostic analysis results for E1 (in Figures 9i and 9i) suggestshow the dramatic amplification ofthat E1 is dramatically amplified by the mean flow instabilities at the middle-high latitudes between ~50_km and ~70_km, with. With the propagation of EP flux propagating into the polar lower atmosphere, and EP fluxit eventually propagatespropagate toward the equator at ~50 km. The wave-mean flow interaction near the critical layers (~118 h, ~80 h) amplifies and propagates E1, and the promoting effect of the positive refractive index region amplifies E1. Furthermore Besides, the weak instability and strong background wind at ~40-50°N and ~60-70 km generate the provide energy for the propagation and amplification of EP flux into the polar lower atmosphere during days 25-34. The E1 obtains sufficient energy from weak instability and suitable background wind on days 41-50 at ~40-50°N and ~60-70 km, and is amplified and propagated into the polar lower atmosphere through the critical layer and positive refractive index action. The background wind at ~40-50°N and ~60-70 km is stronger on days 25-34 than on days 41-50, but their instability is similar, indicating that stronger background winds might weakenmay be unfavorable to E1

propagation and amplification at the mid-northern latitudes. According to 531 Figure 9a, 9bOur results showshows that E1 absorbshas absorbed 532 sufficient adequate energy to be amplified under the background 533 conditions during days 41-50, reflectingshowing a stronger temperature 534 amplitude (see Figures 9a, 9b). 535 For E2, the The spectra are observed to be at ~59.2 km and ~60-70°N 536 on days 25-30, and 69-74 for E2, when the eastward wavenumber -2 537 signal with the period of ~36 h and ~53 h_z (as shown in Figures Figure 10a, 538 10b). The corresponding temperature spatial structures of these E2 (i.e., 539 ~36 h and ~53 h) are presented is shown in Figures Figure 10c, 10d. The 540 temperature spatial structure of E2 demonstratesshows an obvious 541 amplitude bimodal structure at ~60-70°N and ~60 km, and ~60-70°N and 542 \sim 70 km, with the maximum at \sim 60-70°N and \sim 60 km. The maximum 543 temperature amplitude of E2 occurs at ~60-70°N and ~60 km with an 544 amplitude of ~5 K on days 25-30, and the other peak is ~4 K (~60-70°N 545 and ~70 km). The temperature amplitude of ~9 K occurs on days 69-74 at 546 $\sim 60^{\circ}$ S and ~ 60 km, and the other peaks are ~ 7 K ($\sim 60-70^{\circ}$ N and ~ 70 km), 547 ~5 K (~60-70°N and ~50 km). The corresponding spatial structures of 548 zonal wind and meridional wind of these E2 isare shown in Figures 10e, 549 10f, $10g_{\bar{z}}$ and 10h. The zonal wind spatial structure of E2 shows an 550 obvious amplitude bimodal structure at ~60-70°N and ~60_km, and 551 \sim 40-50°N and \sim 60 km, with the maximum at \sim 40-50°N and \sim 60 km. The 552

maximum zonal wind amplitude of E2 appearsoccurs at ~60-70°N and 553 $\sim 60 \text{ km} (\sim 40-50^{\circ} \text{N} \text{ and } \sim 60 \text{ km})$ with an amplitude of $\sim 6 \text{ m/s}$ on days 554 25-30. Zonal wind amplitude occurs at ~40-50°N and ~60 km with an 555 amplitude of ~18 m/s on days 41-50, and the other peak is ~16 K 556 (\sim 60-70°N and \sim 60km). The amplitude of E2 meridional wind reaches \sim 7 557 m/s at $\sim 60-70$ °N and ~ 70 km (days 25-30) and ~ 18 m/s at $\sim 60-70$ °N and 558 \sim 60 km (days 41-50), respectively. 559 Figures 10i and 10j show The diagnostic analysis of E2 on days 560 25-30, and 69-74 are shown in Figures 10i and 10j, respectively for E2. It 561 is clear that Apparently, E2 is significantly dramatically amplified by the 562 mean flow instabilities at the middle-high latitudes between ~40 km and 563 ~70 km, with EP flux propagating into the polar lower atmosphere, and 564 EP flux eventually propagate toward the equator at ~50 km. E2 is 565 amplified and propagated by the wave-mean flow interaction near the 566 critical layers (~36 h, ~53 h), and the positive refractive index region 567 provides the promoting effect. The weak instability and strong 568 background wind at ~50-60°N and ~60-70 km provide the energy for the 569 propagation and amplification of EP flux into the polar lower atmosphere 570 during days 25-30. Moreover Besides, E2 obtains sufficient energy from 571 strong instability and suitable background wind at ~50-60°N and ~60-70 572 km on days 69-74, and it is amplified and propagated into the polar lower 573 atmosphere. The background wind at ~50-60°N and ~60-70 km on days 574

127-130 is similar to on days 213-216, and the instability at ~50-60°S and ~60-70_km is stronger on days 127-30 than on days 213-216.

Although The the background wind at ~50-60°N and ~60-70_km is stronger on days 25-30 than on days 69-74, but the instability at ~50-60°N and ~60-70_km is stronger on days 69-74 than on days 25-30.

According to Figure 10a, 10b The temperature amplitude results indicates hows that E2 absorbs has absorbed sufficient energy to be amplified under the background conditions on days 69-74, with stronger the temperature amplitude on days 69-74 is stronger (Figures 10a, 10b).

Figures 11a and 11b show the observed spectra of E3 at ~59.2km and ~60-70°N on days 35-38 and 53-56, and the wave periodsperiod of locked wavenumber -3 isare ~29_h and ~27_h, respectively. The corresponding temperature spatial structures of these E3 (i.e., ~29 h and ~27 h) areis shown in FiguresFigure 11c, 11d. The temperature spatial structure of E3 shows an obvious amplitude bimodal structure at ~50-60°N and ~60_km, and ~50-60°N and ~70_km, with the maximum at ~50-60°N and ~60_km. The strongest temperature amplitude of E3 occurs at ~60_km and ~50-60°N with an amplitude of ~6_K on the days 35-38, and the other peak is ~5_K (~50-60°N and ~70_km). The temperature amplitude of ~4_K occurs at ~60_km (~70_km) and ~50-60°N during days 53-56. The corresponding spatial structures of zonal wind and meridional

wind of these E3 are illustratedis shown in Figures 6e, 6f, 6g₅ and 6h. The zonal wind spatial structure of E3 shows an obvious amplitude bimodal structure at ~40-50°N and ~70_km, and ~60-70°N and ~70_km. The zonal wind amplitudes of E3 occur at ~40-50°N and ~70_km with an amplitude of ~15 m/s on days 35-38, and ~12 m/s at ~60-70°N and ~70_km. The maximum zonal wind amplitude of E3 appearsoccurs at ~40-50°N and ~70_km (~60-70°N and ~70_km) with an amplitude of ~7 m/s (~6 m/s) on days 53-56. The amplitude of E3 meridional wind reaches ~22 m/s at ~50-60°N and ~70_km (days 35-38) and ~12 m/s at ~60-70°N and ~70_km (days 53-56), respectively.

Obviously, the instability and appropriate background wind at the

Obviously, the instability and appropriate background wind at the mid-latitudesmid-latitude between ~50 km and ~70 km and the interaction near the critical layers (~29 h, ~27 h) dramatically amplify the propagation of E3, as shown in (see Figures 11i and 11j). The background wind is similar on days 35-38 and 53-56, and the former is relativelymore unstable. This finding indicates that the E3 in propagation is more likely to gatherget sufficient energy to be amplified on days 35-38. The instability and appropriate background wind at the mid-high latitudes between ~50 km and ~70 km drasticallydramatically amplify the propagation of E3, which is enhanced by the interaction near the critical layers (~29 h, ~27 h) and the positive refractive index region-(FiguresFigure 11i, 11j). In particular, It is worth noting that the strong

instability and weak background wind at ~50-60°N and ~60-70_km on days 35-38 generateprovide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere, and ultimately point towardtowards the equator at 50_km. The EP flux propagatespropagate to the lower atmosphere during days 35-38, and it is amplified by interactions at the critical layer (~29 h). In addition, weak instability and weak background winds on days 53-56 at ~50-60°N and ~60-70_km provide the energy to amplify E3 propagation. Combine with FiguresFigure 11c, 11d, the stronger the instability at ~50-60°N and ~60-70_km, the stronger the temperature amplitude of E3. The results show that the instability on days 35-38 at ~50-60°N and ~60-70_km are the primary reasons for the propagation and amplification of EP flux into the lower atmosphere.

3.3 Comparison between SH and NH

The observed latitude and maximum amplitude for eastward planetary waves (i.e., E1, E2, E3, E4) decrease and weaken with increasing zonal wavenumber in the SH, reaching ~70-80°S, ~60-70°S, ~60-70°S, and ~50-60°S, and ~10_K, ~9_K, ~6_K, and ~3_K, respectively. In addition, the occurrence date getsis earlier with increasing zonal wavenumber. The temperature spatial structure demonstrates about a bimodal-peak structure (~50 and ~60_km), mainlyprimarily located at ~50 km. The maximum zonal wind amplitudes of E1 and E2, E3 and E4 are

almost the <u>samcequivalents</u>, which are ~20 m/s and ~10 m/s₂ respectively. The maximum meridional wind amplitudes of E1, E2, E3 and E4 are ~17 m/s, ~27 m/s, ~16 m/s₇ and ~11 m/s₂ respectively. The wave period of E1 tends to get shorter from 5 to 3 days₂₅ while E2 and E3 are close to ~40 h and ~30 h₂₇ and while E4 remains at ~24 h. E1, E2, E3₇ and E4 are more favorable to propagation in the SH winter and are <u>abruptlydramatically</u> amplified by the mean flow instabilities at <u>the middle latitudes between</u> ~40 km and ~70 km₅ with. With the propagation of EP flux propagating into the lower atmosphere, and <u>it finally propagatesEP flux eventually propagate</u> toward the equator at ~50 km. In addition, the propagation of EP flux for E1 to the upper atmosphere <u>mightmay</u> be influenced by the instability and background wind at the Antarctic ~50km.

The observed latitudes of E1, E2 (E3) decrease with increasing wavenumber in the NH, which are ~70-80°N, ~60-70°N; and ~60-70°N. With bimodal-peak structure located at ~70 km, the The temperature spatial structures structure of E1, E2; and E3 presents a bimodal-peak structure, primarily located at ~70km, reaches reach ~10 K, ~9 K; and ~6 K, respectively. The maximum zonal wind amplitude for E1, E2 and E3 occur occurs at ~50-80°N and ~70 km, and their amplitude are almost equal to ~18 m/s. The maximum meridional windswind of E1, E2 and E3 occur at ~50-80°N and ~70 km; with amplitudes of ~22 m/s, ~18 m/s and ~22 m/s, respectively. The wave period of E1 tends to be shorter from 5-3

days; and E2 and E3 are close to ~48 h and ~30 h. In addition, E1, E2, and E3 are more favorable to propagation in the NH winter and are dramatically amplified by the mean flow instabilities at the middle latitudes between ~40 km and ~70 km, with the propagation of EP flux propagating into the lower atmosphere and then, and EP flux eventually propagate toward the equator at ~50 km.

4 Summary and Conclusions

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Based on the MERRA-2 temperature and wind observations in 2019, weWe present for the first time an extensive study of the global variation for eastward planetary wave activity, including zonal wave numbers of -1 (E1), -2 (E2), -3 (E3), -4 (E4), in the stratosphere and mesosphere. using the MERRA-2 temperature and wind observations in 2019. The temperature and wind amplitude amplitudes and wave periods of each event were determined using by 2-D least-squares fitting. Our study coveredincludes the spatial and temporal patternsbehaviors of the eastward planetary waves in both hemispheres with a comprehensive diagnostic analysis on their propagation and amplification. The key findings of thisthe study are summarized belowas follows: 1. The latitudes for the maximum (temperature, zonal and meridional wind) amplitudes of E1, E2, E3, and E4 decrease with increasing wavenumber in the SH and NH. The E1, E2, E3, and E4 events occur

earlier with increasing zonal wavenumber in the SH. In addition,

- eastward wave modes exist during summer periods with westward background wind in both hemispheres.
- 2. The temperature spatial structures of E1, E2, E3, and E4 present a
- double-peak structure, which is located at ~50 km and ~60 km in SH, ~60
- 689 km₇ and ~ 70 km in SH. Furthermore In addition, the lower peak is usually
- larger than the higher one.
- 691 3. The maximum (temperature, zonal and meridional wind)
- 692 amplitude amplitudes of E1, E2, and E3 declinedecrease with
- 693 risinginereasing zonal wavenumber in the SH and NH. The maximum
- temperature amplitude in the SH are slightly larger and lie
- lower than those in the NH. In addition, the meridional wind
- amplitude amplitudes are slightly larger than the zonal wind in the SH and
- 697 NH.
- 698 4. The wave period of the E1 mode <u>ranges varies from 3 to 3-5</u> days in
- both hemispheres, while the period of E2 mode is slightly longer in the
- NH (~48 h) than in the SH (~40 h). The periods of E3 are ~30 h in both
- SH and NH are $\sim 30 \text{ h}$, while and the period of E4 is $\sim 24 \text{ h}$.
- 702 5. The eastward planetary wave is more favorable to propagate in the
- winter hemisphere and is <u>drastically</u> amplified by the mean
- flow instabilities and appropriate background winds at polar region and
- the middle latitudes between ~40 km and ~80 km. Furthermore, the
- amplification of planetary waves through wave-mean flow interaction

occursmost easily occurs nearclose to its critical layer. In addition, the 707 direction of EP flux ultimately points towards the equator. 708 6. The strong instability and appropriate background wind in the lower 709 layer of the Antarctic region might generate adequatemay provide 710 sufficient energy to promote the E1 propagation and amplification to the 711 upper atmosphere. 712 Overall, this study demonstrated This study demonstrates how the 713 background zonal wind in the polar middle atmosphere affects the 714 dynamics of eastward planetary waves in the polar middle atmosphere. 715 716

availability. MERRA-2 data available Data 718 are at http://disc.gsfc.nasa.gov. 719 720 Code availability. Code is available 721 at http://hdl.pid21.cn/21.86116.7/04.99.01293. 722 723 Author contributions. LT carried out the data processing and analysis and 724 wrote the manuscript. SYG and XKD contributed to reviewing the article. 725 726 Competing interests. The authors declare that they have no conflict of 727 interest. 728 729 Acknowledgements. This work was performed in the framework of the 730 Space Physics Research (SPR). The authors thank NASA for free online 731 access to the MERRA-2 temperature reanalysis. 732 733 Financial support. This research work was supported by the National 734 Natural Science Foundation of China (41704153, 41874181, and 735 41831071). 736

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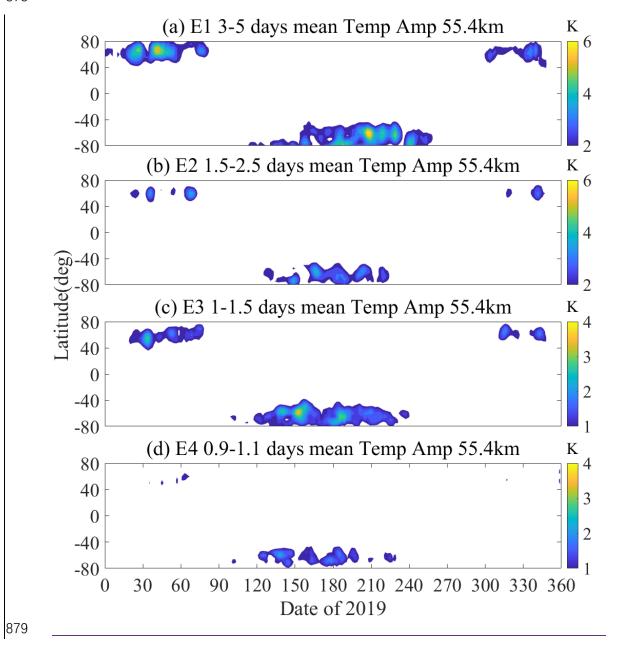


Figure 1. The global latitude-temporal variation structures of the (a) E1, (b) E2, (c) E3, and (d) E4 planetary waves during 2019. White areas represent small amplitude data (corresponds to the right color bar). The confidence interval is 0.95.

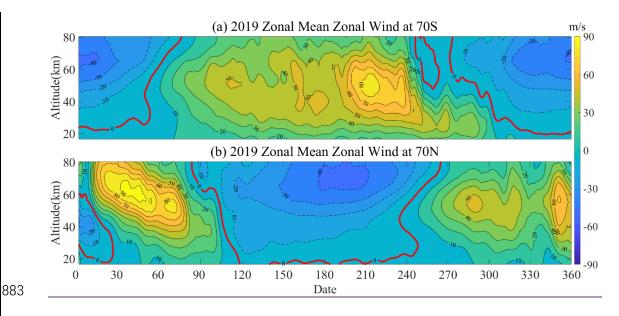


Figure 2. The zonal mean zonal wind variations of the (a) the 70°S and (b) 70°N during 2019. The dotted line represents east wind, the solid line represents west wind, and the red solid line is 0 m/s.

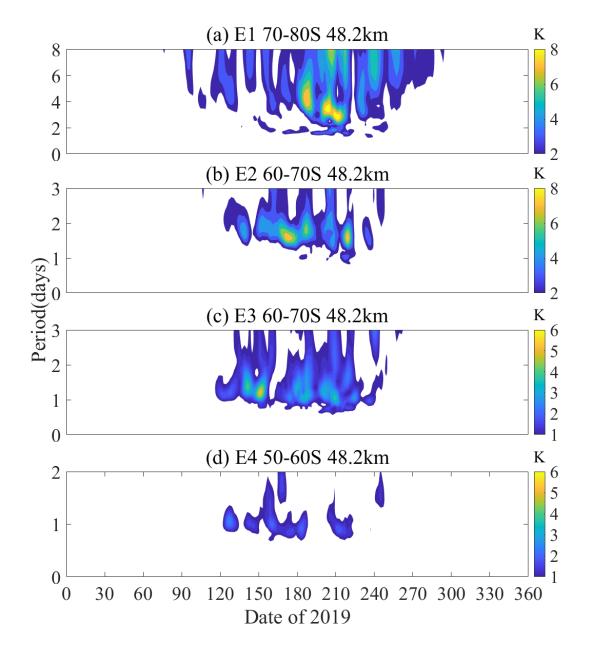


Figure 3. The temporal variations of the (a) E1, (b) E2, (c) E3, and (d) E4 QTDWs during 2019 austral winter period.

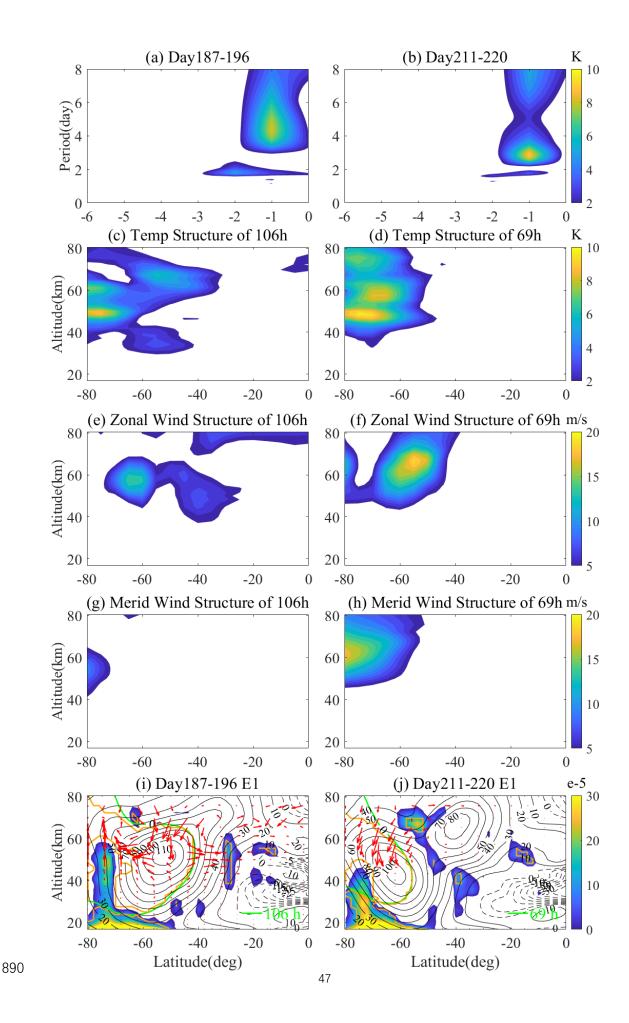


Figure 4. The (a, b) spectra, (c, d) temperature spatial structures, (e, f) zonal wind spatial structures, (g, h) meridional wind spatial structures, and (i, j) diagnostic analysis of the E1 typical events during 2019 austral winter period. The MERRA-2 temperature data observations at 48.2 km and 70-80°S during days 187–196 (Figure 4a), 211–220 (Figure 4d) are utilized, respectively. The instability (blue shaded region), EP fluxes (red arrow), and critical layers (green line) for E1 typical event. The green line represents critical layers of the E1 with the natural period. Regions enclosed by orange solid lines are characterized by the positive refractive index for the E1.

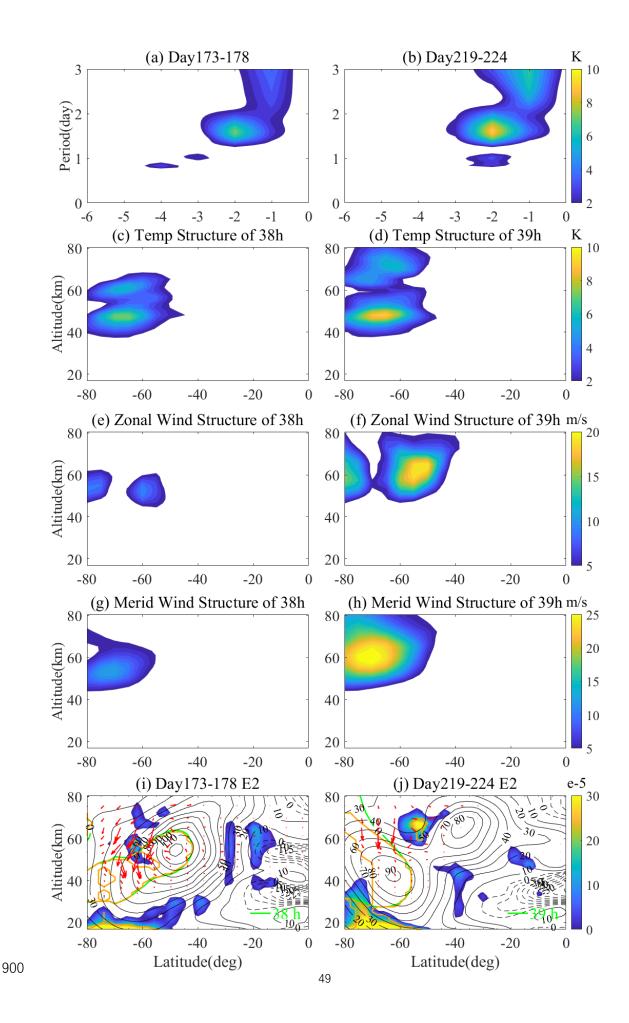


Figure 5. The same Same as Figure 4 but for the E2 during the 2019 austral winter 902 period.

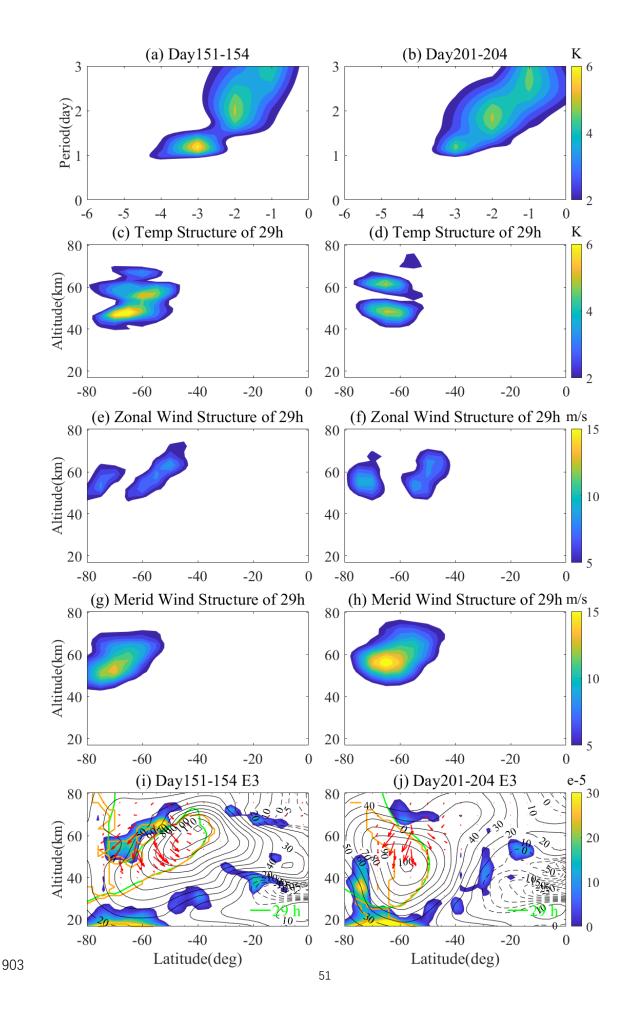


Figure 6. The same Same as Figure 4 but for the E3 during the 2019 austral winter period.

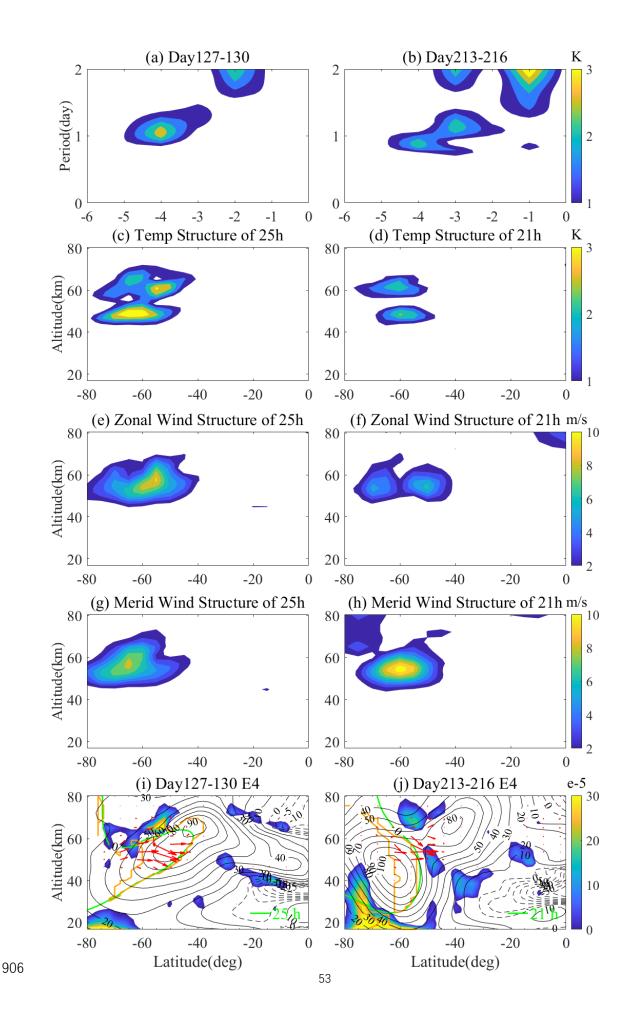


Figure 7. The same Same as Figure 4 but for the E4 during the 2019 austral winter period.

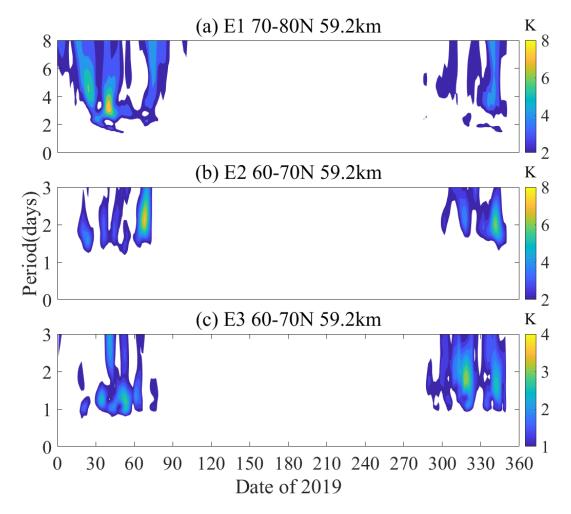


Figure 8. The temporal variations of the (a) E1, (b) E2, and (c) E3 QTDWs during the 2019 boreal winter period.

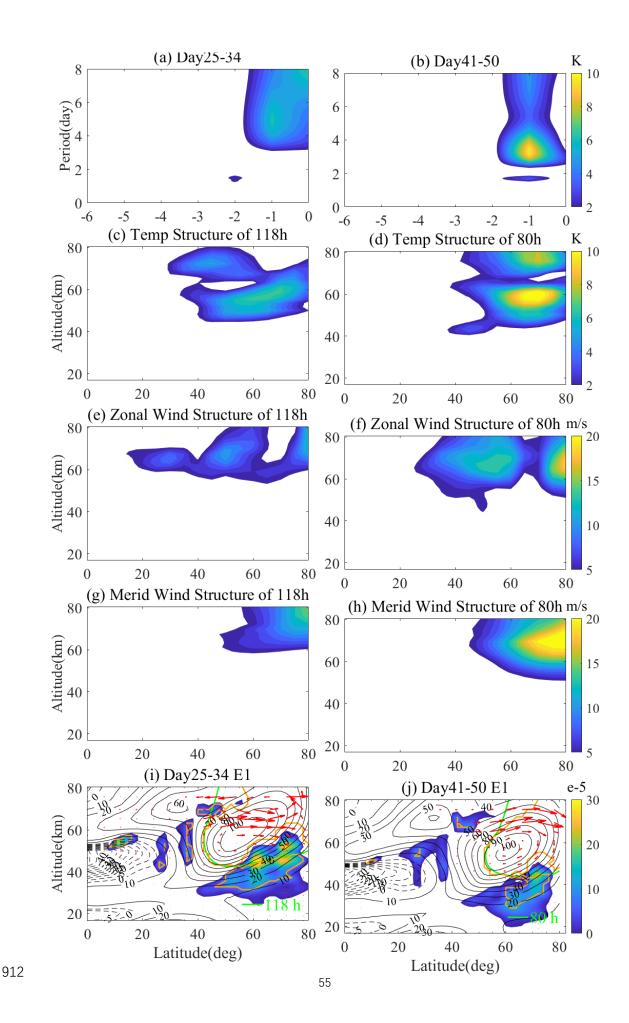


Figure 9. heThe (a, b) spectra, (c, d) temperature spatial structures, (e, f) zonal wind spatial structures, (g, h) meridional wind spatial structures, and (i, j) diagnostic analysis of the E1 typical events during 2019 boreal winter period. The E1 events at 48.2 km and 70-80°N were obtained from the MERRA-2 reanalysis.

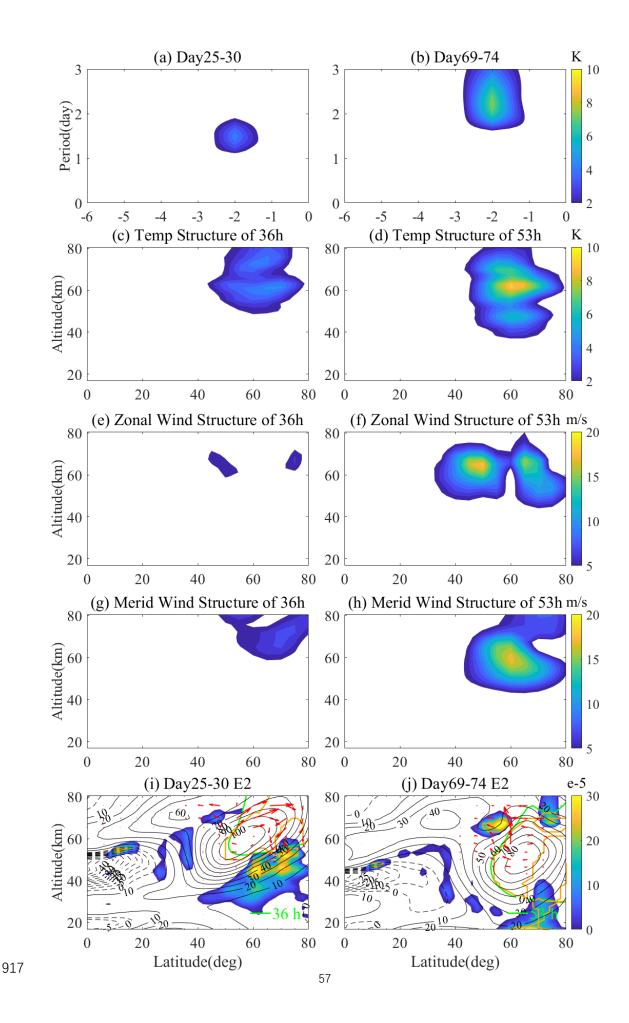


Figure 10. The same Same as Figure 9 but for the E2 during the 2019 boreal winter

919 period.

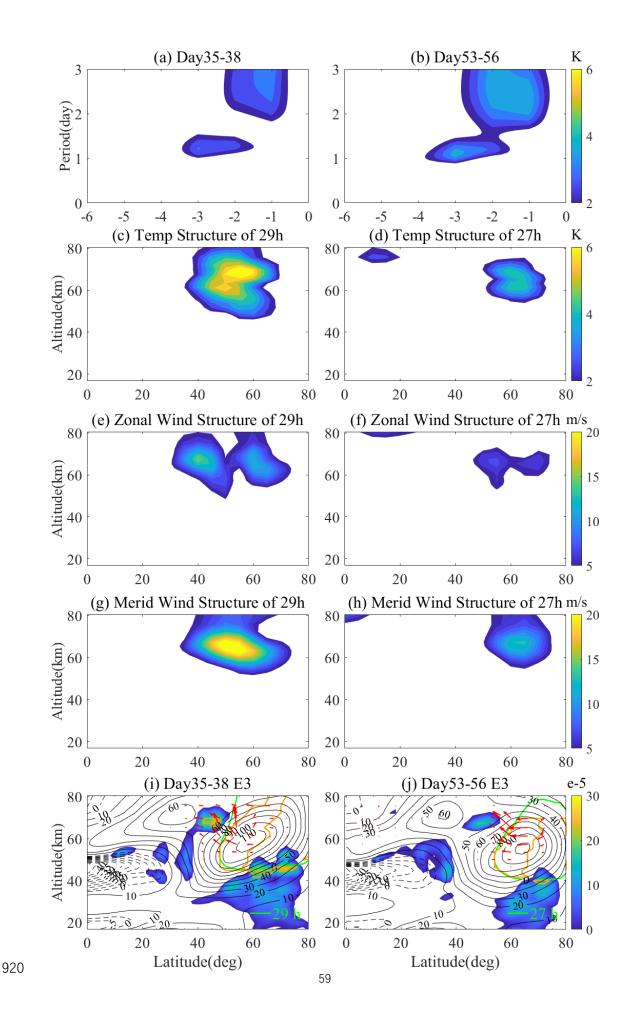


Figure 11. The same Same as Figure 9 but for the E3 during the 2019 boreal winter period.

Eastward-propagating planetary wave in the polar

2 middle atmosphere

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Abstract. According to MERRA-2 temperature and wind datasets in 9 2019, this study presented the global variations of the eastward 10 propagating wavenumber 1 (E1), 2 (E2), 3 (E3) and 4 (E4) planetary 11 waves (PWs) and their diagnostic results in the polar middle atmosphere. 12 We clearly demonstrated the eastward wave modes exist during winter 13 periods with westward background wind in both hemispheres. The 14 maximum wave amplitudes in the southern hemisphere (SH) are slightly 15 larger and lie lower than those in the northern hemisphere (NH). 16 Moreover, the wave perturbations peak at lower latitudes with smaller 17 amplitude as the wavenumber increases. The period of the E1 mode 18 varies 3-5 days in both hemispheres, while the period of E2 mode is 19 slightly longer in the NH (~48 h) than in the SH (~40 h). The periods of 20 the E3 are ~30 h in both SH and NH, and the period of E4 is ~24 h. 21 Despite the shortening of wave periods with the increase of wavenumber, 22 their mean phase speeds are relatively stable, which are ~53 m/s, ~58 m/s, 23 ~55 m/s and ~52 m/s at 70° latitudes for W1, W2, W3 and W4, 24 respectively. The eastward PWs occur earlier with increasing zonal 25 wavenumber, which agrees well with the seasonal variations of the 26 critical layers generated by the background wind. Our diagnostic analysis 27 also indicated that the mean flow instability in the upper stratosphere and 28 upper mesosphere might contribute to the amplification of the eastward 29 PWs. 30

1 Introduction

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The dominance of large amplitude planetary waves in the 32 stratosphere, mesosphere and lower thermosphere regions and their 33 interactions with zonal mean winds are the primary driving force of 34 atmospheric dynamics. In addition, sudden stratospheric warmings 35 (SSWs) and quasi-biennial oscillation (QBO) events can dynamically 36 couple the entire atmosphere from the lower atmosphere to the 37 ionosphere (Li et al., 2020; Yamazaki et al., 2020; Yadav et al., 2019; 38 Matthias and Ern, 2018; Stray et al., 2015). Westward propagating 39 planetary wave is one of the prominent features during austral and boreal 40 summer. Westward quasi-2-day waves (Q2DWs) are the most obvious 41 representative waves and one of the most investigated phenomena using 42 planetary wave observations. Most of the previous studies focused on the 43 westward propagating Q2DWs, i.e., zonal wavenumbers of 2 (W2), 3 44 (W3) and 4 (W4) modes (Lainer et al., 2018; Gu et al., 2018b; Wang et al., 45 2017; Pancheva et al., 2016; Gu et al., 2016a; Gu et al., 2016b; Lilienthal 46 and Jacobi, 2015; Gu et al., 2013; Limpasuvan and Wu, 2009; Salby, 47 1981). However, limited studies were conducted to understand the 48 seasonal variations of the occurrence date, peak amplitude and wave 49 period for the eastward Q2DWs (Gu et al., 2017; Lu et al., 2013; 50 Alexander and Shepherd, 2010; Sandford et al., 2008; Palo et al., 2007; 51 Merzlyakov and Pancheva, 2007; Manney and Randel, 1993; Venne and 52

Stanford, 1979).

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Typically, Q2DWs maximize after the summer solstice in the middle 54 latitudes. The largest wave amplitudes generally appear near the 55 mesopause in January–February in the Southern Hemisphere (SH), while 56 in the Northern Hemisphere (NH) in July–August (Tunbridge et al., 2011). 57 W3 and W4 Q2DWs reach amplitudes during austral and boreal summer 58 in the mesosphere and lower thermosphere, respectively. The seasonal 59 variation of westward Q2DWs activity is obvious (Liu et al., 2019; Gu et 60 al., 2018b; Rao et al., 2017). By observing the long-term Q2DW in the 61 NH and SH, Tunbridge et al. (2011) reported that W3 is generally 62 stronger than the other two modes in the SH, reaching the amplitude of 63 64 ~12K; while W4 is stronger than W3 in the NH, reaching ~4K. Moreover, W4 generally lives longer than W3, and W4 can still be observed after the 65 ending of W3. A previous study has demonstrated that wave source, 66 instability, critical layer and mean zonal wind are the primary reasons for 67 the seasonal variation of Q2DWs (Liu et al., 2004). By studying the 68 long-term satellite datasets in the SH, Gu et al. (2019) suggested that the 69 strongest events of W2, W3 and W4 could be delayed with increasing the 70 zonal wavenumber, and these events would be indistinguishable during 71 SSWs. The wave periods of W4, W3 and W2 vary around ~41-56 h, 72 ~45-52 h, and ~45-48 h, respectively. Furthermore, W2 can be observed 73 using global satellite datasets, but it has an amplitude weaker than W3 74

and W4 in the NH and SH (Meek et al., 1996). The propagation and amplification of Q2DWs are primarily modulated by instability, refractive index and critical layer, while the variation of background wind may cause different zonal wavenumber events (Gu et al., 2016a; Gu et al., 2016b). By analyzing the variation of Q2DWs activity during SSWs, Xiong et al. (2018) noticed that W1 is generated by the nonlinear interaction between SPW2 and W3. During SSWs, the coupling between the NH and SH can enhance the summer easterly and promote the nonlinear interaction between W3 and SPW1 (Gu et al., 2018b).

Some recent studies have discovered significant eastward planetary waves in the polar stratosphere and mesosphere regions, with periods of nearly two and four days (Gu et al., 2017; Sandford et al., 2008; Merzlyakov and Pancheva, 2007; Coy et al., 2003; Manney and Randel, 1993). Planetary waves with zonal wavenumbers -1 (E1) and -2 (E2) correspond to 4- and 2-day waves, respectively. Furthermore, planetary waves of 1.2-day with wavenumber -3 (E3) and 0.8-day with wavenumber -4 (E4) have been reported to contain the same phase speeds as E1 and E2 (Manney and Randel, 1993). This series of eastward planetary wave can significantly affect the thermal and dynamic structure of the polar stratosphere, resulting in profound changes in the wind and temperature of the polar stratosphere (Coy et al., 2003; Venne and Stanford, 1979). Beyond the knowledge about nonlinear interactions

between migrating tides and Q2DWs (Palo et al., 1999), further investigation has confirmed that E2 Q2DW is ecouldoupled be generated by the nonlinear interaction between planetary wave and tides in the mesosphere and lower thermosphere (MLT) (Palo et al., 2007). We should note that the E2 Q2DW generated in the MLT region is different from that in the polar stratosphere, which is discussed in this paper.

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By studying and analyzing satellite datasets, Merzlyakov and Pancheva. (2007) indicated that the wave periods of E1 and E2 events range 1.5-5 days. They reported that EP flux travels from the upper to the lower atmosphere, meaning that the upper atmosphere has a dynamic influence on the lower atmosphere. Sandford et al. (2008) reported about significant fluctuations of E2 Q2DW in the polar mesosphere. They indicated the influence of changes in mean zonal winds during a major SSW on the propagation of polar E2. In addition, they proposed the significance of E2 fluctuation in the mesosphere driven by the instabilities in the polar night jet. For E2, amplitude of temperature, zonal wind and meridional wind during the austral winter can reach ~10 K, ~20 m/s and ~30 m/s, respectively; while those during the boreal winter can drop by almost two-thirds. Lu et al. (2013) found that eastward planetary wave propagation is limited to the winter high latitudes probably because the negative refractive indices equatorward of ~45°S result in evanescent wave characteristics. That study suggested that the instability region at ~50-60°S might be induced by the stratospheric polar night jet and/or the "double-jet" structure.

In this study, we use the second modern retrospective research and application analysis (MERRA-2) datasets to investigate the eastward propagating wave characteristics of the stratosphere and mesosphere in polar region in 2019, including E1, E2, E3 and E4. Specifically, we investigate the variation of the occurrence date, peak amplitude and wave period of eastward waves; as well as the role of instability, background wind structure and critical layer in the propagation and amplification of eastward waves. The remaining parts of this paper are organized as follows. Section 2 describes the data and methods used in this study. Section 3 analyzes the global latitude-temporal variation structure of eastward waves during winter in 2019. The amplification and propagation features of the eastward planetary waves in the NH and SH with different wavenumber events are examined in Sections 3.1 and 3.2, respectively. Section 3.3 compares and analyzes the eastward waves in the NH and SH. All research results are summarized in Section 4.

2 Data and Analysis

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To extract the E1-, E2-, E3- and E4-wave, we apply the least-square method to each time window (e.g., 10-day, 6-day, 4-day and 4-day), and then use time window to determine the amplitude. (Gu et al., 2013). This method has been shown to successfully identify planetary waves from

satellite measurements (Gu et al., 2019; Gu et al., 2018a; Gu et al., 2018b;

Gu et al., 2018c; Gu et al., 2013).

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$$y = A\cos[2\pi(\sigma \cdot t + s \cdot \lambda)] + B\sin[2\pi(\sigma \cdot t + s \cdot \lambda)] + C \tag{1}$$

The least-squares method is used to fit the a set of parameters (A, B and C), where σ , t, s and λ are the frequency, UT time, zonal wavenumber and longitudes. The amplitude of wave R can be expressed as $R = \sqrt{A^2 + B^2}$.

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The second modern retrospective research and application analysis (MERRA-2) covers the long-term atmospheric reanalysis datasets initiated by NASA in 1980. It has been upgraded recently using the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. Briefly, MERRA-2 includes some updates to the model (Molod et al., 2014; Molod et al., 2012) and the Global Statistical Interpolation (GSI) analysis scheme of Wu et al. (2002). The MERRA-2 data consist of various meteorological variables, e.g., net radiation, temperature, relative humidity and wind speed. The spatial coverage of MERRA-2 data is the globe (spatial resolution: 0.5°×0.625°; temporal resolution: 1 h). This meteorological data are widely used to detect the middle atmosphere such as the planetary wave in the polar atmosphere, global thermal tides, climate variability and aerosol (Ukhov et al., 2020; Sun et al., 2020; Bali et al., 2019; Lu et al., 2013). Many recent studies indicated the feasibility of using MERRA-2 data for the kind of research

in present study. Therefore, we apply the MERRA-2 datasets to obtain the variation in background wind, instability, refractive index and critical layer; and explore the patterns of eastward planetary waves propagation and amplification through diagnostic analysis.

The critical layer will absorb or reflect planetary waves from the lower atmosphere during upward propagation. Planetary waves that gain sufficient energy in the unstable region will be amplified during reflection. In a sense, the critical layer plays an important role in regulating the amplification and propagation of planetary waves (Gu et al., 2016a; Gu et al., 2016b; Liu et al., 2004).

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$$\overline{q_{\varphi}} = 2\Omega \cos \varphi - \left(\frac{\left(\overline{u}\cos\varphi\right)_{\varphi}}{a\cos\varphi}\right)_{\varphi} - \frac{a}{\rho}\left(\frac{f^2}{N^2}\rho\overline{u}_z\right)_z \tag{2}$$

The baroclinic/barotropic instability in the atmospheric space structure is caused by the simultaneous equalization of the negative latitude gradient and the quasi-geostrophic potential vorticity $(\overline{q_{\varphi}})$. In Equation (2), Ω is the angular speed of the Earth's rotation; φ is the latitude; \overline{u} is the zonal mean zonal wind; a is the Earth radius; ρ is the air density; f is the Coriolis parameter; N is the buoyancy frequency; subscripts z and φ are the vertical and latitudinal gradients.

According to Andrews et al. (1987), the properties of planetary wave propagation can be calculated using the Eliassen-Palm (EP) flux vectors (F), i.e.,

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$$F = \rho a \cos \varphi \left[\frac{\overline{u_z} \overline{v \theta}}{\overline{\theta_z}} - \overline{v u} \right]$$

$$\left[f - \frac{(\overline{u} \cos \varphi)_{\varphi}}{a \cos \varphi} \right] \frac{\overline{v \theta}}{\overline{\theta_z}} - \overline{w u}$$
(3)

where u and v are the planetary wave perturbations in the zonal and meridional wind, respectively; θ and w are the potential temperature and vertical wind, respectively. The planetary wave propagation is only favorable where the square of refractive index m^2 is positive:

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$$m^{2} = \frac{\overline{q_{\varphi}}}{a(\overline{u} - c)} - \frac{s^{2}}{(a\cos\varphi)^{2}} - \frac{f^{2}}{4N^{2}H^{2}}$$
 (4)

where s is the zonal wavenumber, c is the phase speed and H is the scale height. The square of the refractive index is taken as the waveguide of planetary waves, i.e.,

$$c = -v_0 \cos\left(\frac{\varphi \pi}{180}\right) / sT \tag{5}$$

where ν_0 is the equatorial linear velocity, ν_0 is the zonal wavenumber and ν_0 is the wave period.

3 Results and Discussion

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Figure 1 shows the global temporal-latitude variation structures of E1, E2, E3 and E4 extracted from the 2019 MERRA-2 temperature datasets using time windows 10-, 6-, 4- and 4-days, respectively. The mean temperature amplitude of E1, E2, E3 and E4 at 55.4 km during the periods 3~5-, 1.5~2.5-, 1~1.5- and 0.9~1.1-day are displayed in Figure 1a, 1b, 1c and 1d, respectively. Eastward waves are characterized by obvious

seasonal variations in the SH and NH. In addition, E1, E2 (E3) and E4 reach their maximum amplitude at 50-80°(S/N). In the SH, the strongest E1 and E2 events occur on days 209-218 and 167-172; while E3 and E4 events occur on days 151-154 and 139-142. This means that their occurrence date of maximum amplitude gets earlier with increasing zonal wavenumber. In addition, the maximum amplitude of E1, E2, E3 and E4 are ~6.0 K, ~4.2 K, ~3.6 K and ~2.4 K, respectively, indicating that their peak amplitude drop with rising zonal wavenumber. In the NH, the strongest E1, E2, E3 and E4 events occur on days 41-50, 69-74, 35-38 and 63-66, respectively; the corresponding peak amplitude are ~5.5 K, ~3.8 K, ~2.8 K and ~1.2 K, respectively. Whilst the results demonstrate the decline of the peak amplitude with increasing zonal wavenumber in the NH, the occurrence date is irregular. Moreover, E4 is relatively weak in the NH and difficult to find, so W4 is insignificant in the NH. Figure 2 presents the changes in zonal mean zonal wind at 70°S and 70°N in 2019. It can be seen that the background wind on days 90-240 (70°S) is dominated by westward wind, and reaches ~80 m/s at ~50 km on days 210; it is dominated by eastward wind in late and early 2019, and reaches ~-40 m/s at ~60 km. Meanwhile, the background wind is primarily westerly wind in late and early 2019 (70°N), and reaches ~90 m/s at ~60 km on days 50; while on days 120-240, the background wind is primarily easterly wind, and the amplitude reaches -40 m/s on days 200. Compared

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with Figure 1, the results show that the eastward wave modes exist during winter periods with westward background wind in both hemispheres.

3.1 In the Southern Hemisphere

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Figure 3 shows that observed maximum temperature amplitude is at 228 ~48.2 km and ~70-80°S for E1; ~48.2km and ~60-70°S for E2 and E3; 229 ~48.2km and ~50-60°S for E4. For E1, the observed maximum 230 perturbation occurs on days 211-220 (with an amplitude of ~8.5 K), and 231 the remaining fluctuations occur on days 161-170, 187-196 and 231-240. 232 For E2, the observed maximum perturbation happens at days 219-224 233 (with an amplitude of ~ 7.8 K), and three peaks appear on days 139-144, 234 173-178 and 187-192. Regarding E3, the strongest perturbation occurs on 235 days 151-154 (with an amplitude of ~5.2 K), while the rest are distributed 236 on days 141-144, 201-204 and 209-202. E4 perturbations are distributed 237 on days 127-130, 145-148, 161-164, 213-216, with weak amplitude of ~3 238 K. Since earlier studies mentioned that the wave period of the eastward 239 wave can vary, we also investigate the periodic variabilities of E1, E2, E3 240 and E4. The results show that the period corresponding to the maximum 241 perturbation of E1 falls between ~106 (days 187-196) and ~69 h (days 242 211-220), and their wave periods vary significantly. Nonetheless, the 243 wave period of E2 gradually changes from ~42 h (days 139-144) to ~38 h 244 (days 219-224), and its stability is stronger than that of E1. The wave 245 periods of E3 and E4 are about ~39 h and ~24 h, respectively. These 246

results reflect that E2, E3 and E4 wave periods are more stable compared to E1.

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spectra, spatial (vertical and latitudinal) structures of temperature, zonal and meridional wind, and diagnostic analysis of E1 are extracted from the two corresponding events (refer to Figure 4). Figures 4a, 4b show the least-squares fitting spectra for MERRA-2 temperature on days 187–196, 211-220 at ~48.2 km and ~70-80°S, when and where the E1 maximizes. An eastward wavenumber -1 signal with the periods of ~106 h and ~69 h clearly dominates the whole spectrum. The temperature spatial structures corresponding to these E1 (i.e., ~106 h and ~69 h) are displayed in Figures 4c, 4d. The temperature spatial structure of E1 exhibits obvious amplitude bimodal structure at ~70-80°S and ~50 km, and $\sim 70-80^{\circ}$ S and ~ 60 km, with the maximum at $\sim 70-80^{\circ}$ S and ~ 50 km. The strongest temperature amplitude of E1 occurs at ~50 km and \sim 70-80°S with an amplitude of \sim 10 K on the days 211-220, and the other peak is $\sim 9K$ ($\sim 70-80$ °S and ~ 60 km). The temperature amplitude of $\sim 9K$ occurs at ~ 50 km and $\sim 70-80$ °S during days 187-196, and the rest is ~ 7 K (~70-80°S and ~60 km). The corresponding spatial structures of zonal wind and meridional wind of these E1 are shown in Figures 4e, 4f, 4g and 4h. The maximum zonal wind amplitude of E1 occurs at ~60-70°S and \sim 60 km with an amplitude of \sim 14 m/s on days 187-196, and \sim 20 m/s at ~50-60°S and ~60 km on days 211-220. The amplitude of E1 meridional

wind hits \sim 10 m/s at \sim 70-80°S and \sim 55 km (days 187-196) and \sim 17 m/s at \sim 70-80°S and \sim 60 km (days 211-220), respectively.

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Figures 4i, 4j show the diagnostic analysis results for the E1 events during days 187–196 and 211–220, respectively. Apparently, the EP flux vectors is more favorable to propagate in the SH winter and is dramatically amplified by the mean flow instabilities and appropriate background winds at polar region and between ~40 km and ~80 km, with EP flux propagating into the upper atmosphere (Figure 4i). Meanwhile, there is an EP flux at the mid-latitudes and ~60-80 km, which propagates into the lower atmosphere. The wave-mean flow interaction near its critical layer (106 h) of the green curve amplifies E1, and the positive refractive index region surrounded by the yellow curve also enhances E1 propagation. In addition, the strong instability and weak background wind at ~70-80°S and ~40-60 km provide sufficient energy for the upward EP flux to propagate and amplify. Nevertheless, the downward propagating EP flux is amplified by weak instability and strong background wind at ~50-60°S and ~60-70 km. Besides, both upward and downward EP fluxes eventually propagate toward the equator at ~50 km. Figure 4j shows that EP flux on days 211-220 propagates downward and amplifies after the interaction of the critical layer (~69 h). The positive refractive index region, strong instability and weak background wind at ~50-60°S and ~60-70 km provide sufficient energy for E1 amplification and propagation, and ultimately point towards the equator at ~50 km. The results show that the weak background wind and strong instability in the polar region can promote the upward propagation and amplification of EP flux. Meanwhile, the appropriate background wind and instability in the mid-latitudes are also conducive to the downward propagation and amplification of EP flux. In other words, instability and appropriate background wind dominate the propagation and amplification of E1.

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For E2, the spectra are observed at ~48.2 km and ~60-70°S on days 173-178 and 219-224 when the eastward wavenumber -2 becomes the primary wave mode with the wave periods ~38 h and ~39 h, respectively (as shown in Figures 5a, 5b). The temperature spatial structures corresponding to these E2 (~38 h and ~39 h) are presented in Figures 5c, 5d. The temperature spatial structure of E2 shows an obvious amplitude bimodal structure at ~60-70°S and ~50 km, and ~60-70°S and ~60 km, with the maximum at \sim 60-70°S and \sim 50 km. The maximum temperature amplitude of E1 occurs at ~50 km and ~60-70°S with an amplitude of \sim 7.5 K on the days 173-178, and the other peak is \sim 6 K (\sim 70°S and \sim 60 km). The temperature amplitude of ~10 K happens at ~50 km and \sim 60-70°S during days 219-224, and the rest is \sim 6 K (\sim 70°S and \sim 60 km). The corresponding spatial structures of zonal wind and meridional wind of these E2 are illustrated in Figures 5e, 5f, 5g and 5h. The zonal wind spatial structure of E2 shows an obvious amplitude bimodal structure at

~50-60°S and ~60 km, and ~70-80°S and ~60 km, with the maximum at ~50-60°S and ~60 km. The maximum zonal wind amplitude of E2 appear at ~50-60°S and ~60 km with an amplitude of ~10 m/s on days 173-178, and the other peak is ~9 m/s (~70-80°S and ~60 km). The zonal wind amplitude of ~20 m/s occurs at ~50-60°S and ~60 km on days 219-224, and the rest is ~15 m/s (~70-80°S and ~60 km). The amplitude of E2 meridional wind reaches ~13 m/s at ~70-80°S and ~60 km (days 173-178) and ~27 m/s at ~70-80°S and ~60 km (days 219-224), respectively.

Figures 5i and 5j illustrate the diagnostic analysis during days 173-178 and 219-224 for E2, respectively. Obviously, E2 is more likely to propagate in the SH winter and is dramatically amplified by the mean flow instabilities at the middle-high latitudes between ~40 km and ~80 km. With EP flux propagating into the lower atmosphere, it eventually propagates toward the equator at ~50 km. Besides, E2 is amplified and propagated by the wave-mean flow interactions near its critical layer (~38) h) of the green curve, and the promoting effect of the positive refractive index region surrounded by the yellow curve. Meanwhile, the weak instability and strong background wind at ~50-60°S and ~50-70 km provide the energy for the propagation and amplification of EP flux into the lower atmosphere during days 173-178 (Figure 5i). According to the diagnostic analysis of days 219-224, E2 obtains sufficient energy from strong instability and strong background wind at ~50-60°S and ~60-70

km. It is amplified and propagated into the lower atmosphere through the critical layer and positive refractive index action (as shown in Figure 5j). The results show that the background wind at ~50-60°S and ~50-70 km is weaker on days 173-178 than on days 219-224; and the instability at ~50-60°S and ~60-70 km is stronger on days 219-224 than on days 173-178. Our results show that E2 has absorbed sufficient energy to be amplified under the background conditions during days 219-224 (Figures 5a, 5b).

Figures 6a and 6b show the observed spectra of E3 at ~48.2 km and ~60-70°S on days 151-154 and 201-204, and the wave periods of locked wavenumber -3 are ~29 h and ~29 h, respectively. The corresponding temperature spatial structures of these E3 (i.e., ~29 h and ~29 h) are displayed in Figures 6c, 6d. The temperature spatial structure of E3 shows an obvious amplitude bimodal structure at ~60-70°S and ~50 km, and ~60-70°S and ~60 km, with the maximum at ~60-70°S and ~50 km. Besides, E3 also has a weak peak at ~60-70°S and ~70 km. The strongest temperature amplitude of E3 occurs at ~50 km and ~60-70°S with an amplitude of ~6K on the days 151-154, and the other peak is ~5 K (~60-70°S and ~60 km). The temperature amplitude of ~5 K happens at ~50 km (~60 km) and ~60-70°S during days 201-204. The corresponding spatial structures of zonal wind and meridional wind of these E3 are shown in Figures 6e, 6f, 6g and 6h. The zonal wind spatial structure of E3

shows an obvious amplitude bimodal structure at \sim 70-80°S and \sim 60 km, and \sim 50-60°S and \sim 60 km. The zonal wind amplitudes of E3 occur at \sim 70-80°S and \sim 60 km (\sim 50-60°S and \sim 60 km) with an amplitude of \sim 9 m/s on days 151-154, and \sim 9 m/s at \sim 70-80°S and \sim 60 km (\sim 50-60°S and \sim 60 km) on days 201-204. The amplitude of E3 meridional wind hits \sim 13 m/s at \sim 60-70°S and \sim 55 km (days 151-154) and \sim 16 m/s at \sim 60-70°S and \sim 55 km (days 201-204), respectively.

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EP flux of E3 is similar to that of E2. The instability and appropriate background wind at the mid-high latitudes between ~50 km and ~70 km dramatically amplify the propagation of E3, which is enhanced by the interaction near the critical layer (~29 h) and the positive refractive index region (Figures 6i and 6j). Notably, the strong instability and weak background wind at ~50-60°S and ~60-70 km on days 151-154 provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere, and ultimately point toward the equator at 50 km. During days 201-204, the EP flux propagates into the lower atmosphere and gets amplified by interaction at the critical layer (~29 h). Besides, weak instability and weak background wind at ~50-60°S and ~60-70 km provide the energy to amplify the E3 propagation. Figures 6c 6d indicate that the stronger the instability at $\sim 50-60^{\circ}$ S and $\sim 60-70$ km, the stronger the temperature amplitude of E3. We believe that the background wind and instability at ~50-60°S and ~60-70 km are the main reasons for the

propagation and amplification of EP flux into the lower atmosphere.

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For E4, the spectra appear at ~48.2 km and ~50-60°S on days 380 127-130 and 213-216 when the eastward wavenumber -4 signal with the wave period of ~25 h and ~21 h (see Figures 7a, 7b). The corresponding 382 temperature spatial structures of these E4 (i.e., ~25 h and ~21 h) are shown in Figures 7c, 7d. The temperature spatial structure of E4 shows an 384 obvious amplitude bimodal structure at ~50-60°S and ~50 km, and 385 \sim 50-60°S and \sim 60 km, with the maximum at \sim 50-60°S and \sim 50 km. The 386 maximum temperature amplitude of E4 occurs at ~50 km and ~50-60°S with an amplitude of ~ 4 K on the days 127-130, and the other peak is ~ 3 K (\sim 60-70°S and \sim 60 km). The temperature amplitude of \sim 3 K occurs at ~50 km (~60 km) during days 213-216. The corresponding spatial 390 structures of zonal wind and meridional wind of these E4 are presented in Figures 7e, 7f, 7g and 7h. The zonal wind spatial structure of E4 shows 392 an obvious amplitude bimodal structure at ~50-60°S and ~55 km, and 393 \sim 60-70°S and \sim 55 km, with the maximum at \sim 50-60°S and \sim 55 km. The 394 maximum zonal wind amplitude of E4 happens at ~50-60°S and ~55 km 395 with an amplitude of ~ 9 m/s on days 127-130, and the other peak is ~ 5 K 396 (\sim 60-70°S and \sim 55 km). The zonal wind amplitude of \sim 5 m/s occurs at 397 \sim 50-60°S (\sim 60-70°S) and \sim 55 km on days 213-216. The amplitude of E4 398 meridional wind reaches ~ 8 m/s at $\sim 60-70$ °S and ~ 55 km (days 127-130) 399 and ~ 10 m/s at $\sim 60-70$ °S and ~ 55 km (days 213-216), respectively. 400

Diagnostic analysis for E4 on days 127-130 and 213-216 are shown in Figures 7i and 7j, respectively. The results demonstrate that E4 is dramatically amplified by the mean flow instabilities at the middle-high latitudes between ~50 km and ~70 km. With EP flux propagating into the lower atmosphere, it finally propagates toward the equator at ~50 km. E4 is amplified and propagated by the wave-mean flow interaction near the critical layer (~25 h, ~21 h), and the positive refractive index region generates the promoting effect. The strong instability and weak background wind at ~50-60°S and ~60-70 km provide sufficient energy for the propagation and amplification of EP flux into the lower atmosphere during days 127-130. Besides, E4 obtains energy from weak instability and weak background wind at ~50-60°S and ~60-70 km on days 213-216, and it is amplified and propagated into the lower atmosphere. The background wind at ~50-60°S and ~60-70 km on days 127-130 is similar to on days 213-216, and the instability at ~50-60°S and ~60-70 km is stronger on days 127-30 than on days 213-216. According to Figures 7a and 7b, E4 absorbs sufficient energy to be amplified under the background conditions on days 127-130, and the temperature amplitude on 127-130 days is stronger.

3.2 In the Northern Hemisphere

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Figure 8 shows that the observed maximum temperature amplitude appears at \sim 59.2 km and \sim 70-80°N for E1, and the E2 and E3 peaks at

~59.2 km and ~60-70°N. The maximum perturbation of E1 occurs on days 41-50 (with an amplitude of $\sim 8K$), while the remaining fluctuations occur on days 25-34 and 339-348. Besides, the strongest E2 occurs on days 69-74 (with an amplitude of \sim 7 K), and the rest are distributed on days 25-30, 317-322 and 341-346. By contrast, the E3 maximizes on days 35-38 (with an amplitude of \sim 3K), and also shows a peak on days 53-56. Based on the study of the wave period in the SH for eastward wave, the periodic variabilities of E1, E2 and E3 in the NH are also examined. The wave period of E1 decreases from a maximum of ~118 h (days 25-34) to ~80 h (days 41-50), indicating the instability of the wave period of E1 in the NH. The E2 events occur on days 25-30, 69-74, 317-322 and 341-346, of which the corresponding wave periods are ~36, ~53, ~52 and ~48 h, which are stronger and more stable than E1. Besides, the wave period of E3 is relatively stable at ~29 h and ~27 h. Thus, E2 and E3 wave periods are more stable than E1.

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The spectra, spatial (vertical and latitudinal) structures of temperature, zonal and meridional wind, and diagnostic analysis of E1 are extracted from the corresponding representative events (as shown in Figure 9). Figures 9a and 9b show the observed spectra of E1 at ~59.2 km and ~70-80°N on days 25-34 and 41-50, and the wave periods of locked wavenumber -1 are ~118 h and ~80 h, respectively. The corresponding temperature spatial structures of these E1 (~118 h and ~80 h) are shown

in Figures 9c, 9d. The temperature spatial structure of E1 shows an 445 obvious amplitude bimodal structure during days 25-34 at ~60-70°N and 446 \sim 60 km, and \sim 40-50°N and \sim 70 km, with the maximum at \sim 60-70°N and 447 ~60 km. On top of that, E1 also has bimodal structure on days 41-50 at 448 $\sim 60-70^{\circ}N$ and ~ 60 km, and $\sim 60-70^{\circ}N$ and ~ 70 km. The strongest 449 temperature amplitude of E1 occurs at ~60-70°N and ~60 km with an 450 amplitude of ~7 K on the days 25-34, and the other peak is ~4 K 451 $(\sim 40-50$ °N and ~ 70 km). The temperature amplitude of ~ 10 K occurs at 452 \sim 60 km and \sim 60-70°N during days 41-50, and the rest is \sim 8 K (\sim 60-70°N 453 and ~70 km). The corresponding spatial structures of zonal wind and 454 meridional wind of these E1 are illustrated in Figures 9e, 9f, 9g and 9h. 455 The zonal wind spatial structure of E1 presents an obvious amplitude 456 bimodal structure at $\sim 70-80$ °N and ~ 70 km, and $\sim 50-60$ °N and ~ 70 km. 457 The zonal wind amplitude of \sim 13 m/s occurs at \sim 70-80°N and \sim 70 km on 458 days 25-34, and the rest is ~ 10 m/s ($\sim 50-60^{\circ}$ N and ~ 70 km). In addition, 459 there is a weak peak of 9K during days 25-34 (~30-40°N and ~70 km). 460 The maximum zonal wind amplitude of E1 occurs at \sim 70-80°N and \sim 70 461 km with an amplitude of \sim 19 m/s on days 41-50, and the other peak is 462 \sim 13K (\sim 50-60°N and \sim 70 km). The amplitude of E1 meridional wind hits 463 \sim 14 m/s at \sim 70-80°N and \sim 70 km (days 25-34) and \sim 22 m/s at \sim 70-80°N 464 and \sim 70 km (days 41-50), respectively. 465

The diagnostic analysis results for E1 (in Figures 9i and 9j) suggest

the dramatic amplification of E1 by the mean flow instabilities at the middle-high latitudes between ~50 km and ~70 km. With the propagation of EP flux into the polar lower atmosphere, it eventually propagates toward the equator at ~50 km. The wave-mean flow interaction near the critical layers (~118 h, ~80 h) amplifies and propagates E1, and the promoting effect of the positive refractive index region amplifies E1. Furthermore, the weak instability and strong background wind at ~40-50°N and ~60-70 km generate the energy for the propagation and amplification of EP flux into the polar lower atmosphere during days 25-34. The E1 obtains sufficient energy from weak instability and suitable background wind on days 41-50 at ~40-50°N and ~60-70 km, and is amplified and propagated into the polar lower atmosphere through the critical layer and positive refractive index action. The background wind at ~40-50°N and ~60-70 km is stronger on days 25-34 than on days 41-50, but their instability is similar, indicating that stronger background winds might weaken E1 propagation and amplification at the mid-northern latitudes. Our results show that E1 absorbs adequate energy to be amplified under the background conditions during days 41-50, reflecting stronger temperature amplitude (see Figures 9a, 9b).

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For E2, the spectra are at \sim 59.2 km and \sim 60-70°N on days 25-30 and 69-74 when the eastward wavenumber -2 signal with the period \sim 36 h and \sim 53 h (as shown in Figures 10a, 10b). The corresponding temperature

spatial structures of these E2 (i.e., ~36 h and ~53 h) are presented in Figures 10c, 10d. The temperature spatial structure of E2 demonstrates an obvious amplitude bimodal structure at ~60-70°N and ~60 km, and $\sim 60-70$ °N and ~ 70 km, with the maximum at $\sim 60-70$ °N and ~ 60 km. The maximum temperature amplitude of E2 occurs at ~60-70°N and ~60 km with an amplitude of ~ 5 K on days 25-30, and the other peak is ~ 4 K (\sim 60-70°N and \sim 70 km). The temperature amplitude of \sim 9 K occurs on days 69-74 at \sim 60°S and \sim 60 km, and the other peaks are \sim 7 K (\sim 60-70°N and ~70 km), ~5 K (~60-70°N and ~50 km). The corresponding spatial structures of zonal wind and meridional wind of these E2 are shown in Figures 10e, 10f, 10g and 10h. The zonal wind spatial structure of E2 shows an obvious amplitude bimodal structure at ~60-70°N and ~60 km, and $\sim 40-50^{\circ}$ N and ~ 60 km, with the maximum at $\sim 40-50^{\circ}$ N and ~ 60 km. The maximum zonal wind amplitude of E2 appears at $\sim 60-70^{\circ}$ N and ~ 60 km (\sim 40-50°N and \sim 60 km) with an amplitude of \sim 6 m/s on days 25-30. Zonal wind amplitude occurs at ~40-50°N and ~60 km with an amplitude of \sim 18 m/s on days 41-50, and the other peak is \sim 16 K (\sim 60-70°N and ~60km). The amplitude of E2 meridional wind reaches ~7 m/s at \sim 60-70°N and \sim 70 km (days 25-30) and \sim 18 m/s at \sim 60-70°N and \sim 60 km (days 41-50), respectively.

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The diagnostic analysis of E2 on days 25-30 and 69-74 are shown in Figures 10i and 10j, respectively. Apparently, E2 is significantly

amplified by the mean flow instabilities at the middle-high latitudes between ~40 km and ~70 km, with EP flux propagating into the polar lower atmosphere, and EP flux eventually propagate toward the equator at ~50 km. E2 is amplified and propagated by the wave-mean flow interaction near the critical layers (~36 h, ~53 h), and the positive refractive index region provides the promoting effect. The weak instability and strong background wind at ~50-60°N and ~60-70 km provide the energy for the propagation and amplification of EP flux into the polar lower atmosphere during days 25-30. Moreover, E2 obtains sufficient energy from strong instability and suitable background wind at \sim 50-60°N and \sim 60-70 km on days 69-74, and it is amplified and propagated into the polar lower atmosphere. The background wind at \sim 50-60°N and \sim 60-70 km on days 127-130 is similar to on days 213-216, and the instability at $\sim 50-60^{\circ}$ S and $\sim 60-70$ km is stronger on days 127-30 than on days 213-216. Although the background wind at ~50-60°N and \sim 60-70 km is stronger on days 25-30 than on days 69-74, the instability at \sim 50-60°N and \sim 60-70 km is stronger on days 69-74 than on days 25-30. The temperature amplitude results indicate that E2 absorbs sufficient energy to be amplified under the background conditions on days 69-74, with stronger temperature amplitude on days 69-74 (Figures 10a, 10b).

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Figures 11a and 11b show the observed spectra of E3 at \sim 59.2km and \sim 60-70°N on days 35-38 and 53-56, and the wave periods of locked

wavenumber -3 are ~29 h and ~27 h, respectively. The corresponding temperature spatial structures of these E3 (i.e., ~29 h and ~27 h) are shown in Figures 11c, 11d. The temperature spatial structure of E3 shows an obvious amplitude bimodal structure at ~50-60°N and ~60 km, and \sim 50-60°N and \sim 70 km, with the maximum at \sim 50-60°N and \sim 60 km. The strongest temperature amplitude of E3 occurs at ~60 km and ~50-60°N with an amplitude of \sim 6 K on the days 35-38, and the other peak is \sim 5 K (\sim 50-60°N and \sim 70 km). The temperature amplitude of \sim 4 K occurs at ~60 km (~70 km) and ~50-60°N during days 53-56. The corresponding spatial structures of zonal wind and meridional wind of these E3 are illustrated in Figures 6e, 6f, 6g and 6h. The zonal wind spatial structure of E3 shows an obvious amplitude bimodal structure at ~40-50°N and ~70 km, and $\sim 60-70$ °N and ~ 70 km. The zonal wind amplitudes of E3 occur at \sim 40-50°N and \sim 70 km with an amplitude of \sim 15 m/s on days 35-38, and \sim 12 m/s at \sim 60-70°N and \sim 70 km. The maximum zonal wind amplitude of E3 appears at $\sim 40-50$ °N and ~ 70 km ($\sim 60-70$ °N and ~ 70 km) with an amplitude of ~7 m/s (~6 m/s) on days 53-56. The amplitude of E3 meridional wind reaches \sim 22 m/s at \sim 50-60°N and \sim 70 km (days 35-38) and \sim 12 m/s at \sim 60-70°N and \sim 70 km (days 53-56), respectively.

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Obviously, the instability and appropriate background wind at the mid-latitudes between ~ 50 km and ~ 70 km and the interaction near the critical layers (~ 29 h, ~ 27 h) dramatically amplify the propagation of E3

(see Figures 11i and 11j). The background wind is similar on days 35-38 and 53-56, and the former is relatively unstable. This finding indicates that the E3 in propagation is more likely to gather sufficient energy to be amplified on days 35-38. The instability and appropriate background wind at the mid-high latitudes between ~50 km and ~70 km drastically amplify the propagation of E3, which is enhanced by the interaction near the critical layers (~29 h, ~27 h) and the positive refractive index region (Figures 11i, 11j). In particular, the strong instability and weak background wind at ~50-60°N and ~60-70 km on days 35-38 generate sufficient energy for the propagation and amplification of EP flux into the lower atmosphere, and ultimately point toward the equator at 50 km. The EP flux propagates to the lower atmosphere during days 35-38, and it is amplified by interactions at the critical layer (~29 h). In addition, weak instability and weak background winds on days 53-56 at ~50-60°N and ~60-70 km provide the energy to amplify E3 propagation. Combine with Figures 11c, 11d, the stronger the instability at ~50-60°N and ~60-70 km, the stronger the temperature amplitude of E3. The results show that the instability on days 35-38 at ~50-60°N and ~60-70 km are the primary reasons for the propagation and amplification of EP flux into the lower atmosphere.

3.3 Comparison between SH and NH

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The observed latitude and maximum temperature amplitude for

eastward planetary waves (i.e., E1, E2, E3, E4) decrease and weaken with increasing zonal wavenumber in the SH, reaching ~70-80°S, ~60-70°S, $\sim 60-70^{\circ}$ S and $\sim 50-60^{\circ}$ S, and ~ 10 K, ~ 9 K, ~ 6 K, and ~ 3 K, respectively. In addition, the occurrence date gets earlier with increasing zonal wavenumber. The temperature spatial structure demonstrates bimodal-peak structure (~50 and ~60 km), mainly located at ~50 km. The maximum zonal wind amplitudes of E1 and E2, E3 and E4 are almost the same, which are ~ 20 m/s and ~ 10 m/s, respectively. The maximum meridional wind amplitudes of E1, E2, E3 and E4 are ~17 m/s, ~27 m/s, ~16 m/s and ~11 m/s, respectively. The wave period of E1 tends to get shorter from 5 to 3 days; while E2 and E3 are close to ~40 h and ~30 h; and E4 remains at ~24 h. E1, E2, E3 and E4 are more favorable to propagation in the SH winter and are abruptly amplified by the mean flow instabilities at the middle latitudes between ~40 km and ~70 km. With the propagation of EP flux into the lower atmosphere, and it finally propagates toward the equator at ~50 km. In addition, the propagation of EP flux for E1 to the upper atmosphere might be influenced by the instability and background wind at the Antarctic ~50km.

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The observed latitudes of E1, E2 (E3) decrease with increasing wavenumber in the NH, which are ~70-80°N, ~60-70°N and ~60-70°N. With bimodal-peak structure located at ~70 km, the temperature spatial structures of E1, E2 and E3 reach ~10 K, ~9 K and ~6 K, respectively.

The maximum zonal wind amplitude for E1, E2 and E3 occur at ~50-80°N and ~70 km, and their amplitude are almost equal to ~18 m/s. The maximum meridional winds of E1, E2 and E3 occur at ~50-80°N and ~70 km with amplitudes of ~22 m/s, ~18 m/s and ~22 m/s, respectively. The wave period of E1 tends to be shorter from 5-3 days; and E2 and E3 are close to ~48 h and ~30 h. In addition, E1, E2 and E3 are more favorable to propagation in the NH winter and are dramatically amplified by the mean flow instabilities at the middle latitudes between ~40 km and ~70 km, with the propagation of EP flux into the lower atmosphere and then toward the equator at ~50 km.

4 Summary and Conclusions

Based on the MERRA-2 temperature and wind observations in 2019, we present for the first time an extensive study of the global variation for eastward planetary wave activity, including zonal wave numbers of -1 (E1), -2 (E2), -3 (E3), -4 (E4) in the stratosphere and mesosphere. The temperature and wind amplitude and wave periods of each event were determined using 2-D least-squares fitting. Our study covered the spatial and temporal patterns of the eastward planetary waves in both hemispheres with a comprehensive diagnostic analysis on their propagation and amplification. The key findings of this study are summarized below:

1. The latitudes for the maximum (temperature, zonal and meridional

- wind) amplitudes of E1, E2, E3 and E4 decrease with increasing
- wavenumber in the SH and NH. The E1, E2, E3 and E4 events occur
- 623 earlier with increasing zonal wavenumber in the SH. In addition,
- 624 eastward wave modes exist during summer periods with westward
- background wind in both hemispheres.
- 2. The temperature spatial structures of E1, E2, E3 and E4 present a
- double-peak structure, which is located at ~50 km and ~60 km in SH, ~60
- 628 km and ~70 km in SH. Furthermore, the lower peak is usually larger than
- 629 the higher one.
- 630 3. The maximum (temperature, zonal and meridional wind) amplitude of
- E1, E2 and E3 decline with rising zonal wavenumber in the SH and NH.
- The maximum temperature amplitude in the SH are slightly larger and lie
- lower than those in the NH. In addition, the meridional wind amplitude
- are slightly larger than the zonal wind in the SH and NH.
- 635 4. The wave period of the E1 mode ranges 3-5 days in both hemispheres,
- while the period of E2 mode is slightly longer in the NH (~48 h) than in
- 637 the SH (~40 h). The periods of E3 in both SH and NH are ~30 h, while
- 638 the period of E4 is \sim 24 h.
- 5. The eastward planetary wave is more favorable to propagate in the
- 640 winter hemisphere and is drastically amplified by the mean flow
- 641 instabilities and appropriate background winds at polar region and the
- 642 middle latitudes between ~40 km and ~80 km. Furthermore, the

amplification of planetary waves through wave-mean flow interaction occurs easily close to its critical layer. In addition, the direction of EP flux ultimately points towards the equator.

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- 6. The strong instability and appropriate background wind in the lower layer of the Antarctic region might generate adequate energy to promote the E1 propagation and amplification to the upper atmosphere.
- Overall, this study demonstrated how the background zonal wind in the polar middle atmosphere affects the dynamics of eastward planetary waves in the polar middle atmosphere.

652	Data	availability.	MERRA-2	data	are	available	at
653	http://disc.gsfc.nasa.gov.						
654							
655	Code	availability.	Code	is	8	available	at
656	http://hdl.pid21.cn/21.86116.7/04.99.01293.						
657							
658	Author contributions. LT carried out the data processing and analysis and						
659	wrote the manuscript. SYG and XKD contributed to reviewing the article.						
660							
661	Competing interests. The authors declare that they have no conflict of						
662	interest.						
663							
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665	Space Physics Research (SPR). The authors thank NASA for free online						line
666	access to the MERRA-2 temperature reanalysis.						
667							
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670	41831071).						

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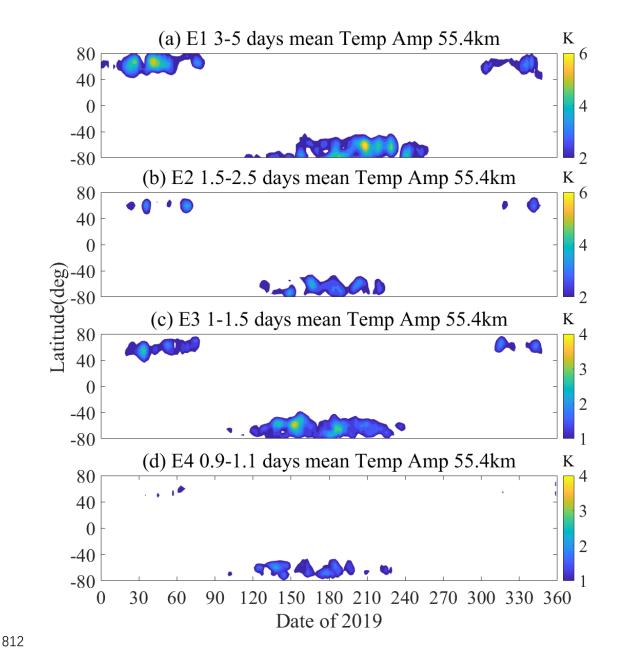


Figure 1. The global latitude-temporal variation structures of the (a) E1, (b) E2, (c) E3 and (d) E4 planetary waves during 2019. White areas represent small amplitude data (corresponds to the right color bar).

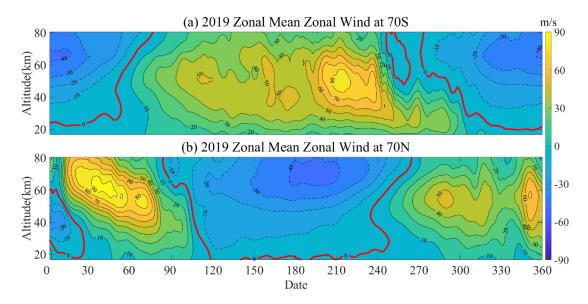


Figure 2. The zonal mean zonal wind variations of (a) 70°S and (b) 70°N during 2019. The dotted line represents east<u>ward</u> wind, the solid line represents west<u>ward</u> wind, and the red solid line is 0 m/s.

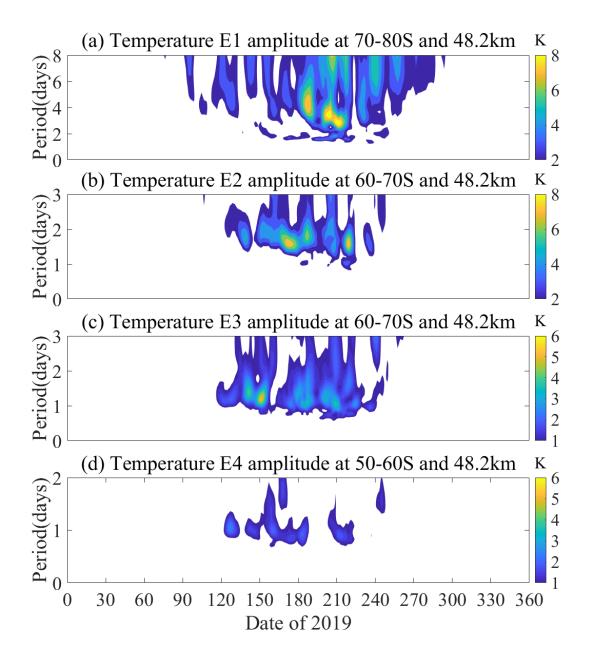


Figure 3. The temporal variations of (a) E1, (b) E2, (c) E3 and (d) E4 QTDWs during 2019 austral winter period.

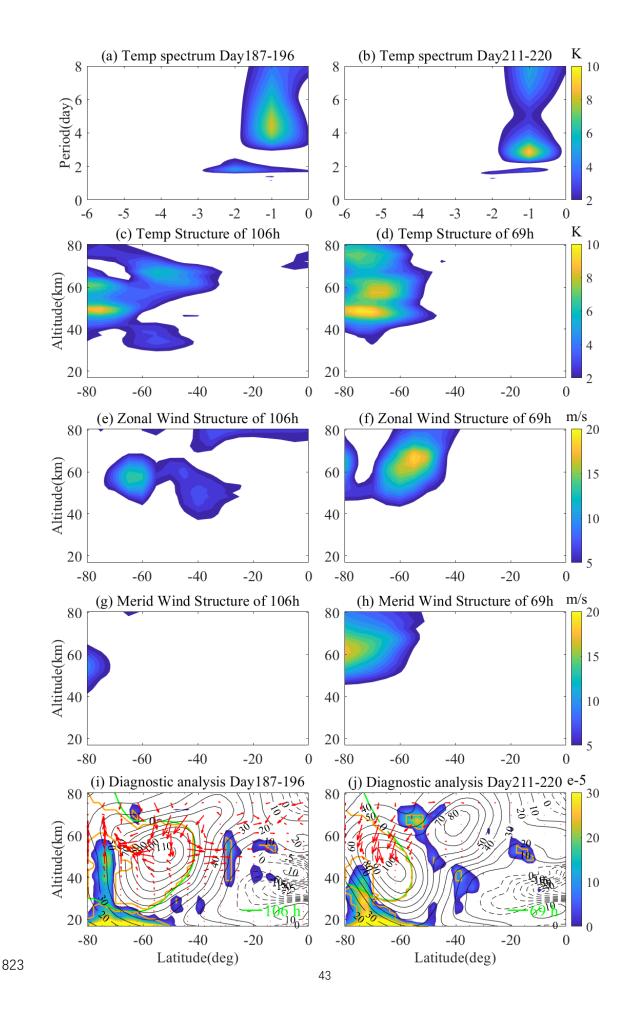


Figure 4. The (a, b) spectra, (c, d) temperature spatial structures, (e, f) zonal wind spatial structures, (g, h) meridional wind spatial structures, and (i, j) diagnostic analysis of the E1 typical events during 2019 austral winter period. The MERRA-2 temperature data observations at 48.2 km and 70-80°S during days 187–196 (Figure 4a), 211–220 (Figure 4d) are utilized, respectively. In the diagnostic analysis of E1 events, the blue shaded region is instability, the red arrow is EP flux, and the green line is critical layer. The green line represents critical layers of E1 with the natural period. Regions enclosed by orange solid lines are characterized by the positive refractive index for the E1.

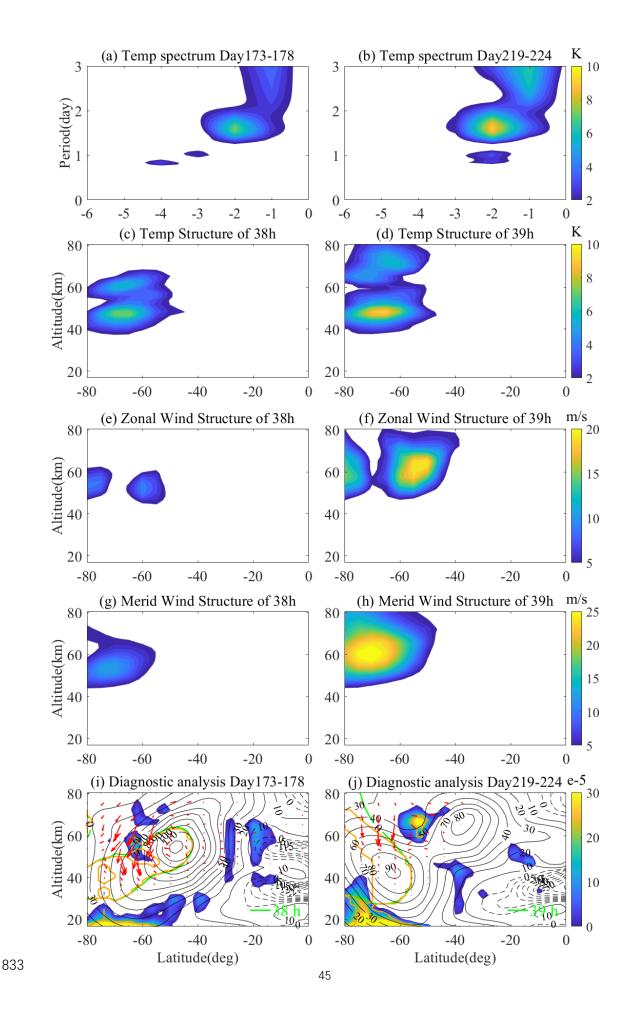


Figure 5. Same as Figure 4 but for E2 during the 2019 austral winter period.

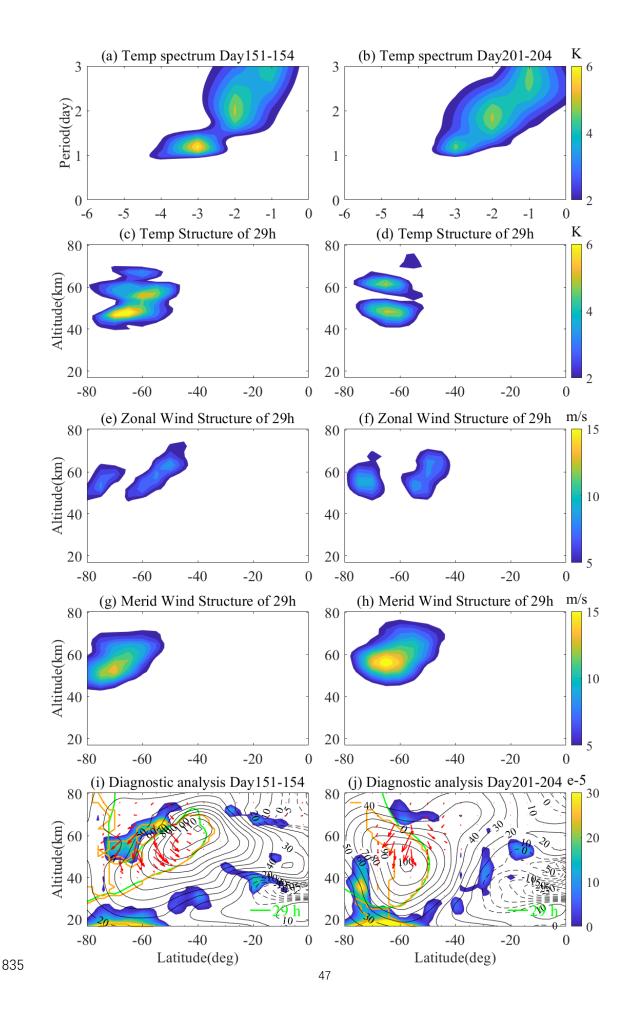
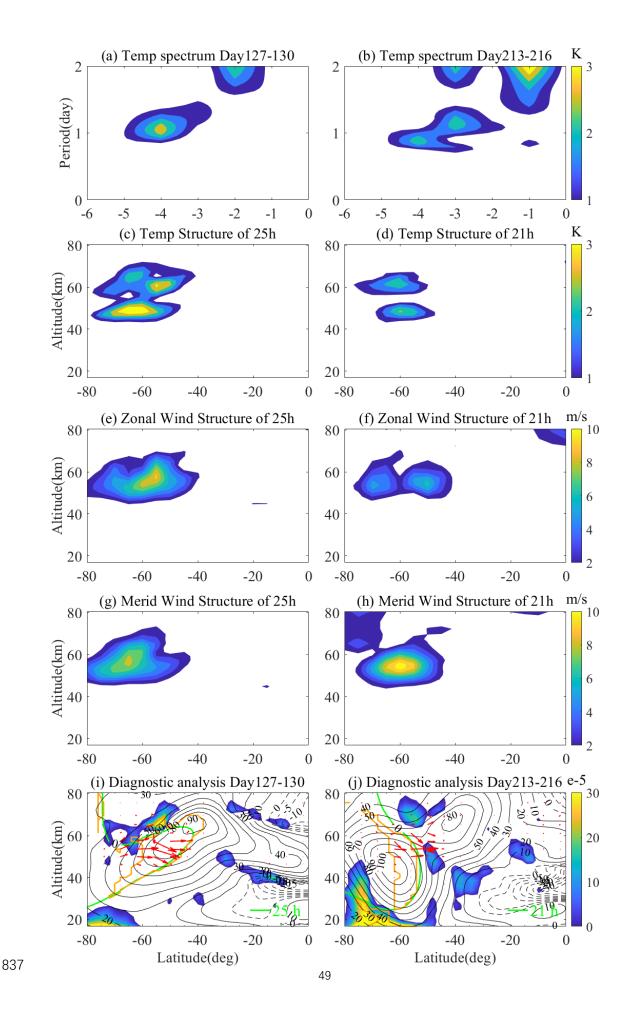


Figure 6. Same as Figure 4 but for E3 during the 2019 austral winter period.





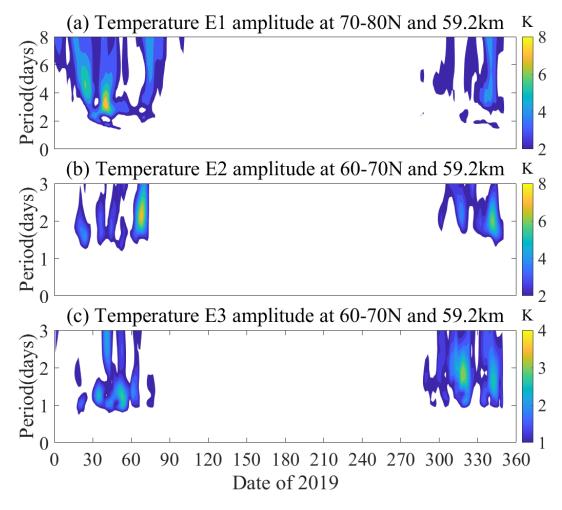


Figure 8. The temporal variations of (a) E1, (b) E2 and (c) E3 QTDWs during the 2019 boreal winter period.

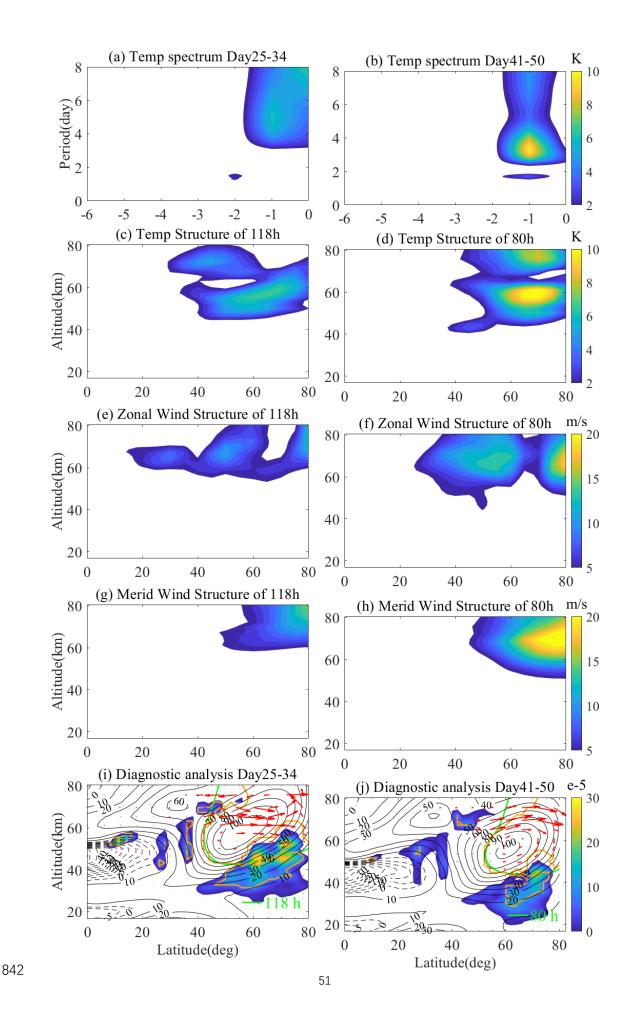


Figure 9. The (a, b) spectra, (c, d) temperature spatial structures, (e, f) zonal wind spatial structures, (g, h) meridional wind spatial structures and (i, j) diagnostic analysis of the E1 typical events during 2019 boreal winter period. The E1 events at 48.2 km and 70-80°N were obtained from the MERRA-2 reanalysis.

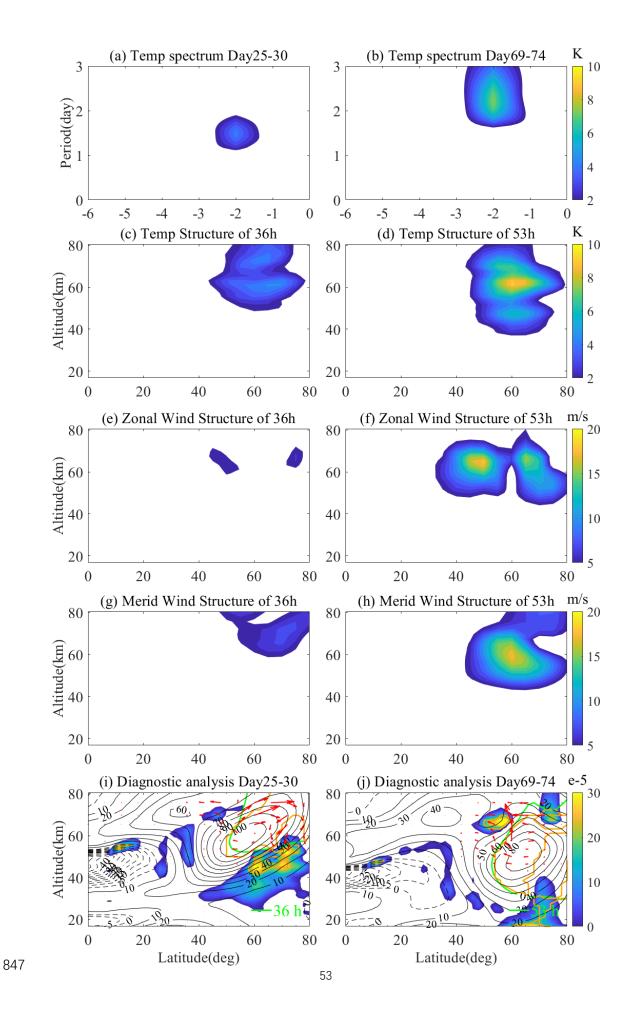


Figure 10. Same as Figure 9 but for E2 during the 2019 boreal winter period.

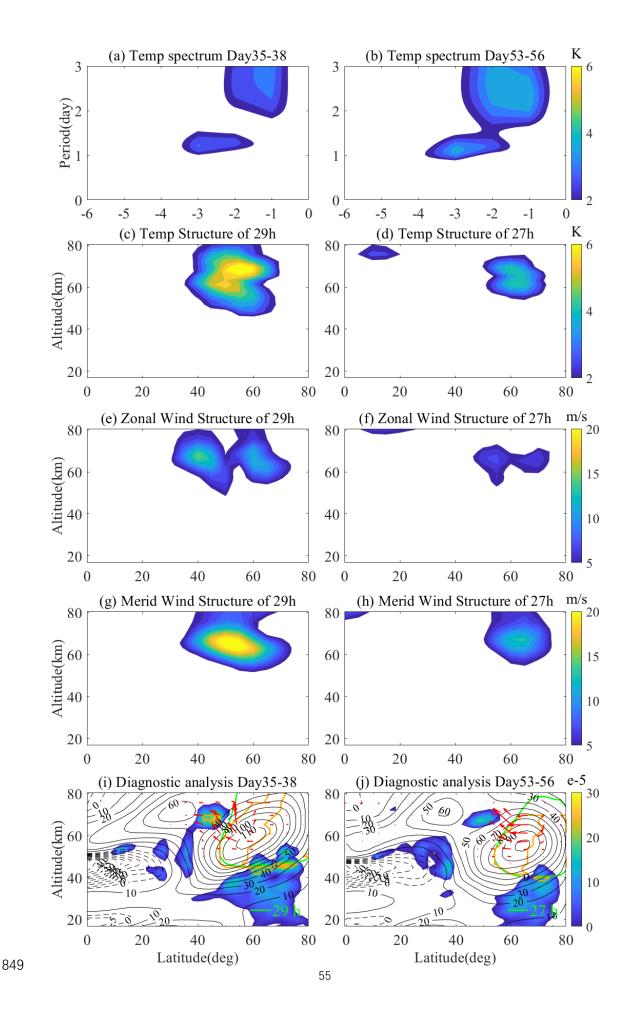


Figure 11. Same as Figure 9 but for E3 during the 2019 boreal winter period.