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## Zonally Asymmetric Temperature Trends near the Northern Middle and High Latitude Stratopause during Winter

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# Zonally Asymmetric Temperature Trends near the Northern Middle and High Latitude Stratopause during Winter

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35

**Abstract**

36 The temperature trend near the stratopause is rarely evaluated owing to the limited long-  
37 term observations of global temperature. In this study, the spatial patterns of the  
38 temperature trends near the stratopause are investigated using satellite and reanalysis  
39 datasets. Our analysis reveals a zonally asymmetric temperature trend pattern near the  
40 northern mid-to-high latitude stratopause during January, and this pattern underwent an  
41 evident transition around the 2000s. From 1980 to 2003, there was a cooling trend in  
42 the western hemisphere and a warming trend in the eastern hemisphere. In contrast, a  
43 reversed zonally asymmetric temperature trend pattern existed in the east-west direction  
44 from 2003 to 2020. Although the warming trends are statistically insignificant, they  
45 contrasted with the overall cooling trend in the upper stratosphere due to ozone  
46 depletion and an increase in well-mixed greenhouse gases in recent decades. The  
47 zonally asymmetric temperature trends were induced by the transition in the intensity  
48 of quasi-stationary planetary wavenumber 1 (wave 1) near the stratopause. The  
49 increasing (decreasing) trend of the intensity of wave 1 enhanced (reduced) its  
50 meridional temperature advection near the stratopause before (after) the 2000s,  
51 consequently, a zonally asymmetric temperature trend pattern exists in the east-west  
52 direction near the stratopause. The transition in the intensity of the stratospheric wave  
53 1 around the 2000s is most likely caused by the transition in the intensity of wave 1  
54 activity in the troposphere.

55 Key words: Stratospheric temperature trend, zonally asymmetric temperature pattern,  
56 quasi-stationary planetary wavenumber 1

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58 temperature trends near the northern middle and high latitude stratopause during winter.  
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## 63 **1. Introduction**

64 The stratospheric temperature is a crucial climate marker that is affected by both  
65 thermal-dynamic and chemical processes. In response to ozone depletion and  
66 increasing well-mixed greenhouse gases (GHGs), the stratospheric temperature has  
67 experienced a significant cooling trend over the past several decades, which has been  
68 noted by a wide variety of observations and reproduced by multiple climate models  
69 (e.g., Golitsyn et al., 1996; Ramaswamy et al., 2001; Wang et al., 2012; Thompson et  
70 al., 2009, 2012; Randel et al., 2009, 2017; Rao et al., 2015; Garcia et al., 2019;  
71 Remsberg, 2019; Steiner et al., 2020). Notably, recently updated and extended satellite  
72 data has provided relatively reliable zonal mean temperature observations throughout  
73 the stratosphere and revealed that the zonal mean temperature trends decreased with  
74 altitude from the lower stratosphere to the upper stratosphere from 1979 to 2015  
75 (McLandress et al., 2015; Randel et al., 2016; Zou and Qian, 2016). However, the long-  
76 term trends in stratospheric temperature still have uncertainties in both their magnitudes  
77 and spatial variations (e.g., Shine et al., 2003; Fu et al., 2010; Seidel et al., 2011;  
78 Funatsu et al., 2016; Maycock et al., 2018). These uncertainties are partly due to  
79 discrepancies in different observations (e.g., Zou et al., 2009; Thompson et al., 2012;  
80 Keckhut et al., 2019; Seidel et al., 2016) and are partly relate to the challenges involved  
81 in clarifying the factors that contribute to stratospheric temperature trends (e.g., Hu and  
82 Fu, 2009; Hu et al., 2009; Ivy et al., 2016; Xia et al., 2020; Zhou et al., 2022).

83 Various factors may influence temperature trends in the stratosphere. Although  
84 well-mixed GHGs are still increasing, a weak recovery signal has appeared in

85 stratospheric ozone in the last two decades (e.g., Hu et al., 2015; Chipperfield et al.,  
86 2017). Consequently, future trends in stratospheric temperatures (Arblaster et al., 2014;  
87 WMO, 2018) will mainly result from the opposing effects of increasing CO<sub>2</sub> (colder  
88 stratosphere) and increasing ozone (the warmer stratosphere). Moreover, the increasing  
89 stratospheric water vapor and volcanic aerosols have potentially impacted the  
90 temperature trends in the tropical lower stratosphere in recent decades (e.g., Maycock  
91 et al., 2014). Apart from the radiative contributions of chemical constituents, dynamic  
92 processes also have a large impact on stratospheric temperature trends, particularly at  
93 middle and high latitudes. It is known that temperatures in the stratosphere at middle  
94 and high latitudes are dominated by both the radiative balance and dynamic heating  
95 originating from tropospheric wave forcing (Andrews et al., 1987; Haynes, 2005; He et  
96 al., 2022). Given that GHGs trends are monotonically increasing, the temperature trends  
97 in the stratosphere at middle and high latitudes are strongly modulated by changes in  
98 planetary wave forcing in the stratosphere (Hu and Tung, 2002; Fu et al., 2019). As a  
99 result, the large interannual and decadal variations in dynamical forcing may lead to  
100 large uncertainties in stratospheric temperature trends (e.g., Matsuno, 1971; Yamashita  
101 et al., 2010; Long et al., 2017).

102 On the other hand, previous studies have mainly focused on trends in global or  
103 zonal mean temperatures in the stratosphere, but the longitudinal variations in the  
104 temperature trend in the stratosphere have rarely been evaluated. In particular, the  
105 spatial variations in the temperature trend near the stratopause are still poorly  
106 understood due to the shortage of long-term global observations there. It is well known

107 that the polar night jet is persistent in the Northern Hemisphere (NH) winter, indicating  
108 strong baroclinicity there (France and Harvey, 2013; Harvey et al., 2002). Harvey and  
109 Hitchman (1996) noted that the maximum longitudinal differences between the  
110 Aleutian High and the polar vortex were located near the stratopause. In addition,  
111 previous studies have reported the shift in the tropospheric and stratospheric climate  
112 around the 2000s (e.g., Chen and Tung, 2014; Hu et al., 2019). However, whether the  
113 climate shift occurs near the stratopause is still unclear. Therefore, it is of interest to  
114 investigate the changes in the temperature near the stratopause in recent decades.

115 In this study, we employ the Modern-Era Retrospective Analysis for Research  
116 and Applications, version 2 (MERRA-2) reanalysis datasets from 1980 to 2020 and the  
117 TIMED/SABER satellite temperature data from 2003 to 2020 to investigate spatial  
118 variations in the temperature trend near the stratopause during the northern winter as  
119 well as the possible factors responsible for the temperature trends near the stratopause.  
120 The organization of our paper is as follows. Section 2 describes the data and method  
121 we used. In Section 3, we exhibit and compare the temperature trends near the  
122 stratopause during the northern winter derived from TIMED/SABER observations and  
123 the MERRA-2 reanalysis dataset. In Section 4, we investigate possible factors  
124 responsible for the temperature trends. The conclusions and discussions are  
125 summarized in Section 5.

126

## 127 **2. Data and Methods**

### 128 **2.1 Data**

129 SABER is an infrared limb sounder launched on the TIMED satellite, which  
130 provides reliable global temperature data above the troposphere. Its latitudinal coverage  
131 ranges from a north-looking mode (53°S–83°N) to a south-looking mode (53°N–83°S)  
132 approximately every 60 days. The SABER temperature profiles have been retrieved  
133 from infrared emissions of CO<sub>2</sub> from approximately 16 km to 105 km altitude with an  
134 effective vertical resolution of 2 km. TIMED/SABER temperature has been evaluated  
135 by Remsberg et al. (2003, 2008). In this study, we use the TIMED/SABER (version  
136 2.0) temperature dataset from 2003 to 2020 and bin the data into 2° × 4° (longitude by  
137 latitude) monthly mean maps.

138 MERRA-2 is produced by the National Aeronautics and Space Administration  
139 (NASA) Global Modeling and Assimilation Office (GMAO). The temperature data  
140 from the Microwave Limb Sounder (MLS) are assimilated in MERRA-2 above 5 hPa,  
141 providing more accurate temperature data for the upper stratosphere than MERRA  
142 (Gelaro et al. (2017)). The zonal mean temperature comparisons between observations  
143 and reanalysis datasets, including MERRA-2, were investigated by Long et al. (2017).  
144 The MERRA-2 instM\_3d\_asm\_Np monthly mean datasets (Version 5.12.4) are used  
145 during the period from 1980 to 2020, with a horizontal resolution of 0.5° × 0.625°  
146 (latitude × longitude) and 42 vertical levels up to a height of 0.1 hPa.

## 147 **2.2 Method**

148 In this study, the Eliassen-Palm (EP) flux (Andrews et al., 1987) and the Plumb  
149 flux (Plumb, 1985) are applied to measure the strength and propagation of wave  
150 activities in two dimensions and three dimensions, respectively. The meridional ( $F^{(\varphi)}$ )



151 and vertical ( $F^{(z)}$ ) components of the EP flux and its divergence ( $\nabla \cdot \mathbf{F}$ ) are defined as  
 152 follows:

$$153 \quad F^{(\varphi)} = \rho_0 a \cos \varphi \left( \overline{u_z \frac{v'\theta'}{\theta_z}} - \overline{u'v'} \right) \quad (1)$$

$$154 \quad F^{(z)} = \left( f - \frac{(\overline{u' \cos \varphi})_{\varphi}}{\cos \varphi} \right) \overline{v'\theta'} - \overline{u'w'} \quad (2)$$

$$155 \quad \nabla \cdot \mathbf{F} = \frac{\partial F^{(\varphi)}}{\partial \varphi} + \frac{\partial F^{(z)}}{\partial z} \quad (3)$$

156 where  $\varphi$  is latitude,  $z$  is height,  $\rho$  is air density,  $a$  is the Earth's radius,  $f$  is the  
 157 Coriolis parameter,  $\theta$  is potential temperature,  $u$  is zonal wind,  $v$  is meridional  
 158 wind, and  $w$  is vertical wind. The overbars and primes denote the zonal mean and the  
 159 departure from the zonal mean, respectively. The subscript 0 is for the background  
 160 variables. The subscript  $z$  is for the partial derivative for the variables in the vertical  
 161 direction.

162 The longitude ( $F^{(\lambda)}$ ), latitude ( $F^{(\varphi)}$ ), and vertical ( $F^{(z)}$ ) components of the Plumb  
 163 flux and its divergence ( $\nabla \cdot \mathbf{F}$ ) are defined as follows:

$$164 \quad F^{(\lambda)} = \rho_0 \cos \varphi \left( \frac{1}{2a^2 \cos^2 \varphi} \left[ \left( \frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \right) \quad (4)$$

$$165 \quad F^{(\varphi)} = \rho_0 \cos \varphi \left( \frac{1}{2a^2 \cos^2 \varphi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \varphi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \varphi} \right] \right) \quad (5)$$

$$166 \quad F^{(z)} = \rho_0 \cos \varphi \left( \frac{2\Omega^2 \sin^2 \varphi}{N^2 a \cos \varphi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial z} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial z} \right] \right) \quad (6)$$

$$167 \quad \nabla \cdot \mathbf{F} = \frac{\partial F^{(\lambda)}}{\partial \lambda} + \frac{\partial F^{(\varphi)}}{\partial \varphi} + \frac{\partial F^{(z)}}{\partial z} \quad (7)$$

168 where  $\lambda$  is longitude,  $\Omega$  is the Earth's angular velocity,  $N$  is the Brunt-Väisälä  
 169 frequency,  $\psi = \Phi/2\Omega \sin \varphi$ , and  $\Phi$  is potential height.

### 170 **3. Temperature Trends Near the Stratopause during the**

## 171 Northern Winter

172 Figs. 1a and 1c present the spatial patterns of the 3 hPa temperature trends over the NH  
173 during January from 1980-2003 and from 2003-2020 derived from MERRA-2  
174 reanalysis data, respectively. A noticeable feature is that there is a zonally asymmetric  
175 pattern in temperature trends at mid-high latitudes shown in Fig. 1a, with a cooling  
176 trend in the western hemisphere and a warming trend in the eastern hemisphere. In  
177 contrast, a reversal temperature trend in the east-west direction can be noted in Fig. 1c,  
178 with a warming (cooling) trend in the western (eastern) hemisphere. Note that the  
179 results here are not sensitive to slight changes in the starting/ending year of the time  
180 series. Thompson et al. (2012) indicated that due to ozone depletion and increasing  
181 well-mixed GHGs in recent decades, the stratospheric cooling in the upper stratosphere  
182 is more robust than that in the lower-middle stratosphere. Hence, although these  
183 warming trends in Figs. 1a and 1c are statistically insignificant at the 95% confidence  
184 level, they contrast with the overall cooling trend in the upper stratosphere. To  
185 understand the unusual warming near the stratopause, we separate the temperature into  
186 two components, i.e., zonal mean and deviations from the zonal mean (hereafter zonal  
187 temperature deviations). The zonal mean temperature denotes the background field,  
188 which is dominated by chemical and radiative balances. The temperature deviations  
189 denote the disturbed field, which is largely controlled by adiabatic/diabatic  
190 thermodynamic processes.

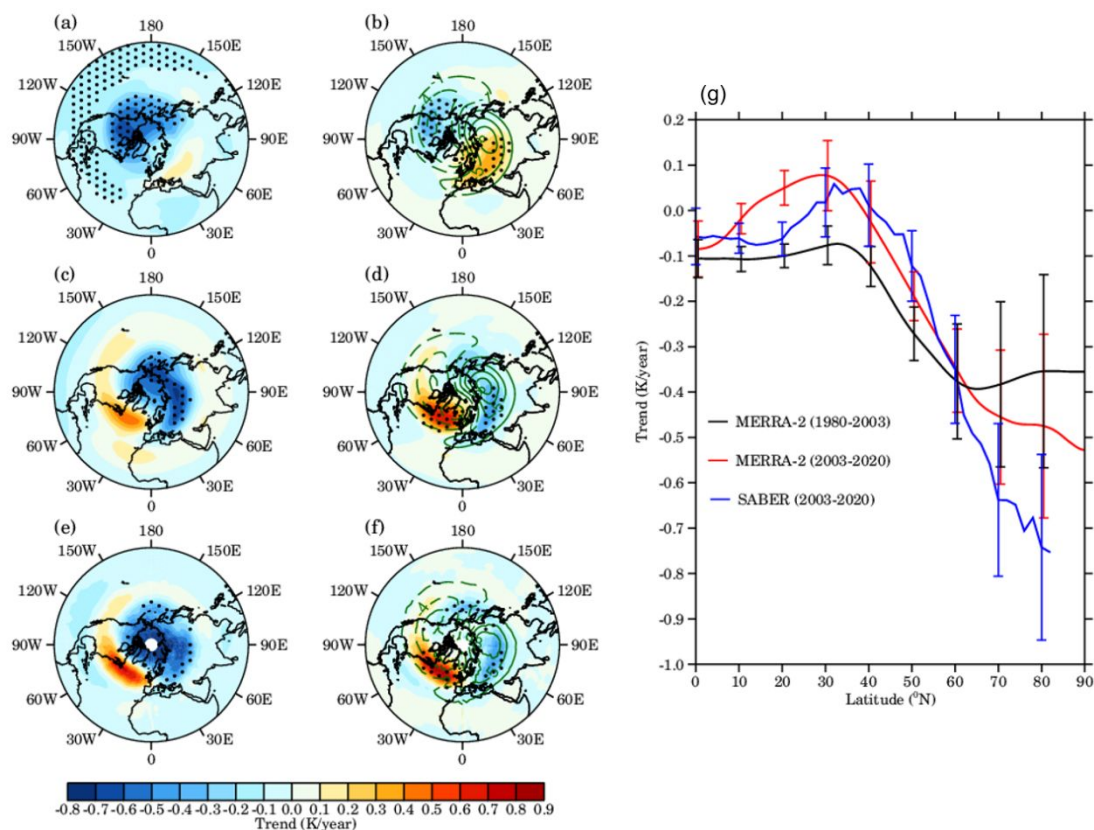
191 Figs. 1b and 1d show the spatial patterns of trends in zonal temperature deviations  
192 at 3 hPa over the NH during January from 1998 to 2003 and from 2003 to 2020 derived

193 from MERRA-2 reanalysis data, respectively. The trends in zonal temperature  
194 deviations also present zonally asymmetric patterns at mid-high latitudes, with a  
195 statistically significant cooling (warming) trend in the western (eastern) hemisphere in  
196 Fig. 1b, and a reversal temperature trend in the east-west direction in Fig. 1d. The  
197 warming (cooling) trends in the zonal temperature deviations are stronger (weaker)  
198 compared to those in the original temperature. The green contours superimposed on  
199 Figs. 1b and 1d are the climatology of the zonal temperature deviations, which are  
200 likewise zonally asymmetric at mid-high latitudes, with negative (positive) anomalies  
201 in the western (eastern) hemisphere. The climatology of the zonal temperature  
202 deviations is generally in phase (out of phase) with the trends of the zonal temperature  
203 deviations in Fig. 1b (1d), suggesting that the zonal asymmetry of temperature  
204 variations was strengthened (weakened) before (after) the 2000s, and there was a  
205 transition in the zonally asymmetric temperature trend pattern around the 2000s.

206 The latitudinal variations in the 3 hPa zonal mean temperature trends over the NH  
207 during January from 1980 to 2003 and from 2003 to 2020 derived from MERRA-2  
208 reanalysis data are shown in Fig. 1g, respectively. The morphology of zonal mean  
209 temperature trend before the 2000s is similar to that after the 2000s. The zonal mean  
210 temperature trend is close to zero at lower latitudes but decreases with increasing  
211 latitudes at mid-high latitudes. Overall, the zonal mean temperature trend before/after  
212 the 2000s is cooling in the NH, which is consistent with the increase in well-mixed  
213 GHGs in recent decades. The results shown in Fig. 1 as derived from MERRA-2  
214 reanalysis data suggest that the zonal asymmetry of the temperature trends near the

215 stratopause is the product of changes in disturbed fields.

216 To further verify the trends exhibited in Fig. 1 derived from MERRA-2 reanalysis  
217 data, TIMED/SABER satellite temperature observations (from 2003-2020) are  
218 analyzed. Figs. e, f, and g (blue line) are the same as Figs. c, d, and g (red line),  
219 respectively, but the data is derived from TIMED/SABER observations. It is seen that  
220 the zonally asymmetric temperature trend pattern is also apparent in TIMED/SABER  
221 observations, and the corresponding results derived from MERRA-2 reanalysis data  
222 agree well with those derived from TIMED/SABER observations in both morphology  
223 and magnitude. Since the temperature trends near the stratopause in MERRA-2  
224 reanalysis data are in good agreement with those from the TIMED/SABER temperature  
225 observations, the MERRA-2 dataset is utilized to investigate the possible factors  
226 responsible for the zonally asymmetric variations in the temperature. Note that the  
227 spatial pattern of 3 hPa temperature shows an almost uniform cooling trend over the  
228 NH during January from 1980 to 2020 derived from MERRA-2 reanalysis data (not  
229 shown).

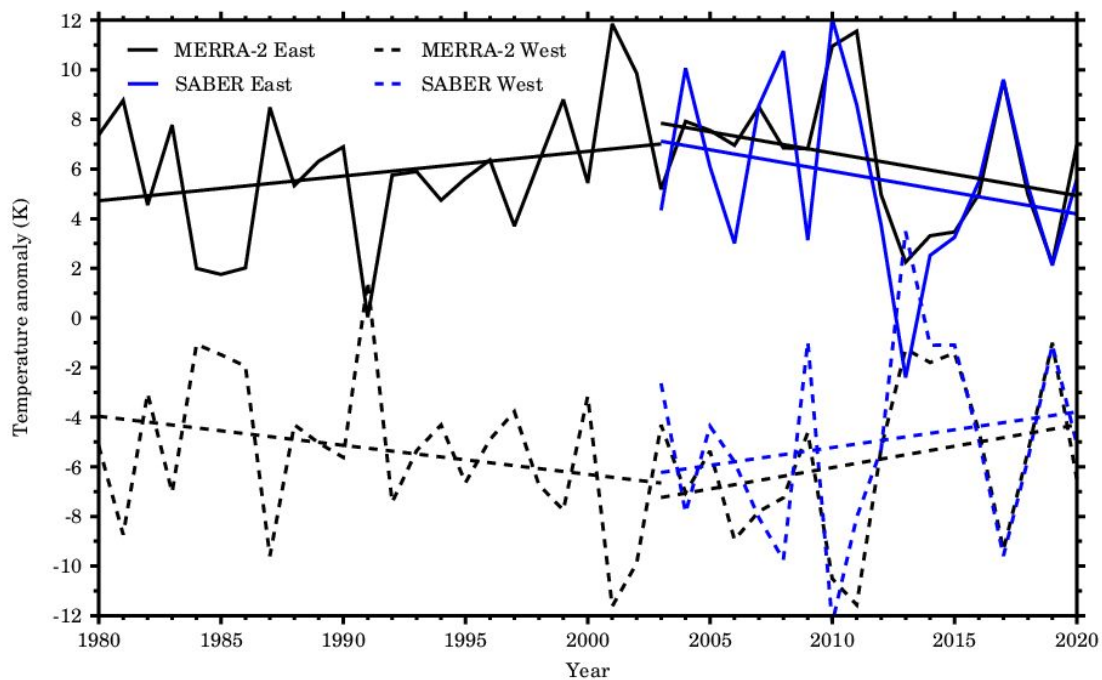


230

231 **Fig. 1.** Spatial pattern of trends in (a) temperature and (b) zonal temperature deviations  
 232 over the NH at 3 hPa during January from 1980 to 2003 derived from MERRA-2  
 233 reanalysis data. (c) and (d) are the same as (a) and (b), respectively, but the time period  
 234 is from 2003 to 2020. (e) and (f) are the same as (c) and (d), respectively, but the data  
 235 is derived from TIMED/SABER observations. The values over the stippled areas are  
 236 statistically significant at the 95% confidence level according to Student's t test. The  
 237 green contour lines denote the climatology of the zonal temperature deviations (the  
 238 contour interval is 3 K, solid and dashed lines indicate positive and negative values,  
 239 respectively). (g) Latitude variations in the zonal mean temperature trends over the NH  
 240 at 3 hPa during January from 1980 to 2003 derived from MERRA-2 reanalysis dataset  
 241 (black line), from 2003 to 2020 derived from MERRA-2 reanalysis dataset (red line),  
 242 and from 2003 to 2020 derived from TIMED/SABER observations (blue line). Error

243 bars show the  $2\sigma$  statistical uncertainty.

244 Fig. 2 presents the time series of the zonal temperature deviations averaged over  
245 the climatological high-temperature lobe (hereafter East) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ )  
246 (solid lines) and the climatological low-temperature lobe (hereafter West) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  
247  $0$ - $150^{\circ}\text{W}$ ) (dashed lines) at 3 hPa during January from 1980 to 2020 derived from  
248 MERRA-2 reanalysis data (black lines) and from 2003 to 2020 derived from  
249 TIME/SABER observations (blue lines), respectively. The straight lines represent the  
250 linear fits of the zonal temperature deviations before and after 2003, respectively. The  
251 time series of the zonal temperature deviations derived from MERRA-2 agree well with  
252 those derived from the TIMED/SABER observations in both magnitudes and variations.  
253 The East underwent a statistically significant increasing trend ( $0.1$  K/year) from 1980  
254 to 2003 and a statistically significant decreasing trend ( $-0.17$  K/year) from 2003 to 2020.  
255 The West has similar magnitudes but opposite signs in both interannual variations and  
256 long-term trends compared to the East, indicating a close negative correlation in the  
257 zonal temperature deviations between the two lobes. The correlation coefficients  
258 between the East and West are  $-0.89$  ( $-0.90$ ) derived from the MERRA-2 reanalysis  
259 data (TIMED/SABER observations). Note that the results here are not sensitive to slight  
260 changes in the latitude/longitude bounds used for averaging the data.



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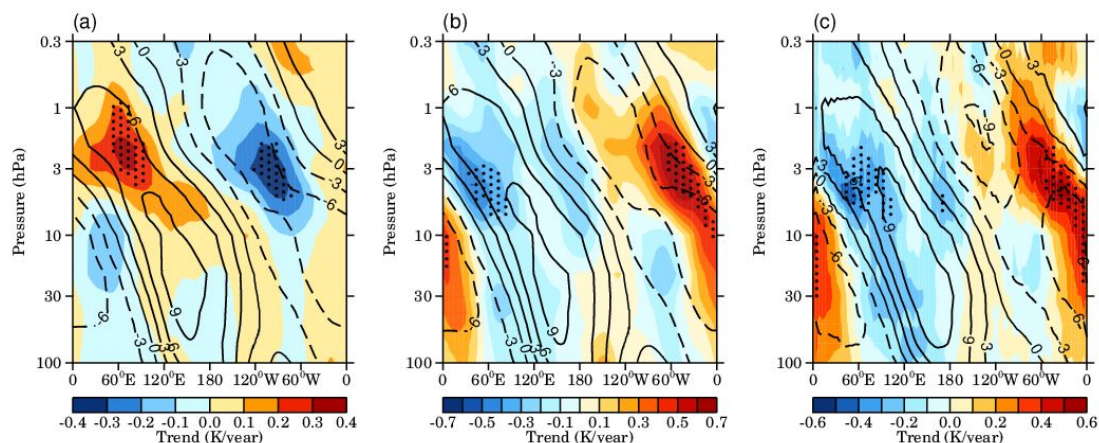
262 **Fig. 2.** Time series of the zonal temperature deviations averaged over the climatological  
 263 high-temperature lobe (hereafter East) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ ) (solid lines) and the  
 264 climatological low-temperature lobe (hereafter West) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $0$ - $150^{\circ}\text{W}$ ) (dashed  
 265 lines) at 3 hPa during January from 1980 to 2020 derived from the MERRA-2 reanalysis  
 266 data (black lines) and from 2003 to 2020 TIME/SABER observations (blue lines),  
 267 respectively. The straight lines represent the linear fits of the zonal temperature  
 268 deviations before and after 2003, respectively.

269 To depict the zonally asymmetric temperature trend variations with heights, Fig.  
 270 3 shows the longitude-height cross sections of the trends in zonal temperature deviation  
 271 at  $70^{\circ}\text{N}$  during January (a) from 1980 to 2003 derived from MERRA-2 reanalysis data,  
 272 (b) from 2003 to 2020 derived from MERRA-2 reanalysis data, and (c) from 2003 to  
 273 2020 derived from TIMED/SABER observations. The black contours superimposed on  
 274 Fig. 3 denote the climatology of the zonal temperature deviations. The climatology of  
 275 the zonal temperature deviations in the upper stratosphere and lower mesosphere

276 (hereinafter USLM) also present a zonally asymmetric pattern, with the climatological  
277 high-temperature (low-temperature) lobe mainly located in the eastern (western)  
278 hemisphere. The climatology of the zonal temperature deviations tilts westward with  
279 heights, exhibiting a pattern analogous to that of the quasi-stationary planetary  
280 wavenumber 1 (wave 1).

281 As shown in Fig. 3a, the trend in the zonal temperature deviation is generally in  
282 phase with the climatology of the zonal temperature deviation in the USLM, with a  
283 statistically significant warming (cooling) trend in the eastern (western) hemisphere  
284 near the stratopause before the 2000s. In contrast, Fig. 3b shows the trend in the zonal  
285 temperature deviation is generally out of phase with the climatology of the zonal  
286 temperature deviation in the USLM, with a statistically significant cooling (warming)  
287 trend mainly located in the eastern (western) hemisphere near the stratopause after the  
288 2000s. The longitude-height cross section of the zonal temperature deviation derived  
289 from MERRA-2 reanalysis data (Fig. 3b) is comparable to that derived from  
290 TIMED/SABER observations (Fig. 3c). The results in Fig. 3 further support that the  
291 zonally asymmetric temperature trend pattern undergoes a transition in the east-west  
292 direction around the 2000s and is most pronounced near the stratopause.





293

294 **Fig. 3.** Longitude-height cross sections of the trends (color shading) and climatology  
 295 (black contours, the contour interval is 3 K, solid and dashed lines indicate positive and  
 296 negative values, respectively) of zonal temperature deviations at 70°N during January  
 297 (a) from 1980 to 2003 derived from MERRA-2 reanalysis dataset, (b) from 2003 to  
 298 2020 derived from MERRA-2 reanalysis dataset, and (c) from 2003 to 2020 derived  
 299 from TIMED/SABER observations. The values over the stippled areas are statistically  
 300 significant at the 95% confidence level according to Student's t test.

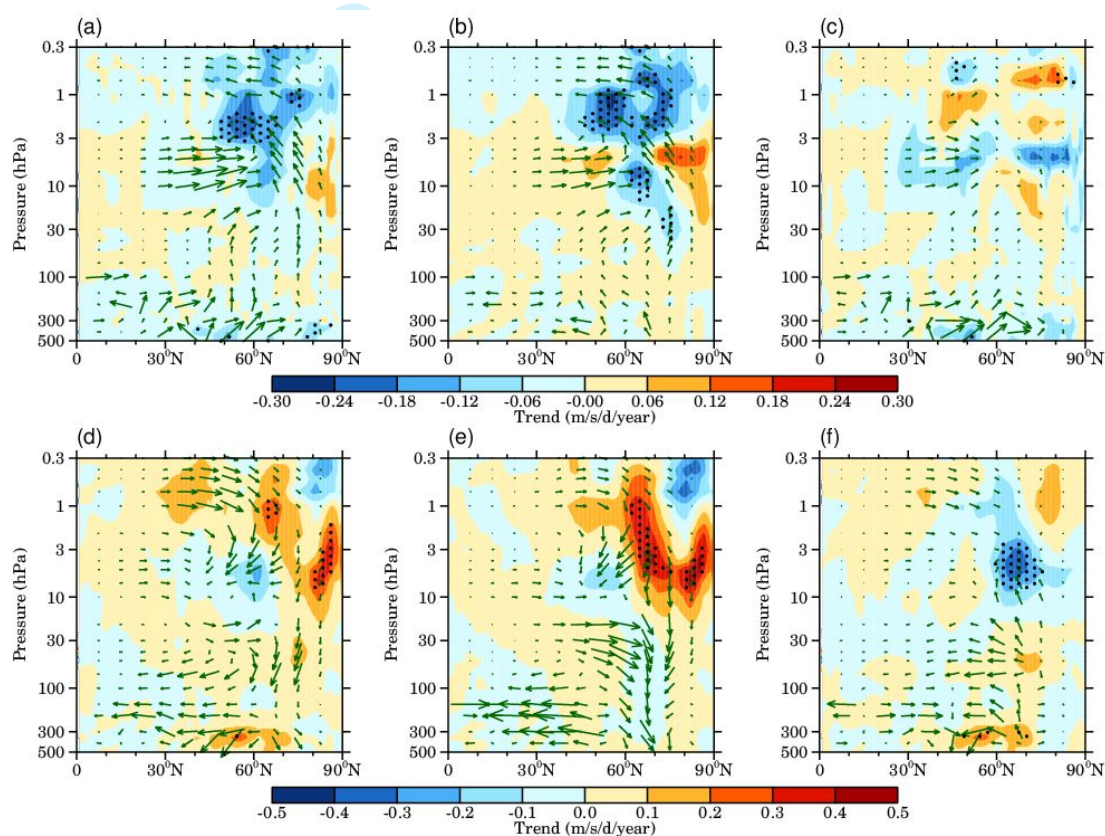
#### 301 4. Factors Responsible for the Temperature Trends

302 The previous section mentioned that the zonally asymmetric temperature trends  
 303 near the NH stratopause result from changes in the zonal temperature deviations and  
 304 may be controlled by thermodynamic factors. France et al. (2012) reported that the  
 305 advection and dissipation of quasi-stationary planetary waves could largely influence  
 306 the spatial structure of temperatures at mid-high latitudes in the upper stratosphere.  
 307 Therefore, the contributions of wave activities to the zonally asymmetric temperature  
 308 trends are first examined here. Figs. 4a and 4d shows the latitude-height distributions  
 309 of the trends in the EP flux (green vectors) and its divergence (color shading) during  
 310 January from 1980 to 2003 and from 2003 to 2020 derived from MERRA-2 reanalysis

311 datasets, respectively. The signs of trends in EP flux are upward (downward) from the  
312 troposphere to the lower mesosphere at mid-high latitudes, indicating enhanced  
313 (weakened) wave activities throughout the troposphere and stratosphere before (after)  
314 the 2000s. In particular, the magnitudes of EP flux trends are robust in the mid-high  
315 latitude USLM, where the zonally asymmetric temperature trends exist. The negative  
316 (positive) trend in EP flux divergence is robust and statistically significant near the mid-  
317 high latitudes stratopause, supporting the enhanced (weakened) wave activities are  
318 most pronounced near the mid-high latitudes stratopause before (after) the 2000s. The  
319 trends of EP flux and its divergence in Fig. 4a are generally opposite to those in Fig.  
320 4d, indicating the intensity of wave activities also underwent a transition around the  
321 2000s from the troposphere to the lower mesosphere at mid-high latitudes.

322 According to Fig. 3, the climatology and trends of the zonal temperature deviations  
323 in the mid-high latitude USLM display a wave 1 pattern, suggesting that wave 1  
324 activities may play a key role in modulating zonal temperature deviations. Therefore,  
325 we separate total waves into wave 1 and residual waves. Figs. 4b and 4e are the same  
326 as Figs. 4a and 4d, but for the EP flux and its divergence associated with wave 1,  
327 respectively. Figs. 4c and 4f are the same as Figs. 4a and 4d, but for the EP flux and its  
328 divergence associated with residual waves, respectively. The morphology and  
329 magnitude shown in Fig. 4b (4e) are much similar to those in Fig. 4a (Fig. 4d),  
330 confirming that the intensity of wave 1 are enhanced (weakened) before (after) the  
331 2000s, and the changes in wave activities are dominated by changes in wave 1 activities.  
332 Besides, Fig. 4c depicts that the EP flux and its divergence associated with residual

333 waves do not show statistically significant changes in the USLM from 1980 to 2003.  
 334 Fig. 4f presents a statistically significant negative trend in EP flux divergence in the  
 335 high latitude upper stratosphere, along with the upward sign of the EP flux trend, which  
 336 indicates that the intensity of residual waves is enhanced in this region from 2003 to  
 337 2020 but is contrary to that of wave 1 (Fig. 4e). The combine effects of enhanced  
 338 residual waves and weakened wave 1 result in slightly weakened total waves in this  
 339 region (Fig. 4d).



340

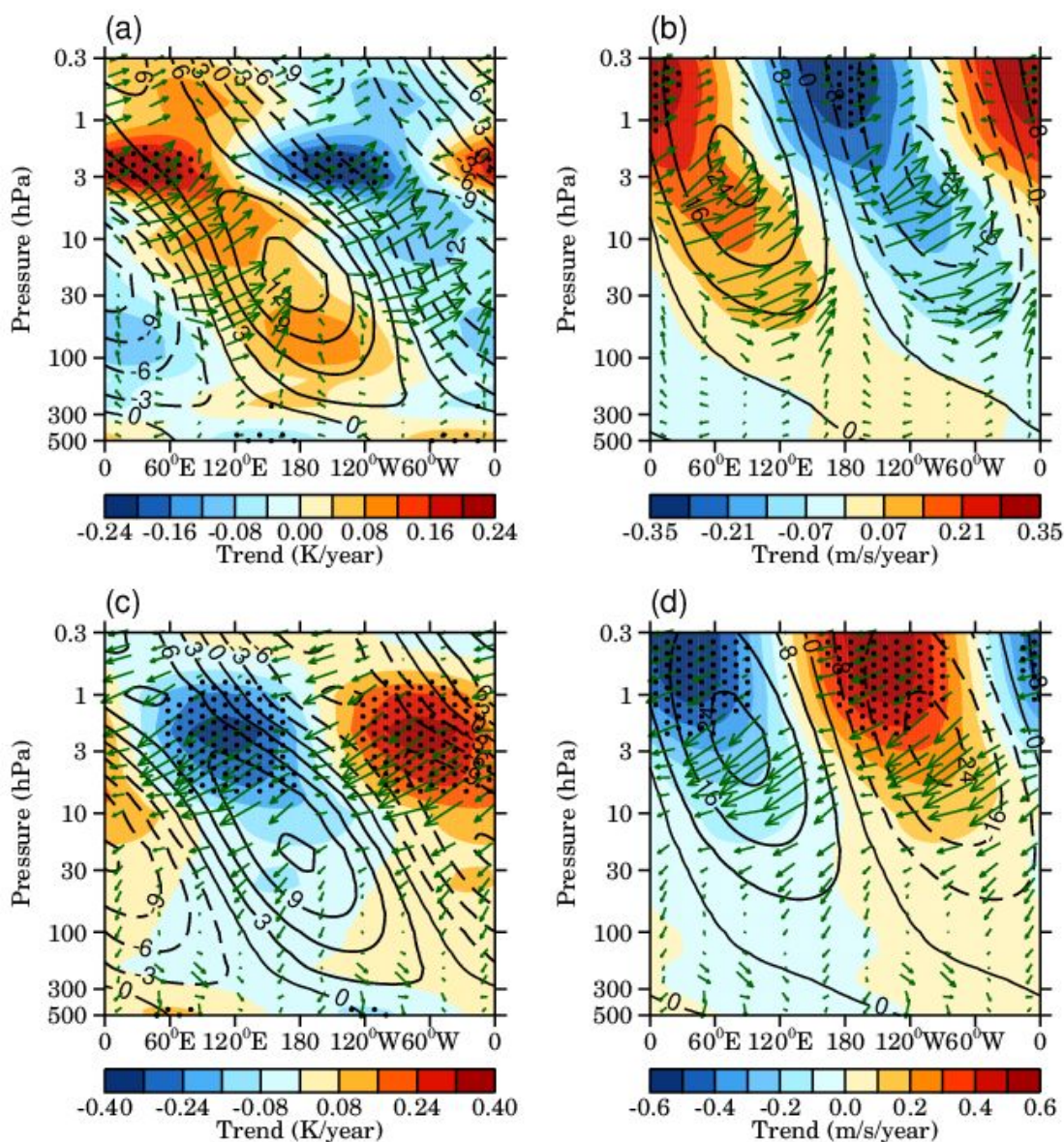
341 **Fig. 4.** (a) Latitude-height distribution of trends in Eliassen-Palm (EP) fluxes (green  
 342 vectors, units in the horizontal and vertical components are  $10^{-2}$  and  $10^{-4}$   $m^2/s^2/year$ ,  
 343 respectively) and the EP flux divergence (color shading) in January during the period  
 344 from 1980 to 2003. (b) The same as (a), but for the EP flux and its divergence associated

345 with wave 1. (c) The same as (a), but for the EP flux and its divergence associated with  
346 residual waves. (d), (e), and (f) are the same as (a), (b), and (c), respectively, but the  
347 time period is from 2003 to 2020. The EP fluxes are multiplied by the square root of  
348  $1000/\text{pressure (hPa)}$ . The trends over stippled areas are statistically significant at the 95%  
349 confidence level according to Student's t test. The results are derived from the  
350 MERRA-2 reanalysis dataset.

351 Since the changes in zonal mean wave 1 activities underwent a transition around  
352 the 2000s, which is coincident with the changes in the zonally asymmetric temperature  
353 trend pattern, we further examine the zonal variations in wave 1 and the effects of wave  
354 1 on the zonally asymmetric temperature variations. Figs. 5a and 5c present the  
355 longitude-height cross sections of the trends (color shading) and climatology (black  
356 contours) of temperature associated with wave 1 at 70°N during January from 1980 to  
357 2003 and from 2003 to 2020 derived from the MERRA-2 reanalysis dataset,  
358 respectively. The temperature trends associated with wave 1 tilt westward with heights  
359 and are generally in phase (out of phase) with their climatology throughout the  
360 stratosphere, indicating enhanced (weakened) wave 1 activities before (after) the 2000s.  
361 In particular, the temperature trends associated with wave 1 are robust and statistically  
362 significant near the stratopause. The results in Fig. 5 are comparable to those in Fig. 3  
363 in the USLM, indicating the changes in wave 1 are responsible for the changes in zonal  
364 temperature deviations. Moreover, Both Figs. 5a and 5c show statistically significant  
365 temperature trends associated with wave 1 in the troposphere, suggesting significant  
366 changes in the tropospheric wave 1 before and after the 2000s, respectively. The green

367 vectors superimposed on Figs. 5a and 5c are the trends of Plumb fluxes associated with  
368 wave 1. The signs of the trends of Plumb flux associated with wave 1 are upward  
369 (downward) from the troposphere and the lower mesosphere, which further supports  
370 enhanced (weakened) wave 1 activities from the troposphere and the lower mesosphere  
371 within the whole latitudinal band before (after) the 2000s.

372 Figs. 5b and 5d are the same as Figs. 5a and 5c, respectively, but for the meridional  
373 wind associated with wave 1. Likewise, the trend of the meridional wind associated  
374 with wave 1 is in phase (out of phase) with the climatology of the meridional wind  
375 associated with wave 1 from the troposphere to the lower mesosphere before (after) the  
376 2000s. The strongest amplitude of the meridional wind associated with wave 1 is near  
377 the stratopause and dominates the meridional wind there (Andrews et al, 1987). The  
378 poleward (equatorward) meridional wind associated with wave 1 induces warm (cold)  
379 meridional temperature advection in the eastern (western) hemispheres near the  
380 stratopause, resulting in the climatological high-temperature (low-temperature) mainly  
381 located in the eastern (western) hemispheres. Since the intensity of wave 1 is  
382 strengthened (weakened) before (after) the 2000s, it enhances (reduces) the meridional  
383 temperature advection near the stratopause; consequently, the zonally asymmetric  
384 trends in zonal temperature deviations are in phase (out of phase) with their climatology  
385 near the stratopause. Gabriel et al. (2007, 2011a) also noted that the wave 1 structure  
386 of temperature near the stratopause is controlled by zonally asymmetric transport by  
387 geostrophically balanced winds.



388

389 **Fig. 5.** Longitude-height cross sections of the trends (color shading) and climatology  
 390 (black contours, the contour interval is 3 K, solid and dashed lines indicate positive and  
 391 negative values, respectively) of (a) the temperature associated with wave 1 and (b) the  
 392 meridional wind associated with wave 1 at 70°N from 1980 to 2003, respectively. (c)  
 393 and (d) are the same as (a) and (b), respectively, but the time period is from 2003 to  
 394 2020. The green vectors denote Plumb flux trends associated with wave 1 (units in the  
 395 horizontal and vertical components are  $10^{-2}$  and  $10^{-4}$   $m^2/s^2/year$ , respectively). The  
 396 vertical and horizontal wave fluxes are multiplied by the square root of 1000/pressure

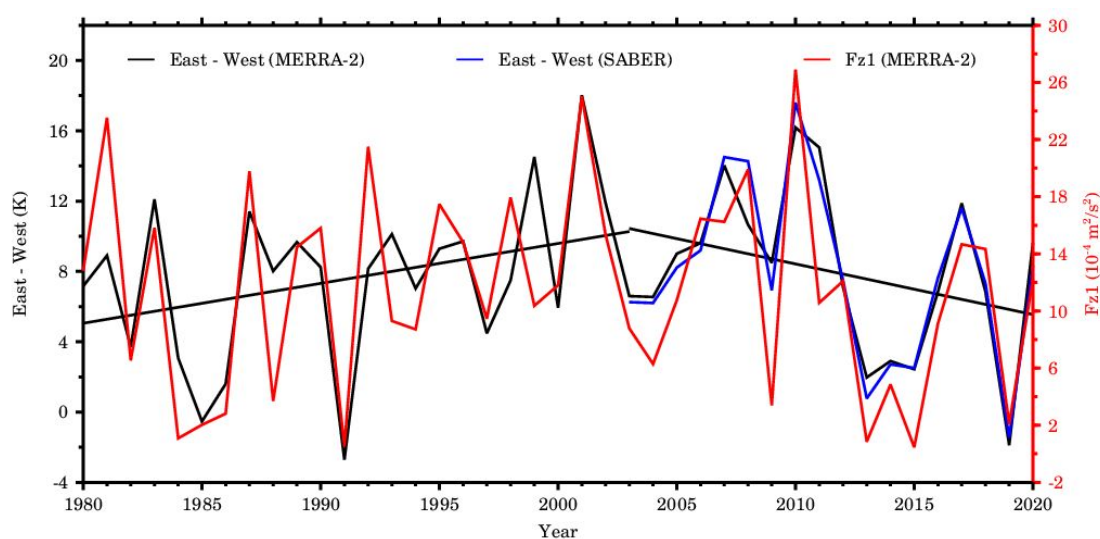
20

397 (hPa). The stippled areas are statistically significant at the 95% confidence level  
398 according to Student's t test. The results are derived from the MERRA-2 dataset.

399 The long-term correlations between the zonally asymmetric temperature variations  
400 and the corresponding wave 1 component are shown in Fig. 6. The black line denotes  
401 the time series of the temperature differences between the climatology high-  
402 temperature region (50°N-70°N, 30°E-180°E) and climatology low-temperature region  
403 (50°N-70°N, 0-150°W) at 3 hPa (hereafter referred to as East–West) during January  
404 from 1980 to 2020 derived from the MERRA-2 reanalysis dataset. The red line denotes  
405 the time series of the vertical wave flux associated with wave 1 averaged between 40°N-  
406 70°N at 3 hPa (hereafter referred to as Fz1) during January from 1980 to 2020 derived  
407 from the MERRA-2 reanalysis dataset. It is seen that there is a strong correlation  
408 between wave 1 and hemispheric temperature differences near the stratopause. The  
409 correlation coefficient between Fz1 and East–West is 0.79 (0.77 when removing their  
410 linear trends), which is statistically significant at the 99% confidence level. Moreover,  
411 there is an apparent transition in the East–West (Fz1) around the 2000s, with a  
412 statistically significant increasing (decreasing) trend from 1980 to 2003 (2003 to 2020)  
413 during January. The increasing trend in East–West (Fz1) is 0.24 K/year ( $2.1 \times 10^{-5}$   
414  $\text{m}^2/\text{s}^2/\text{year}$ ), and the decreasing trend in East–West (Fz1) is -0.30 K/year ( $-2.7 \times 10^{-5}$   
415  $\text{m}^2/\text{s}^2/\text{year}$ ). Furthermore, Fz1 can explain 61% (64%) of the East–West variance and  
416 has a 60% (62%) contribution to the East–West trend from 1980 to 2003 (from 2003 to  
417 2020) during January, as estimated from the linear regression method. Overall, the  
418 changes in the intensity of wave 1 can adequately explain the zonally asymmetric

419 temperature trends near the stratopause.

420 The East–West time series during January from 2003 to 2020 derived from  
 421 TIMED/SABER observations is shown by the green line in Fig. 6. The East–West time  
 422 series derived from TIMED/SABER observations agrees well with that derived from  
 423 the MERRA-2 reanalysis dataset, with a 0.96 correlation coefficient.



424

425 **Fig. 6.** Time series of the differences between the climatology of the high-temperature  
 426 region ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ ) and the climatology of the low-temperature region  
 427 ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $0$ - $150^{\circ}\text{W}$ ) at 3 hPa (East–West) during January derived from the  
 428 MERRA-2 reanalysis data (black line) and TIMED/SABER observations (green line),  
 429 respectively, as well as the vertical wave flux associated with wave 1 (Fz1) averaged  
 430 between  $50^{\circ}\text{N}$  -  $70^{\circ}\text{N}$  at 3 hPa (red line). The black straight lines are linear fits of the  
 431 East–West during 1980–2003 and 2003–2020 derived from MERRA-2 reanalysis  
 432 dataset.

433 It should be noted that the downwelling of the Brewer-Dobson circulation (BDC)  
 434 may also affect the stratospheric temperature via adiabatic processes. Lin et al. (2009)

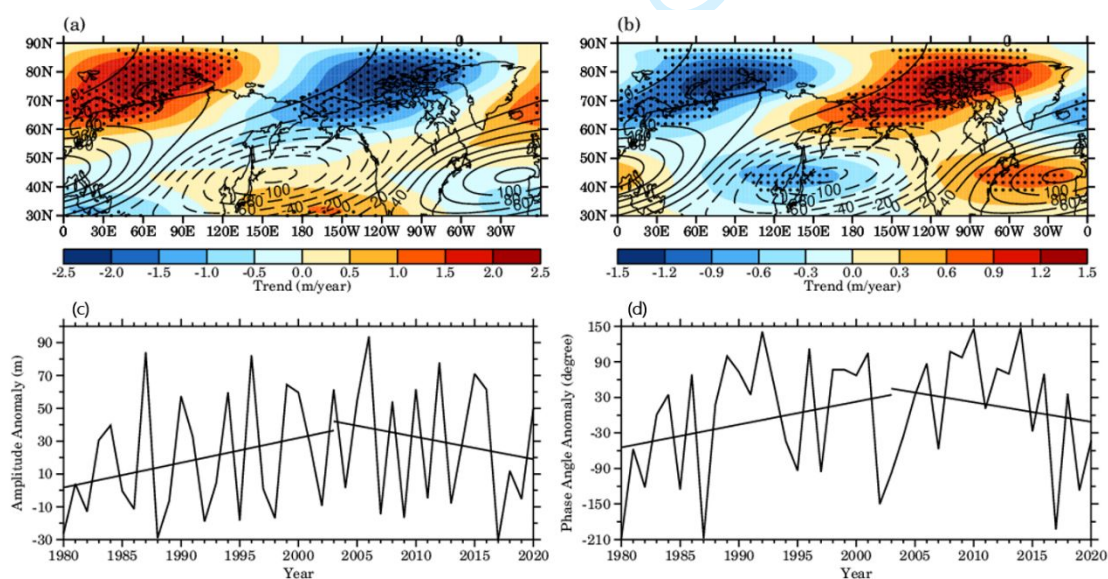


435 noted that enhanced BDC led to dynamic warming and produced a zonally asymmetric  
436 structure along with ozone-induced radiative cooling in the lower and middle  
437 stratosphere during September and October from 1979 to 2007. Thus, a zonally  
438 asymmetric pattern in temperature near the stratopause may be induced not only by the  
439 meridional advection of wave 1 but also by the effects of BDC. However, our analysis  
440 reveals that the residual vertical velocity in the stratosphere (i.e., the downwelling of  
441 BDC) does not have statistically significant changes, which agrees with Fu et al. (2019,  
442 Fig. 3). Therefore, the BDC contributes slightly to the zonally asymmetric temperature  
443 trends during the study period.

444 The intensity of the stratospheric stationary planetary waves is affected by the  
445 tropospheric wave source (e.g., Matsuno, 1970). Thus, the shift in the intensity of wave  
446 1 near the stratopause may also induced by the shift in intensity of tropospheric wave 1  
447 source. Figs. 7a and 7b present the spatial map of trends in 500-hPa geopotential height  
448 associated with wave 1 during January from 1980-2003 and from 2003-2020 derived  
449 from MERRA-2 reanalysis dataset, respectively. Black contour lines overlapped in Figs.  
450 7a and 7b denote the climatology of 500-hPa geopotential height associated with wave  
451 1. It is seen that a transition in the intensity of the tropospheric wave 1 around the 2000s.  
452 There is a statistically significant increasing (decreasing) trend in the geopotential  
453 height over the eastern European and a statistically significant decreasing (increasing)  
454 trend in the geopotential height over North Pacific at mid-high latitude before (after)  
455 the 2000s, which is generally in phase (out of phase) with the climatological eastern  
456 European high and the North Pacific low, respectively, indicating an enhanced

457 (weakened) wave 1 in the mid-high latitude troposphere before (after) the 2000s.  
 458 Garfinkel et al. (2010) noted that the in phase (out of phase) of geopotential height  
 459 anomalies in the eastern European high and the North Pacific low in the troposphere  
 460 can constructively (destructively) interfere with the tropospheric wave 1 and thus  
 461 enhance (weaken) the stratospheric wave 1.

462 Figs. 7c and 7d show the time series of the amplitude and phase anomaly of 500-  
 463 hPa geopotential height associated with wave 1 at 70°N, respectively. The trend in wave  
 464 1 amplitude also underwent a transition before (1.6 m/year) and after (-1.1 m/year) the  
 465 2000s, which agrees with the results in Figs 7a and 7b. According to Smith et al. (2010),  
 466 The increasing trend in phase of wave 1 before the 2000s (3.9 degree/year) and  
 467 decreasing trend in phase of wave 1 after the 2000s (-3.3 degree/year), further  
 468 supporting the constructively and destructively interfere with the tropospheric wave 1  
 469 before and after the 2000s, respectively.



470

471 **Fig. 7.** (a) The spatial map of trends (color shading) and climatology (black contours,  
 472 the contour interval is 20 m, solid and dashed lines indicate positive and negative values,

473 respectively) of 500-hPa geopotential height associated with wave 1 during January  
474 from 1980 to 2003 derived from MERRA-2 reanalysis data. (b) The same as (a), but  
475 the time period is from 2003 to 2020. The values over stippled areas are statistically  
476 significant at the 90% confidence level according to Student's t test. (c) Time series of  
477 the amplitude of 500-hPa geopotential height associated with wave 1 at 70°N. The black  
478 straight lines are linear fits of the amplitude during 1980–2003 and 2003–2020,  
479 respectively. (d) is the same as (c), but for the phase of 500-hPa geopotential height  
480 associated with wave 1.

## 481 **5. Conclusions and discussion**

482 In this study, TIMED/SABER satellite observations and the MERRA-2 reanalysis  
483 dataset were used to investigate the spatial variations in the temperature trend near the  
484 NH stratopause during January from 1980 to 2020 and the possible factors responsible  
485 for these trends. We find that there is a zonally asymmetric temperature trend pattern  
486 near the northern mid-high latitude stratopause during January. There was a warming  
487 (cooling) trend in the eastern (western) hemisphere near the stratopause before the  
488 2000s. However, a reversed zonally asymmetric temperature trend in the east-west  
489 direction was identified after the 2000s. Although the warming trends are statistically  
490 insignificant, they contrasted with the overall cooling trend in the upper stratosphere  
491 due to ozone depletion and increasing well-mixed GHGs in recent decades. Both  
492 datasets reveal that the zonal mean temperature has an overall cooling trend during the  
493 northern winter near the stratopause. The temperature deviations from the zonal mean  
494 have similar zonally asymmetric trends and are in phase (out of phase) with the

495 climatology of the zonal temperature deviations before (after) the 2000s. Moreover, the  
496 zonally asymmetric trend in zonal temperature deviations tilts westward with height in  
497 the USLM and is most pronounced near the stratopause. The results derived from the  
498 MERRA-2 reanalysis dataset agree well with those derived from TIMED/SABER  
499 temperature observations in both morphology and magnitude during the  
500 TIMED/SABER satellite era.

501 Further analysis reveals that the meridional perturbation of wave 1 dominates the  
502 meridional wind near the stratopause, resulting in the zonally asymmetric pattern of the  
503 zonal temperature deviations. The increasing (decreasing) trend in the strength of wave  
504 1 enhances (reduce) its meridional temperature advection near the stratopause before  
505 (after) the 2000s. Consequently, zonally asymmetric temperature trends alter in the  
506 east-west direction after (before) the 2000s. The effects of meridional temperature  
507 advection of wave 1 on the temperature in the USLM have also been reported in  
508 previous studies (e.g., Gabriel et al., 2011a). The results derived from the MERRA-2  
509 reanalysis dataset indicate that wave 1 has a close correlation with the zonally  
510 asymmetric temperature pattern, with a statistically significant correlation coefficient  
511 of 0.79 (0.77 when removing their linear trends). The temperature variations associated  
512 with wave 1 can explain 61% (64%) of the variance in the zonally asymmetric  
513 temperature variations and contribute 60% (62%) to the zonally asymmetric  
514 temperature trend during January from 1980 to 2003 (from 2003 to 2020).

515 The tropospheric wave 1 at mid-high latitudes shows a strengthening (weakening)  
516 trend during January from 1980 to 2003 (from 2003 to 2020), which is in accordance

517 with the transition in the trend of stratospheric wave 1 intensity around the 2000s. The  
518 in phase (out of phase) of 500-hPa geopotential height anomalies in the eastern  
519 European high and the North Pacific low can constructively (destructively) interfere  
520 with the tropospheric wave 1 and thus enhance (weaken) the stratospheric wave 1  
521 before (after) the 2000s. In addition, some studies have reported that the zonally  
522 asymmetric temperature variations near the stratopause can be modulated by 11-year  
523 solar cycles via their impact on wave 1 (Kodera and Kudora, 2002; Gabriel et al., 2011b;  
524 Liu et al., 2023). The effects of 11-year solar cycles on the zonally asymmetric  
525 temperature pattern will be investigated in future work.

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1 **Zonally Asymmetric Temperature Trends near**  
2 **the Northern Middle and High Latitude**  
3 **Stratopause during Winter**

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30

**Abstract**

31 The temperature trend near the stratopause is rarely evaluated owing to the limited long-  
32 term observations of global temperature. In this study, the spatial patterns of the  
33 temperature trends near the stratopause are investigated using satellite and reanalysis  
34 datasets. Our analysis reveals a zonally asymmetric temperature trend pattern near the  
35 northern mid-to-high latitude stratopause during January, and this pattern underwent an  
36 evident transition around the 2000s. From 1980 to 2003, there was a cooling trend in  
37 the western hemisphere and a warming trend in the eastern hemisphere. In contrast, a  
38 reversed zonally asymmetric temperature trend pattern existed in the east-west direction  
39 from 2003 to 2020. Although the warming trends are statistically insignificant, they  
40 contrasted with the overall cooling trend in the upper stratosphere due to ozone  
41 depletion and an increase in well-mixed greenhouse gases in recent decades. The  
42 zonally asymmetric temperature trends were induced by the transition in the intensity  
43 of quasi-stationary planetary wavenumber 1 (wave 1) near the stratopause. The  
44 increasing (decreasing) trend of the intensity of wave 1 enhanced (reduced) its  
45 meridional temperature advection near the stratopause before (after) the 2000s,  
46 consequently, a zonally asymmetric temperature trend pattern exists in the east-west  
47 direction near the stratopause. The transition in the intensity of the stratospheric wave  
48 1 around the 2000s is most likely caused by the transition in the intensity of wave 1  
49 activity in the troposphere.

50 Key words: Stratospheric temperature trend, zonally asymmetric temperature pattern,  
51 quasi-stationary planetary wavenumber 1

## 1. Introduction

The stratospheric temperature is a crucial climate marker that is affected by both thermal-dynamic and chemical processes. In response to ozone depletion and increasing well-mixed greenhouse gases (GHGs), the stratospheric temperature has experienced a significant cooling trend over the past several decades, which has been noted by a wide variety of observations and reproduced by multiple climate models (e.g., Golitsyn et al., 1996; Ramaswamy et al., 2001; Wang et al., 2012; Thompson et al., 2009, 2012; Randel et al., 2009, 2017; Rao et al., 2015; Garcia et al., 2019; Remsberg, 2019; Steiner et al., 2020). Notably, recently updated and extended satellite data has provided relatively reliable zonal mean temperature observations throughout the stratosphere and revealed that the zonal mean temperature trends decreased with altitude from the lower stratosphere to the upper stratosphere from 1979 to 2015 (McLandress et al., 2015; Randel et al., 2016; Zou and Qian, 2016). However, the long-term trends in stratospheric temperature still have uncertainties in both their magnitudes and spatial variations (e.g., Shine et al., 2003; Fu et al., 2010; Seidel et al., 2011; Funatsu et al., 2016; Maycock et al., 2018). These uncertainties are partly due to discrepancies in different observations (e.g., Zou et al., 2009; Thompson et al., 2012; Keckhut et al., 2019; Seidel et al., 2016) and are partly relate to the challenges involved in clarifying the factors that contribute to stratospheric temperature trends (e.g., Hu and Fu, 2009; Hu et al., 2009; Ivy et al., 2016; Xia et al., 2020; Zhou et al., 2022).

Various factors may influence temperature trends in the stratosphere. Although well-mixed GHGs are still increasing, a weak recovery signal has appeared in



74 stratospheric ozone in the last two decades (e.g., Hu et al., 2015; Chipperfield et al.,  
75 2017). Consequently, future trends in stratospheric temperatures (Arblaster et al., 2014;  
76 WMO, 2018) will mainly result from the opposing effects of increasing CO<sub>2</sub> (colder  
77 stratosphere) and increasing ozone (the warmer stratosphere). Moreover, the increasing  
78 stratospheric water vapor and volcanic aerosols have potentially impacted the  
79 temperature trends in the tropical lower stratosphere in recent decades (e.g., Maycock  
80 et al., 2014). Apart from the radiative contributions of chemical constituents, dynamic  
81 processes also have a large impact on stratospheric temperature trends, particularly at  
82 middle and high latitudes. It is known that temperatures in the stratosphere at middle  
83 and high latitudes are dominated by both the radiative balance and dynamic heating  
84 originating from tropospheric wave forcing (Andrews et al., 1987; Haynes, 2005; He et  
85 al., 2022). Given that GHGs trends are monotonically increasing, the temperature trends  
86 in the stratosphere at middle and high latitudes are strongly modulated by changes in  
87 planetary wave forcing in the stratosphere (Hu and Tung, 2002; Fu et al., 2019). As a  
88 result, the large interannual and decadal variations in dynamical forcing may lead to  
89 large uncertainties in stratospheric temperature trends (e.g., Matsuno, 1971; Yamashita  
90 et al., 2010; Long et al., 2017).

91 On the other hand, previous studies have mainly focused on trends in global or  
92 zonal mean temperatures in the stratosphere, but the longitudinal variations in the  
93 temperature trend in the stratosphere have rarely been evaluated. In particular, the  
94 spatial variations in the temperature trend near the stratopause are still poorly  
95 understood due to the shortage of long-term global observations there. It is well known

96 that the polar night jet is persistent in the Northern Hemisphere (NH) winter, indicating  
97 strong baroclinicity there (France and Harvey, 2013; Harvey et al., 2002). Harvey and  
98 Hitchman (1996) noted that the maximum longitudinal differences between the  
99 Aleutian High and the polar vortex were located near the stratopause. In addition,  
100 previous studies have reported the shift in the tropospheric and stratospheric climate  
101 around the 2000s (e.g., Chen and Tung, 2014; Hu et al., 2019). However, whether the  
102 climate shift occurs near the stratopause is still unclear. Therefore, it is of interest to  
103 investigate the changes in the temperature near the stratopause in recent decades.

104 In this study, we employ the Modern-Era Retrospective Analysis for Research  
105 and Applications, version 2 (MERRA-2) reanalysis datasets from 1980 to 2020 and the  
106 TIMED/SABER satellite temperature data from 2003 to 2020 to investigate spatial  
107 variations in the temperature trend near the stratopause during the northern winter as  
108 well as the possible factors responsible for the temperature trends near the stratopause.  
109 The organization of our paper is as follows. Section 2 describes the data and method  
110 we used. In Section 3, we exhibit and compare the temperature trends near the  
111 stratopause during the northern winter derived from TIMED/SABER observations and  
112 the MERRA-2 reanalysis dataset. In Section 4, we investigate possible factors  
113 responsible for the temperature trends. The conclusions and discussions are  
114 summarized in Section 5.

## 115 **2. Data and Methods**

### 116 **2.1 Data**

117 SABER is an infrared limb sounder launched on the TIMED satellite, which

118 provides reliable global temperature data above the troposphere. Its latitudinal coverage  
119 ranges from a north-looking mode (53°S–83°N) to a south-looking mode (53°N–83°S)  
120 approximately every 60 days. The SABER temperature profiles have been retrieved  
121 from infrared emissions of CO<sub>2</sub> from approximately 16 km to 105 km altitude with an  
122 effective vertical resolution of 2 km. TIMED/SABER temperature has been evaluated  
123 by Remsberg et al. (2003, 2008). In this study, we use the TIMED/SABER (version  
124 2.0) temperature dataset from 2003 to 2020 and bin the data into 2° × 4° (longitude by  
125 latitude) monthly mean maps.

126 MERRA-2 is produced by the National Aeronautics and Space Administration  
127 (NASA) Global Modeling and Assimilation Office (GMAO). The temperature data  
128 from the Microwave Limb Sounder (MLS) are assimilated in MERRA-2 above 5 hPa,  
129 providing more accurate temperature data for the upper stratosphere than MERRA  
130 (Gelaro et al. (2017)). The zonal mean temperature comparisons between observations  
131 and reanalysis datasets, including MERRA-2, were investigated by Long et al. (2017).  
132 The MERRA-2 instM\_3d\_asm\_Np monthly mean datasets (Version 5.12.4) are used  
133 during the period from 1980 to 2020, with a horizontal resolution of 0.5° × 0.625°  
134 (latitude × longitude) and 42 vertical levels up to a height of 0.1 hPa.

## 135 **2.2 Method**

136 In this study, the Eliassen-Palm (EP) flux (Andrews et al., 1987) and the Plumb  
137 flux (Plumb, 1985) are applied to measure the strength and propagation of wave  
138 activities in two dimensions and three dimensions, respectively. The meridional ( $F^{(\varphi)}$ )  
139 and vertical ( $F^{(z)}$ ) components of the EP flux and its divergence ( $\nabla \cdot \mathbf{F}$ ) are defined as

140 follows:

$$141 \quad F^{(\varphi)} = \rho_0 a \cos \varphi \left( u_z \frac{\overline{v'\theta'}}{\theta_z} - \overline{u'v'} \right) \quad (1)$$

$$142 \quad F^{(z)} = \left( f - \frac{(\overline{u' \cos \varphi})_\varphi}{a \cos \varphi} \right) \frac{\overline{v'\theta'}}{\theta_z} - \overline{u'w'} \quad (2)$$

$$143 \quad \nabla \cdot \mathbf{F} = \frac{\partial F^{(\varphi)}}{\partial \varphi} + \frac{\partial F^{(z)}}{\partial z} \quad (3)$$

144 where  $\varphi$  is latitude,  $z$  is height,  $\rho$  is air density,  $a$  is the Earth's radius,  $f$  is the  
 145 Coriolis parameter,  $\theta$  is potential temperature,  $u$  is zonal wind,  $v$  is meridional  
 146 wind, and  $w$  is vertical wind. The overbars and primes denote the zonal mean and the  
 147 departure from the zonal mean, respectively. The subscript 0 is for the background  
 148 variables. The subscript  $z$  is for the partial derivative for the variables in the vertical  
 149 direction.

150 The longitude ( $F^{(\lambda)}$ ), latitude ( $F^{(\varphi)}$ ), and vertical ( $F^{(z)}$ ) components of the Plumb  
 151 flux and its divergence ( $\nabla \cdot \mathbf{F}$ ) are defined as follows:

$$152 \quad F^{(\lambda)} = \rho_0 \cos \varphi \left( \frac{1}{2a^2 \cos^2 \varphi} \left[ \left( \frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \right) \quad (4)$$

$$153 \quad F^{(\varphi)} = \rho_0 \cos \varphi \left( \frac{1}{2a^2 \cos^2 \varphi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \varphi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \varphi} \right] \right) \quad (5)$$

$$154 \quad F^{(z)} = \rho_0 \cos \varphi \left( \frac{2\Omega^2 \sin^2 \varphi}{N^2 a \cos \varphi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial z} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial z} \right] \right) \quad (6)$$

$$155 \quad \nabla \cdot \mathbf{F} = \frac{\partial F^{(\lambda)}}{\partial \lambda} + \frac{\partial F^{(\varphi)}}{\partial \varphi} + \frac{\partial F^{(z)}}{\partial z} \quad (7)$$

156 where  $\lambda$  is longitude,  $\Omega$  is the Earth's angular velocity,  $N$  is the Brunt-Väisälä  
 157 frequency,  $\psi = \Phi/2\Omega \sin \varphi$ , and  $\Phi$  is potential height.

### 158 **3. Temperature Trends Near the Stratopause during the** 159 **Northern Winter**

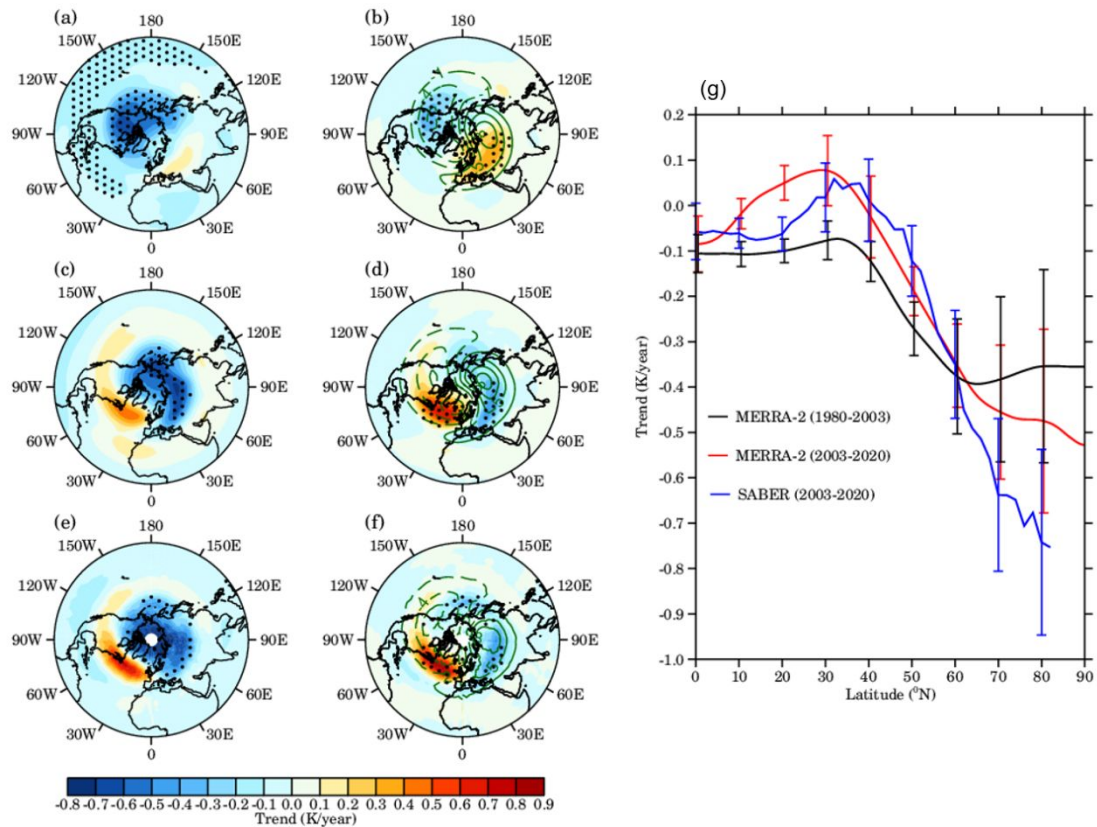
160 Figs. 1a and 1c present the spatial patterns of the 3 hPa temperature trends over the NH  
161 during January from 1980-2003 and from 2003-2020 derived from MERRA-2  
162 reanalysis data, respectively. A noticeable feature is that there is a zonally asymmetric  
163 pattern in temperature trends at mid-high latitudes shown in Fig. 1a, with a cooling  
164 trend in the western hemisphere and a warming trend in the eastern hemisphere. In  
165 contrast, a reversal temperature trend in the east-west direction can be noted in Fig. 1c,  
166 with a warming (cooling) trend in the western (eastern) hemisphere. Note that the  
167 results here are not sensitive to slight changes in the starting/ending year of the time  
168 series. Thompson et al. (2012) indicated that due to ozone depletion and increasing  
169 well-mixed GHGs in recent decades, the stratospheric cooling in the upper stratosphere  
170 is more robust than that in the lower-middle stratosphere. Hence, although these  
171 warming trends in Figs. 1a and 1c are statistically insignificant at the 95% confidence  
172 level, they contrast with the overall cooling trend in the upper stratosphere. To  
173 understand the unusual warming near the stratopause, we separate the temperature into  
174 two components, i.e., zonal mean and deviations from the zonal mean (hereafter zonal  
175 temperature deviations). The zonal mean temperature denotes the background field,  
176 which is dominated by chemical and radiative balances. The temperature deviations  
177 denote the disturbed field, which is largely controlled by adiabatic/diabatic  
178 thermodynamic processes.

179 Figs. 1b and 1d show the spatial patterns of trends in zonal temperature deviations  
180 at 3 hPa over the NH during January from 1998 to 2003 and from 2003 to 2020 derived  
181 from MERRA-2 reanalysis data, respectively. The trends in zonal temperature

182 deviations also present zonally asymmetric patterns at mid-high latitudes, with a  
183 statistically significant cooling (warming) trend in the western (eastern) hemisphere in  
184 Fig. 1b, and a reversal temperature trend in the east-west direction in Fig. 1d. The  
185 warming (cooling) trends in the zonal temperature deviations are stronger (weaker)  
186 compared to those in the original temperature. The green contours superimposed on  
187 Figs. 1b and 1d are the climatology of the zonal temperature deviations, which are  
188 likewise zonally asymmetric at mid-high latitudes, with negative (positive) anomalies  
189 in the western (eastern) hemisphere. The climatology of the zonal temperature  
190 deviations is generally in phase (out of phase) with the trends of the zonal temperature  
191 deviations in Fig. 1b (1d), suggesting that the zonal asymmetry of temperature  
192 variations was strengthened (weakened) before (after) the 2000s, and there was a  
193 transition in the zonally asymmetric temperature trend pattern around the 2000s.

194 The latitudinal variations in the 3 hPa zonal mean temperature trends over the NH  
195 during January from 1980 to 2003 and from 2003 to 2020 derived from MERRA-2  
196 reanalysis data are shown in Fig. 1g, respectively. The morphology of zonal mean  
197 temperature trend before the 2000s is similar to that after the 2000s. The zonal mean  
198 temperature trend is close to zero at lower latitudes but decreases with increasing  
199 latitudes at mid-high latitudes. Overall, the zonal mean temperature trend before/after  
200 the 2000s is cooling in the NH, which is consistent with the increase in well-mixed  
201 GHGs in recent decades. The results shown in Fig. 1 as derived from MERRA-2  
202 reanalysis data suggest that the zonal asymmetry of the temperature trends near the  
203 stratopause is the product of changes in disturbed fields.

204 To further verify the trends exhibited in Fig. 1 derived from MERRA-2 reanalysis  
205 data, TIMED/SABER satellite temperature observations (from 2003-2020) are  
206 analyzed. Figs. e, f, and g (blue line) are the same as Figs. c, d, and g (red line),  
207 respectively, but the data is derived from TIMED/SABER observations. It is seen that  
208 the zonally asymmetric temperature trend pattern is also apparent in TIMED/SABER  
209 observations, and the corresponding results derived from MERRA-2 reanalysis data  
210 agree well with those derived from TIMED/SABER observations in both morphology  
211 and magnitude. Since the temperature trends near the stratopause in MERRA-2  
212 reanalysis data are in good agreement with those from the TIMED/SABER temperature  
213 observations, the MERRA-2 dataset is utilized to investigate the possible factors  
214 responsible for the zonally asymmetric variations in the temperature. Note that the  
215 spatial pattern of 3 hPa temperature shows an almost uniform cooling trend over the  
216 NH during January from 1980 to 2020 derived from MERRA-2 reanalysis data (not  
217 shown).



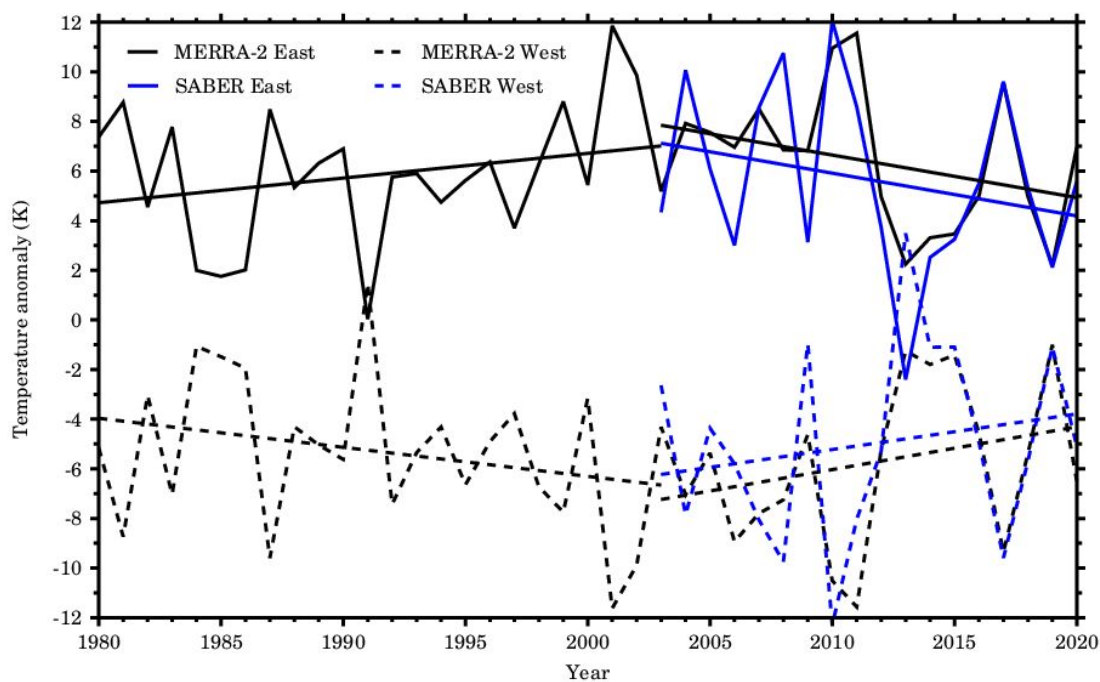
218

219 **Fig. 1.** Spatial pattern of trends in (a) temperature and (b) zonal temperature deviations  
 220 over the NH at 3 hPa during January from 1980 to 2003 derived from MERRA-2  
 221 reanalysis data. (c) and (d) are the same as (a) and (b), respectively, but the time period  
 222 is from 2003 to 2020. (e) and (f) are the same as (c) and (d), respectively, but the data  
 223 is derived from TIMED/SABER observations. The values over the stippled areas are  
 224 statistically significant at the 95% confidence level according to Student's t test. The  
 225 green contour lines denote the climatology of the zonal temperature deviations (the  
 226 contour interval is 3 K, solid and dashed lines indicate positive and negative values,  
 227 respectively). (g) Latitude variations in the zonal mean temperature trends over the NH  
 228 at 3 hPa during January from 1980 to 2003 derived from MERRA-2 reanalysis dataset  
 229 (black line), from 2003 to 2020 derived from MERRA-2 reanalysis dataset (red line),  
 230 and from 2003 to 2020 derived from TIMED/SABER observations (blue line). Error



231 bars show the  $2\sigma$  statistical uncertainty.

232 Fig. 2 presents the time series of the zonal temperature deviations averaged over  
233 the climatological high-temperature lobe (hereafter East) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ )  
234 (solid lines) and the climatological low-temperature lobe (hereafter West) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  
235  $0$ - $150^{\circ}\text{W}$ ) (dashed lines) at 3 hPa during January from 1980 to 2020 derived from  
236 MERRA-2 reanalysis data (black lines) and from 2003 to 2020 derived from  
237 TIME/SABER observations (blue lines), respectively. The straight lines represent the  
238 linear fits of the zonal temperature deviations before and after 2003, respectively. The  
239 time series of the zonal temperature deviations derived from MERRA-2 agree well with  
240 those derived from the TIMED/SABER observations in both magnitudes and variations.  
241 The East underwent a statistically significant increasing trend ( $0.1$  K/year) from 1980  
242 to 2003 and a statistically significant decreasing trend ( $-0.17$  K/year) from 2003 to 2020.  
243 The West has similar magnitudes but opposite signs in both interannual variations and  
244 long-term trends compared to the East, indicating a close negative correlation in the  
245 zonal temperature deviations between the two lobes. The correlation coefficients  
246 between the East and West are  $-0.89$  ( $-0.90$ ) derived from the MERRA-2 reanalysis  
247 data (TIMED/SABER observations). Note that the results here are not sensitive to slight  
248 changes in the latitude/longitude bounds used for averaging the data.



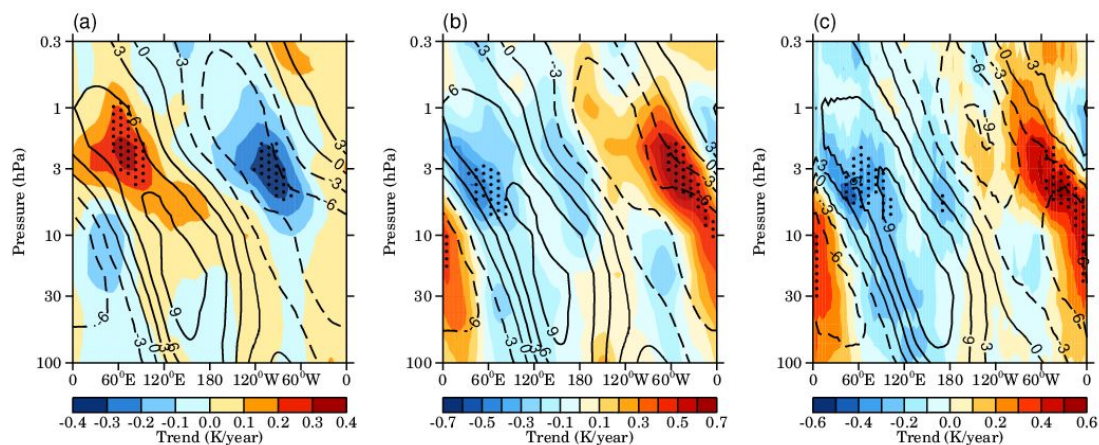
249

250 **Fig. 2.** Time series of the zonal temperature deviations averaged over the climatological  
 251 high-temperature lobe (hereafter East) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ ) (solid lines) and the  
 252 climatological low-temperature lobe (hereafter West) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $0$ - $150^{\circ}\text{W}$ ) (dashed  
 253 lines) at 3 hPa during January from 1980 to 2020 derived from the MERRA-2 reanalysis  
 254 data (black lines) and from 2003 to 2020 TIME/SABER observations (blue lines),  
 255 respectively. The straight lines represent the linear fits of the zonal temperature  
 256 deviations before and after 2003, respectively.

257 To depict the zonally asymmetric temperature trend variations with heights, Fig.  
 258 3 shows the longitude-height cross sections of the trends in zonal temperature deviation  
 259 at  $70^{\circ}\text{N}$  during January (a) from 1980 to 2003 derived from MERRA-2 reanalysis data,  
 260 (b) from 2003 to 2020 derived from MERRA-2 reanalysis data, and (c) from 2003 to  
 261 2020 derived from TIMED/SABER observations. The black contours superimposed on  
 262 Fig. 3 denote the climatology of the zonal temperature deviations. The climatology of  
 263 the zonal temperature deviations in the upper stratosphere and lower mesosphere

264 (hereinafter USLM) also present a zonally asymmetric pattern, with the climatological  
265 high-temperature (low-temperature) lobe mainly located in the eastern (western)  
266 hemisphere. The climatology of the zonal temperature deviations tilts westward with  
267 heights, exhibiting a pattern analogous to that of the quasi-stationary planetary  
268 wavenumber 1 (wave 1).

269 As shown in Fig. 3a, the trend in the zonal temperature deviation is generally in  
270 phase with the climatology of the zonal temperature deviation in the USLM, with a  
271 statistically significant warming (cooling) trend in the eastern (western) hemisphere  
272 near the stratopause before the 2000s. In contrast, Fig. 3b shows the trend in the zonal  
273 temperature deviation is generally out of phase with the climatology of the zonal  
274 temperature deviation in the USLM, with a statistically significant cooling (warming)  
275 trend mainly located in the eastern (western) hemisphere near the stratopause after the  
276 2000s. The longitude-height cross section of the zonal temperature deviation derived  
277 from MERRA-2 reanalysis data (Fig. 3b) is comparable to that derived from  
278 TIMED/SABER observations (Fig. 3c). The results in Fig. 3 further support that the  
279 zonally asymmetric temperature trend pattern undergoes a transition in the east-west  
280 direction around the 2000s and is most pronounced near the stratopause.



281

282 **Fig. 3.** Longitude-height cross sections of the trends (color shading) and climatology  
 283 (black contours, the contour interval is 3 K, solid and dashed lines indicate positive and  
 284 negative values, respectively) of zonal temperature deviations at 70°N during January  
 285 (a) from 1980 to 2003 derived from MERRA-2 reanalysis dataset, (b) from 2003 to  
 286 2020 derived from MERRA-2 reanalysis dataset, and (c) from 2003 to 2020 derived  
 287 from TIMED/SABER observations. The values over the stippled areas are statistically  
 288 significant at the 95% confidence level according to Student's t test.

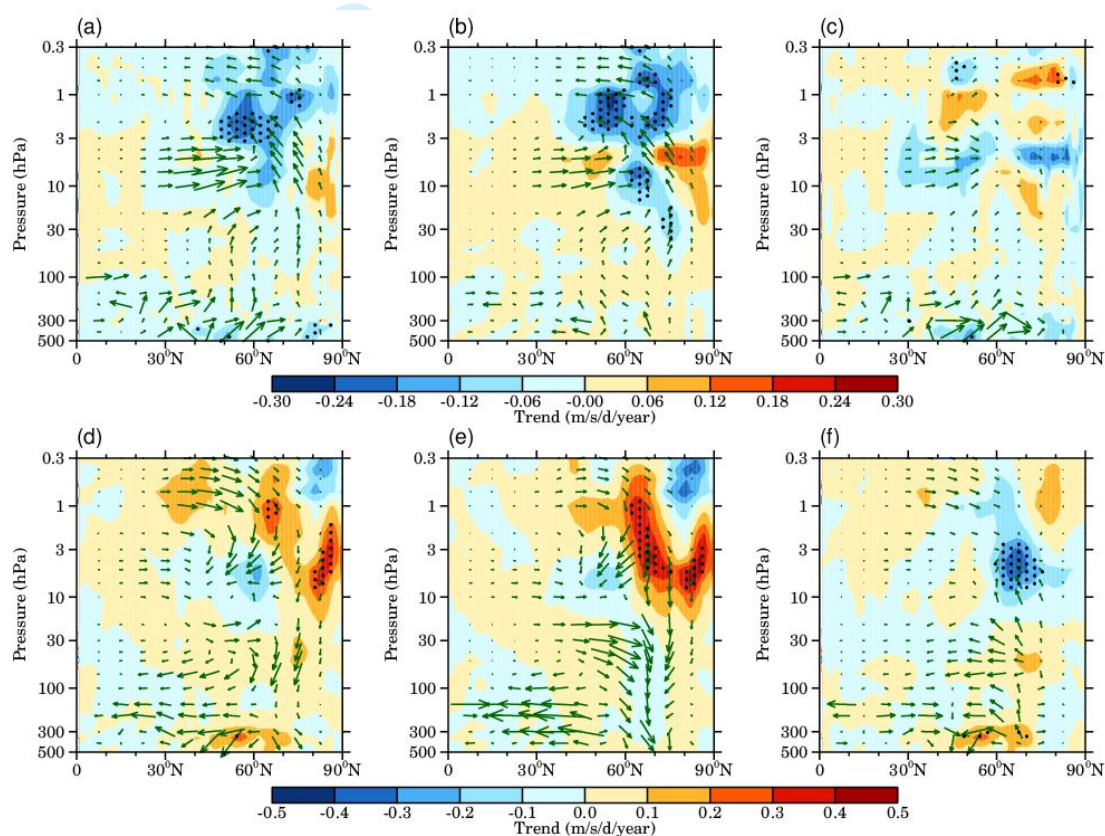
#### 289 4. Factors Responsible for the Temperature Trends

290 The previous section mentioned that the zonally asymmetric temperature trends  
 291 near the NH stratopause result from changes in the zonal temperature deviations and  
 292 may be controlled by thermodynamic factors. France et al. (2012) reported that the  
 293 advection and dissipation of quasi-stationary planetary waves could largely influence  
 294 the spatial structure of temperatures at mid-high latitudes in the upper stratosphere.  
 295 Therefore, the contributions of wave activities to the zonally asymmetric temperature  
 296 trends are first examined here. Figs. 4a and 4d shows the latitude-height distributions  
 297 of the trends in the EP flux (green vectors) and its divergence (color shading) during  
 298 January from 1980 to 2003 and from 2003 to 2020 derived from MERRA-2 reanalysis

299 datasets, respectively. The signs of trends in EP flux are upward (downward) from the  
300 troposphere to the lower mesosphere at mid-high latitudes, indicating enhanced  
301 (weakened) wave activities throughout the troposphere and stratosphere before (after)  
302 the 2000s. In particular, the magnitudes of EP flux trends are robust in the mid-high  
303 latitude USLM, where the zonally asymmetric temperature trends exist. The negative  
304 (positive) trend in EP flux divergence is robust and statistically significant near the mid-  
305 high latitudes stratopause, supporting the enhanced (weakened) wave activities are  
306 most pronounced near the mid-high latitudes stratopause before (after) the 2000s. The  
307 trends of EP flux and its divergence in Fig. 4a are generally opposite to those in Fig.  
308 4d, indicating the intensity of wave activities also underwent a transition around the  
309 2000s from the troposphere to the lower mesosphere at mid-high latitudes.

310 According to Fig. 3, the climatology and trends of the zonal temperature deviations  
311 in the mid-high latitude USLM display a wave 1 pattern, suggesting that wave 1  
312 activities may play a key role in modulating zonal temperature deviations. Therefore,  
313 we separate total waves into wave 1 and residual waves. Figs. 4b and 4e are the same  
314 as Figs. 4a and 4d, but for the EP flux and its divergence associated with wave 1,  
315 respectively. Figs. 4c and 4f are the same as Figs. 4a and 4d, but for the EP flux and its  
316 divergence associated with residual waves, respectively. The morphology and  
317 magnitude shown in Fig. 4b (4e) are much similar to those in Fig. 4a (Fig. 4d),  
318 confirming that the intensity of wave 1 are enhanced (weakened) before (after) the  
319 2000s, and the changes in wave activities are dominated by changes in wave 1 activities.  
320 Besides, Fig. 4c depicts that the EP flux and its divergence associated with residual

321 waves do not show statistically significant changes in the USLM from 1980 to 2003.  
 322 Fig. 4f presents a statistically significant negative trend in EP flux divergence in the  
 323 high latitude upper stratosphere, along with the upward sign of the EP flux trend, which  
 324 indicates that the intensity of residual waves is enhanced in this region from 2003 to  
 325 2020 but is contrary to that of wave 1 (Fig. 4e). The combine effects of enhanced  
 326 residual waves and weakened wave 1 result in slightly weakened total waves in this  
 327 region (Fig. 4d).



328

329 **Fig. 4.** (a) Latitude-height distribution of trends in Eliassen-Palm (EP) fluxes (green  
 330 vectors, units in the horizontal and vertical components are  $10^{-2}$  and  $10^{-4}$   $m^2/s^2/year$ ,  
 331 respectively) and the EP flux divergence (color shading) in January during the period  
 332 from 1980 to 2003. (b) The same as (a), but for the EP flux and its divergence associated

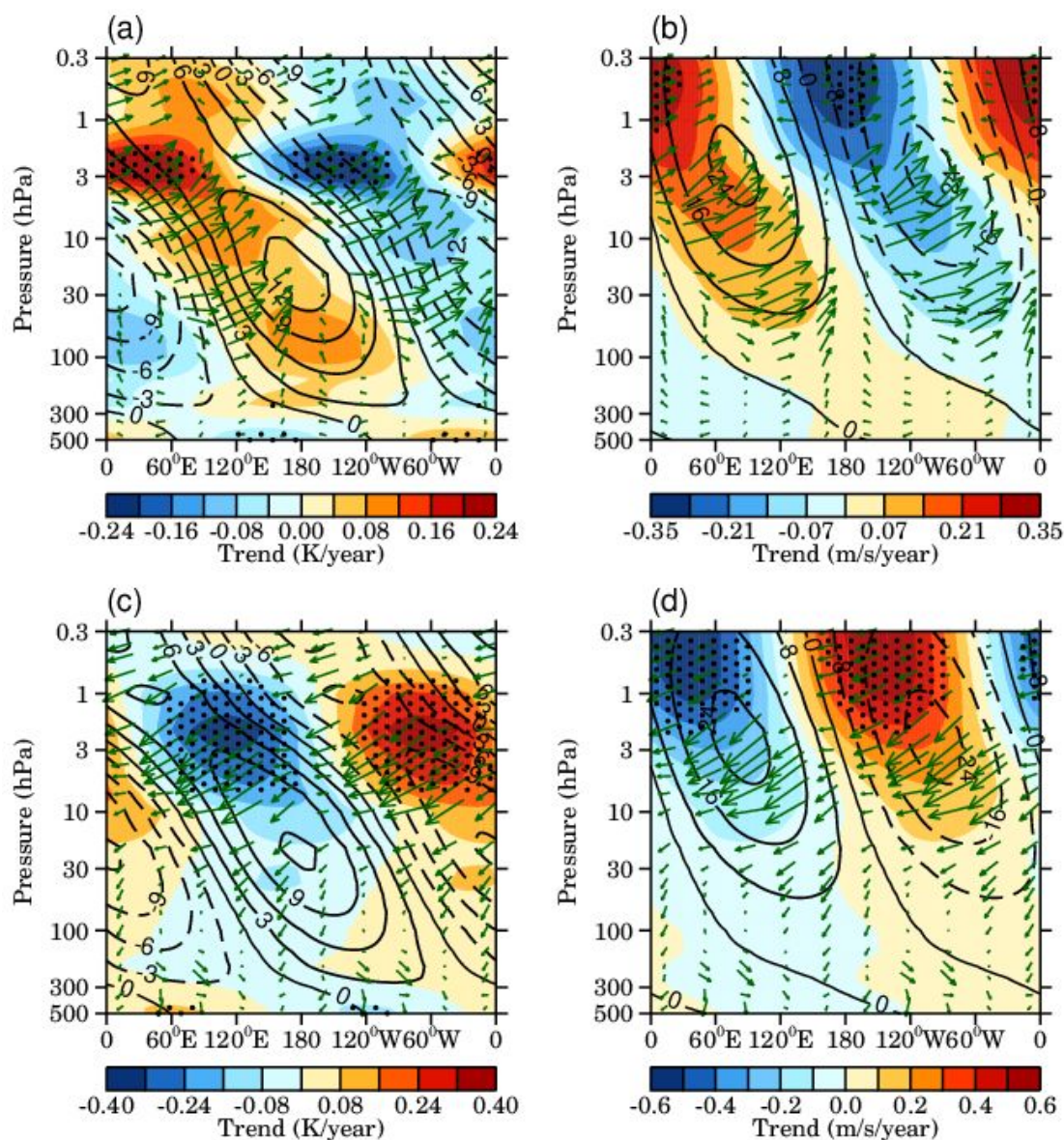
333 with wave 1. (c) The same as (a), but for the EP flux and its divergence associated with  
334 residual waves. (d), (e), and (f) are the same as (a), (b), and (c), respectively, but the  
335 time period is from 2003 to 2020. The EP fluxes are multiplied by the square root of  
336  $1000/\text{pressure (hPa)}$ . The trends over stippled areas are statistically significant at the 95%  
337 confidence level according to Student's t test. The results are derived from the  
338 MERRA-2 reanalysis dataset.

339 Since the changes in zonal mean wave 1 activities underwent a transition around  
340 the 2000s, which is coincident with the changes in the zonally asymmetric temperature  
341 trend pattern, we further examine the zonal variations in wave 1 and the effects of wave  
342 1 on the zonally asymmetric temperature variations. Figs. 5a and 5c present the  
343 longitude-height cross sections of the trends (color shading) and climatology (black  
344 contours) of temperature associated with wave 1 at  $70^\circ\text{N}$  during January from 1980 to  
345 2003 and from 2003 to 2020 derived from the MERRA-2 reanalysis dataset,  
346 respectively. The temperature trends associated with wave 1 tilt westward with heights  
347 and are generally in phase (out of phase) with their climatology throughout the  
348 stratosphere, indicating enhanced (weakened) wave 1 activities before (after) the 2000s.  
349 In particular, the temperature trends associated with wave 1 are robust and statistically  
350 significant near the stratopause. The results in Fig. 5 are comparable to those in Fig. 3  
351 in the USLM, indicating the changes in wave 1 are responsible for the changes in zonal  
352 temperature deviations. Moreover, Both Figs. 5a and 5c show statistically significant  
353 temperature trends associated with wave 1 in the troposphere, suggesting significant  
354 changes in the tropospheric wave 1 before and after the 2000s, respectively. The green

355 vectors superimposed on Figs. 5a and 5c are the trends of Plumb fluxes associated with  
356 wave 1. The signs of the trends of Plumb flux associated with wave 1 are upward  
357 (downward) from the troposphere and the lower mesosphere, which further supports  
358 enhanced (weakened) wave 1 activities from the troposphere and the lower mesosphere  
359 within the whole latitudinal band before (after) the 2000s.

360 Figs. 5b and 5d are the same as Figs. 5a and 5c, respectively, but for the meridional  
361 wind associated with wave 1. Likewise, the trend of the meridional wind associated  
362 with wave 1 is in phase (out of phase) with the climatology of the meridional wind  
363 associated with wave 1 from the troposphere to the lower mesosphere before (after) the  
364 2000s. The strongest amplitude of the meridional wind associated with wave 1 is near  
365 the stratopause and dominates the meridional wind there (Andrews et al, 1987). The  
366 poleward (equatorward) meridional wind associated with wave 1 induces warm (cold)  
367 meridional temperature advection in the eastern (western) hemispheres near the  
368 stratopause, resulting in the climatological high-temperature (low-temperature) mainly  
369 located in the eastern (western) hemispheres. Since the intensity of wave 1 is  
370 strengthened (weakened) before (after) the 2000s, it enhances (reduces) the meridional  
371 temperature advection near the stratopause; consequently, the zonally asymmetric  
372 trends in zonal temperature deviations are in phase (out of phase) with their climatology  
373 near the stratopause. Gabriel et al. (2007, 2011a) also noted that the wave 1 structure  
374 of temperature near the stratopause is controlled by zonally asymmetric transport by  
375 geostrophically balanced winds.





376

377 **Fig. 5.** Longitude-height cross sections of the trends (color shading) and climatology

378 (black contours, the contour interval is 3 K, solid and dashed lines indicate positive and

379 negative values, respectively) of (a) the temperature associated with wave 1 and (b) the

380 meridional wind associated with wave 1 at 70°N from 1980 to 2003, respectively. (c)

381 and (d) are the same as (a) and (b), respectively, but the time period is from 2003 to

382 2020. The green vectors denote Plumb flux trends associated with wave 1 (units in the

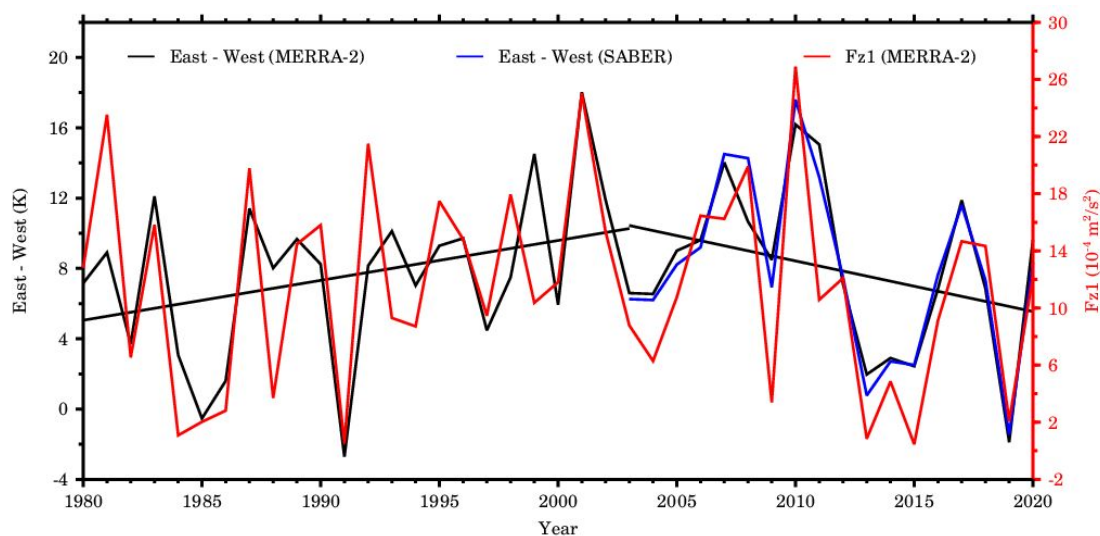
383 horizontal and vertical components are  $10^{-2}$  and  $10^{-4}$   $\text{m}^2/\text{s}^2/\text{year}$ , respectively). The384 vertical and horizontal wave fluxes are multiplied by the square root of  $1000/\text{pressure}$

385 (hPa). The stippled areas are statistically significant at the 95% confidence level  
386 according to Student's t test. The results are derived from the MERRA-2 dataset.

387 The long-term correlations between the zonally asymmetric temperature variations  
388 and the corresponding wave 1 component are shown in Fig. 6. The black line denotes  
389 the time series of the temperature differences between the climatology high-  
390 temperature region (50°N-70°N, 30°E-180°E) and climatology low-temperature region  
391 (50°N-70°N, 0-150°W) at 3 hPa (hereafter referred to as East–West) during January  
392 from 1980 to 2020 derived from the MERRA-2 reanalysis dataset. The red line denotes  
393 the time series of the vertical wave flux associated with wave 1 averaged between 40°N-  
394 70°N at 3 hPa (hereafter referred to as Fz1) during January from 1980 to 2020 derived  
395 from the MERRA-2 reanalysis dataset. It is seen that there is a strong correlation  
396 between wave 1 and hemispheric temperature differences near the stratopause. The  
397 correlation coefficient between Fz1 and East–West is 0.79 (0.77 when removing their  
398 linear trends), which is statistically significant at the 99% confidence level. Moreover,  
399 there is an apparent transition in the East–West (Fz1) around the 2000s, with a  
400 statistically significant increasing (decreasing) trend from 1980 to 2003 (2003 to 2020)  
401 during January. The increasing trend in East–West (Fz1) is 0.24 K/year ( $2.1 \times 10^{-5}$   
402  $\text{m}^2/\text{s}^2/\text{year}$ ), and the decreasing trend in East–West (Fz1) is -0.30 K/year ( $-2.7 \times 10^{-5}$   
403  $\text{m}^2/\text{s}^2/\text{year}$ ). Furthermore, Fz1 can explain 61% (64%) of the East–West variance and  
404 has a 60% (62%) contribution to the East–West trend from 1980 to 2003 (from 2003 to  
405 2020) during January, as estimated from the linear regression method. Overall, the  
406 changes in the intensity of wave 1 can adequately explain the zonally asymmetric

407 temperature trends near the stratopause.

408 The East–West time series during January from 2003 to 2020 derived from  
 409 TIMED/SABER observations is shown by the green line in Fig. 6. The East–West time  
 410 series derived from TIMED/SABER observations agrees well with that derived from  
 411 the MERRA-2 reanalysis dataset, with a 0.96 correlation coefficient.



412

413 **Fig. 6.** Time series of the differences between the climatology of the high-temperature  
 414 region ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ ) and the climatology of the low-temperature region  
 415 ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $0$ - $150^{\circ}\text{W}$ ) at 3 hPa (East–West) during January derived from the  
 416 MERRA-2 reanalysis data (black line) and TIMED/SABER observations (green line),  
 417 respectively, as well as the vertical wave flux associated with wave 1 (Fz1) averaged  
 418 between  $50^{\circ}\text{N}$  -  $70^{\circ}\text{N}$  at 3 hPa (red line). The black straight lines are linear fits of the  
 419 East–West during 1980–2003 and 2003–2020 derived from MERRA-2 reanalysis  
 420 dataset.

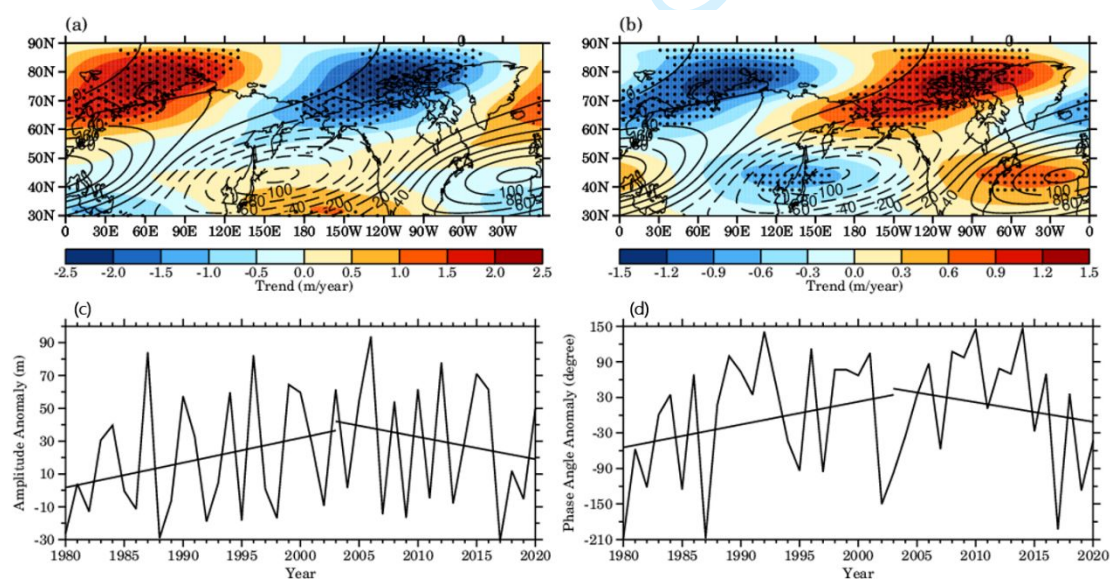
421 It should be noted that the downwelling of the Brewer-Dobson circulation (BDC)  
 422 may also affect the stratospheric temperature via adiabatic processes. Lin et al. (2009)

423 noted that enhanced BDC led to dynamic warming and produced a zonally asymmetric  
424 structure along with ozone-induced radiative cooling in the lower and middle  
425 stratosphere during September and October from 1979 to 2007. Thus, a zonally  
426 asymmetric pattern in temperature near the stratopause may be induced not only by the  
427 meridional advection of wave 1 but also by the effects of BDC. However, our analysis  
428 reveals that the residual vertical velocity in the stratosphere (i.e., the downwelling of  
429 BDC) does not have statistically significant changes, which agrees with Fu et al. (2019,  
430 Fig. 3). Therefore, the BDC contributes slightly to the zonally asymmetric temperature  
431 trends during the study period.

432 The intensity of the stratospheric stationary planetary waves is affected by the  
433 tropospheric wave source (e.g., Matsuno, 1970). Thus, the shift in the intensity of wave  
434 1 near the stratopause may also induced by the shift in intensity of tropospheric wave 1  
435 source. Figs. 7a and 7b present the spatial map of trends in 500-hPa geopotential height  
436 associated with wave 1 during January from 1980-2003 and from 2003-2020 derived  
437 from MERRA-2 reanalysis dataset, respectively. Black contour lines overlapped in Figs.  
438 7a and 7b denote the climatology of 500-hPa geopotential height associated with wave  
439 1. It is seen that a transition in the intensity of the tropospheric wave 1 around the 2000s.  
440 There is a statistically significant increasing (decreasing) trend in the geopotential  
441 height over the eastern European and a statistically significant decreasing (increasing)  
442 trend in the geopotential height over North Pacific at mid-high latitude before (after)  
443 the 2000s, which is generally in phase (out of phase) with the climatological eastern  
444 European high and the North Pacific low, respectively, indicating an enhanced

445 (weakened) wave 1 in the mid-high latitude troposphere before (after) the 2000s.  
 446 Garfinkel et al. (2010) noted that the in phase (out of phase) of geopotential height  
 447 anomalies in the eastern European high and the North Pacific low in the troposphere  
 448 can constructively (destructively) interfere with the tropospheric wave 1 and thus  
 449 enhance (weaken) the stratospheric wave 1.

450 Figs. 7c and 7d show the time series of the amplitude and phase anomaly of 500-  
 451 hPa geopotential height associated with wave 1 at 70°N, respectively. The trend in wave  
 452 1 amplitude also underwent a transition before (1.6 m/year) and after (-1.1 m/year) the  
 453 2000s, which agrees with the results in Figs 7a and 7b. According to Smith et al. (2010),  
 454 The increasing trend in phase of wave 1 before the 2000s (3.9 degree/year) and  
 455 decreasing trend in phase of wave 1 after the 2000s (-3.3 degree/year), further  
 456 supporting the constructively and destructively interfere with the tropospheric wave 1  
 457 before and after the 2000s, respectively.



458

459 **Fig. 7.** (a) The spatial map of trends (color shading) and climatology (black contours,  
 460 the contour interval is 20 m, solid and dashed lines indicate positive and negative values,

461 respectively) of 500-hPa geopotential height associated with wave 1 during January  
462 from 1980 to 2003 derived from MERRA-2 reanalysis data. (b) The same as (a), but  
463 the time period is from 2003 to 2020. The values over stippled areas are statistically  
464 significant at the 90% confidence level according to Student's t test. (c) Time series of  
465 the amplitude of 500-hPa geopotential height associated with wave 1 at 70°N. The black  
466 straight lines are linear fits of the amplitude during 1980–2003 and 2003–2020,  
467 respectively. (d) is the same as (c), but for the phase of 500-hPa geopotential height  
468 associated with wave 1.

## 469 **5. Conclusion and Discussion**

470 In this study, TIMED/SABER satellite observations and the MERRA-2 reanalysis  
471 dataset were used to investigate the spatial variations in the temperature trend near the  
472 NH stratopause during January from 1980 to 2020 and the possible factors responsible  
473 for these trends. We find that there is a zonally asymmetric temperature trend pattern  
474 near the northern mid-high latitude stratopause during January. There was a warming  
475 (cooling) trend in the eastern (western) hemisphere near the stratopause before the  
476 2000s. However, a reversed zonally asymmetric temperature trend in the east-west  
477 direction was identified after the 2000s. Although the warming trends are statistically  
478 insignificant, they contrasted with the overall cooling trend in the upper stratosphere  
479 due to ozone depletion and increasing well-mixed GHGs in recent decades. Both  
480 datasets reveal that the zonal mean temperature has an overall cooling trend during the  
481 northern winter near the stratopause. The temperature deviations from the zonal mean  
482 have similar zonally asymmetric trends and are in phase (out of phase) with the

483 climatology of the zonal temperature deviations before (after) the 2000s. Moreover, the  
484 zonally asymmetric trend in zonal temperature deviations tilts westward with height in  
485 the USLM and is most pronounced near the stratopause. The results derived from the  
486 MERRA-2 reanalysis dataset agree well with those derived from TIMED/SABER  
487 temperature observations in both morphology and magnitude during the  
488 TIMED/SABER satellite era.

489 Further analysis reveals that the meridional perturbation of wave 1 dominates the  
490 meridional wind near the stratopause, resulting in the zonally asymmetric pattern of the  
491 zonal temperature deviations. The increasing (decreasing) trend in the strength of wave  
492 1 enhances (reduce) its meridional temperature advection near the stratopause before  
493 (after) the 2000s. Consequently, zonally asymmetric temperature trends alter in the  
494 east-west direction after (before) the 2000s. The effects of meridional temperature  
495 advection of wave 1 on the temperature in the USLM have also been reported in  
496 previous studies (e.g., Gabriel et al., 2011a). The results derived from the MERRA-2  
497 reanalysis dataset indicate that wave 1 has a close correlation with the zonally  
498 asymmetric temperature pattern, with a statistically significant correlation coefficient  
499 of 0.79 (0.77 when removing their linear trends). The temperature variations associated  
500 with wave 1 can explain 61% (64%) of the variance in the zonally asymmetric  
501 temperature variations and contribute 60% (62%) to the zonally asymmetric  
502 temperature trend during January from 1980 to 2003 (from 2003 to 2020).

503 The tropospheric wave 1 at mid-high latitudes shows a strengthening (weakening)  
504 trend during January from 1980 to 2003 (from 2003 to 2020), which is in accordance

505 with the transition in the trend of stratospheric wave 1 intensity around the 2000s. The  
506 in phase (out of phase) of 500-hPa geopotential height anomalies in the eastern  
507 European high and the North Pacific low can constructively (destructively) interfere  
508 with the tropospheric wave 1 and thus enhance (weaken) the stratospheric wave 1  
509 before (after) the 2000s. In addition, some studies have reported that the zonally  
510 asymmetric temperature variations near the stratopause can be modulated by 11-year  
511 solar cycles via their impact on wave 1 (Kodera and Kudora, 2002; Gabriel et al., 2011b;  
512 Liu et al., 2023). The effects of 11-year solar cycles on the zonally asymmetric  
513 temperature pattern will be investigated in future work.

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# Responses to reviewers

## Zonally Asymmetric Temperature Trends near the Northern Middle and High Latitude Stratopause during Winter

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We sincerely appreciate the three reviewers for their valuable comments and suggestions to improve the quality of our manuscript. The following is the detailed response to the comment of Reviewer 3.

## Response to the Comment of Reviewer 3

Comments to the Author

The authors have basically responded well to my previous comments, and the revised manuscript needs minor modifications.

About the previous comment (3)

The zonally symmetric pattern generally means the latitudinal variation at different latitudes. The longitudinal variation at some latitude as you said, is misleading.

**Response:** We thank the reviewer's careful reading and helpful comment. We double check the original manuscript and find the misleading is induced that we intended to say "the zonally asymmetric pattern", but due to our oversight, it came out as "zonally symmetric pattern". The whole paper is about the zonally asymmetric temperature trend pattern. Therefore, "zonally symmetric" in L483-484 and L573-580 in the original manuscript (or L422-429 in the last revised manuscript) are mistakes. They should be "zonally asymmetric" and are now corrected (please see L423-430 in the revision). Also, our previous response to the major comment (3) should be "But the zonally asymmetric pattern means the longitudinal variation at certain latitudes, not the zonal mean variation.", which may make sense and not be misleading.

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# Zonally Asymmetric Temperature Trends near the Northern Middle and High Latitude Stratopause during Winter

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30

**Abstract**

31 The temperature trend near the stratopause is rarely evaluated owing to the limited long-  
32 term observations of global temperature. In this study, the spatial patterns of the  
33 temperature trends near the stratopause are investigated using satellite and reanalysis  
34 datasets. Our analysis reveals a zonally asymmetric temperature trend pattern near the  
35 northern mid-to-high latitude stratopause during January, and this ~~zonally asymmetric~~  
36 ~~temperature trend~~ pattern underwent an evident transition around the 2000s. From 1980  
37 to 2003, there was a cooling trend in the western hemisphere and a warming trend in  
38 the eastern hemisphere. In contrast, a reversed zonally asymmetric temperature trend  
39 pattern existed in the east-west direction from 2003 to 2020. Although the warming  
40 trends are statistically insignificant, they contrasted with the overall cooling trend in  
41 the upper stratosphere due to ozone depletion and an increase in well-mixed greenhouse  
42 gases in recent decades. The zonally asymmetric temperature trends were induced by  
43 the transition in the intensity of quasi-stationary planetary wavenumber 1 (wave 1) near  
44 the stratopause. The increasing (decreasing) trend of the intensity of wave 1 enhanced  
45 (reduced) its meridional temperature advection near the stratopause before (after) the  
46 2000s, consequently, a zonally asymmetric temperature trend pattern exists in the east-  
47 west direction near the stratopause. The transition in the intensity of the stratospheric  
48 wave 1 around the 2000s is most likely caused by the transition in the intensity of wave  
49 1 activity in the troposphere.

50 Key words: Stratospheric temperature trend, zonally asymmetric temperature pattern,  
51 quasi-stationary planetary wavenumber 1

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## 52 1. Introduction

53 The stratospheric temperature is a crucial climate marker that is affected by both  
54 thermal-dynamic and chemical processes. In response to ozone depletion and  
55 increasing well-mixed greenhouse gases (GHGs), the stratospheric temperature has  
56 experienced a significant cooling trend over the past several decades, which has been  
57 noted by a wide variety of observations and reproduced by multiple climate models  
58 (e.g., Golitsyn et al., 1996; Ramaswamy et al., 2001; Wang et al., 2012; Thompson et  
59 al., 2009, 2012; Randel et al., 2009, 2017; Rao et al., 2015; Garcia et al., 2019;  
60 Remsberg, 2019; Steiner et al., 2020). Notably, recently updated and extended satellite  
61 data has provided relatively reliable zonal mean temperature observations throughout  
62 the stratosphere and revealed that the zonal mean temperature trends decreased with  
63 altitude from the lower stratosphere to the upper stratosphere from 1979 to 2015  
64 (McLandress et al., 2015; Randel et al., 2016; Zou and Qian, 2016). However, the long-  
65 term trends in stratospheric temperature still have uncertainties in both their magnitudes  
66 and spatial variations (e.g., Shine et al., 2003; Fu et al., 2010; Seidel et al., 2011;  
67 Funatsu et al., 2016; Maycock et al., 2018). These uncertainties are partly due to  
68 discrepancies in different observations (e.g., Zou et al., 2009; Thompson et al., 2012;  
69 Keckhut et al., 2019; Seidel et al., 2016) and are partly relate to the challenges involved  
70 in clarifying the factors that contribute to stratospheric temperature trends (e.g., Hu and  
71 Fu, 2009; Hu et al., 2009; Ivy et al., 2016; Xia et al., 2020; Zhou et al., 2022).

72 Various factors may influence temperature trends in the stratosphere. Although  
73 well-mixed GHGs are still increasing, a weak recovery signal has appeared in

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74 stratospheric ozone in the last two decades (e.g., Hu et al., 2015; Chipperfield et al.,  
75 2017). Consequently, future trends in stratospheric temperatures (Arblaster et al., 2014;  
76 WMO, 2018) will mainly result from the opposing effects of increasing CO<sub>2</sub> (colder  
77 stratosphere) and increasing ozone (the warmer stratosphere). Moreover, the increasing  
78 stratospheric water vapor and volcanic aerosols have potentially impacted the  
79 temperature trends in the tropical lower stratosphere in recent decades (e.g., Maycock  
80 et al., 2014). Apart from the radiative contributions of chemical constituents, dynamic  
81 processes also have a large impact on stratospheric temperature trends, particularly at  
82 middle and high latitudes. It is known that temperatures in the stratosphere at middle  
83 and high latitudes are dominated by both ~~by~~ the radiative balance and dynamic heating  
84 originating from tropospheric wave forcing (Andrews et al., 1987; Haynes, 2005; He et  
85 al., 2022). Given that GHGs trends are monotonically increasing, the temperature trends  
86 in the stratosphere at middle and high latitudes are strongly modulated by changes in  
87 planetary wave forcing in the stratosphere (Hu and Tung, 2002; Fu et al., 2019). As a  
88 result, the large interannual and decadal variations in dynamical forcing may lead to  
89 large uncertainties in stratospheric temperature trends (e.g., Matsuno, 1971; Yamashita  
90 et al., 2010; Long et al., 2017).

91 On the other hand, previous studies have mainly focused on trends in global or  
92 zonal mean temperatures in the stratosphere, but the longitudinal variations in the  
93 temperature trend in the stratosphere have rarely been evaluated. In particular, the  
94 spatial variations in the temperature trend near the stratopause are still poorly  
95 understood due to the shortage of long-term global observations there. It is well known

96 that the polar night jet is persistent in the Northern Hemisphere (NH) winter, indicating  
97 strong baroclinicity there (France and Harvey, 2013; Harvey et al., 2002). Harvey and  
98 Hitchman (1996) noted that the maximum longitudinal differences between the  
99 Aleutian High and the polar vortex were located near the stratopause. In addition,  
100 previous studies have reported the shift in the tropospheric and stratospheric climate  
101 around the 2000s (e.g., Chen and Tung, 2014; Hu et al., 2019), ~~if~~. However, whether  
102 the climate shift occurs near the stratopause is still unclear. Therefore, it is of interest  
103 to investigate ~~recent variations~~ the changes in the temperature near the stratopause in  
104 recent decades.

105 In this study, we employ the Modern-Era Retrospective Analysis for Research  
106 and Applications, version 2 (MERRA-2) reanalysis datasets from 1980 to 2020 and the  
107 TIMED/SABER satellite temperature data from 2003 to 2020 to investigate spatial  
108 variations in the temperature trend near the stratopause during the ~~NH~~ northern winter  
109 as well as the possible factors responsible for the temperature trends near the  
110 stratopause. The organization of our paper is as follows. Section 2 describes the data  
111 and method we used. In Section 3, we exhibit and compare the temperature trends near  
112 the stratopause ~~in NH~~ during the northern winter derived from TIMED/SABER  
113 observations and the MERRA-2 reanalysis dataset. In Section 4, we investigate possible  
114 factors responsible for the temperature trends. The conclusions and discussions are  
115 summarized in Section 5.

## 116 **2. Data and Methods**

### 117 **2.1 Data**

118 SABER is an infrared limb sounder launched on the TIMED satellite, which  
119 provides reliable global temperature data above the troposphere. Its latitudinal coverage  
120 ranges from a north-looking mode (53°S–83°N) to a south-looking mode (53°N–83°S)  
121 approximately every 60 days. The SABER temperature profiles have been retrieved  
122 from infrared emissions of CO<sub>2</sub> from approximately 16 km to 105 km altitude with an  
123 effective vertical resolution of 2 km. TIMED/SABER temperature has been evaluated  
124 by Remsberg et al. (2003, 2008). In this study, we use the TIMED/SABER (version  
125 2.0) temperature dataset from 2003 to 2020 and bin the data into 2° × 4° (longitude by  
126 latitude) monthly mean maps.

127 –MERRA-2 is produced by the National Aeronautics and Space Administration  
128 (NASA) Global Modeling and Assimilation Office (GMAO). The temperature data  
129 from the Microwave Limb Sounder (MLS) are assimilated in MERRA-2 above 5 hPa,  
130 providing more accurate temperature data for the upper stratosphere than MERRA  
131 (Gelaro et al. (2017)). The zonal mean temperature comparisons between observations  
132 and reanalysis datasets, including MERRA-2, were investigated by Long et al. (2017).  
133 ~~Here, the~~The MERRA-2 instM\_3d\_asm\_Np monthly mean datasets (Version 5.12.4)  
134 are used ~~over~~during the period from 1980 to 2020, with a horizontal resolution of 0.5°  
135 × 0.625° (latitude × longitude) and 42 vertical levels up to a height of 0.1 hPa.

## 136 2.2 Method

137 In this study, the Eliassen-Palm (EP) flux (Andrews et al., 1987) and the Plumb  
138 flux (Plumb, 1985) are applied to measure the strength and propagation of wave  
139 activities in two dimensions and three dimensions, respectively. The meridional ( $F^{(\varphi)}$ )



140 and vertical ( $F^{(z)}$ ) components of the EP flux and its divergence ( $\nabla \cdot \mathbf{F}$ ) are defined as  
 141 follows:

$$142 \quad F^{(\varphi)} = \rho_0 a \cos \varphi \left( \overline{u_z \frac{v'\theta'}{\theta_z}} - \overline{u'v'} \right) \quad (1)$$

$$143 \quad F^{(z)} = \left( f - \frac{(\overline{u' \cos \varphi})_\varphi}{a \cos \varphi} \right) \overline{v'\theta'} - \overline{u'w'} \quad (2)$$

$$144 \quad \nabla \cdot \mathbf{F} = \frac{\partial F^{(\varphi)}}{\partial \varphi} + \frac{\partial F^{(z)}}{\partial z} \quad (3)$$

145 where  $\varphi$  is latitude,  $z$  is height,  $\rho$  is air density,  $a$  is the Earth's radius,  $f$  is the  
 146 Coriolis parameter,  $\theta$  is potential temperature,  $u$  is zonal wind,  $v$  is meridional  
 147 wind, and  $w$  is vertical wind. The overbars and primes denote the zonal mean and the  
 148 departure from the zonal mean, respectively. The subscript 0 is for the background  
 149 variables. The subscript  $z$  is for the partial derivative for the variables in the vertical  
 150 direction.

151 The longitude ( $F^{(\lambda)}$ ), latitude ( $F^{(\varphi)}$ ), and vertical ( $F^{(z)}$ ) components of the Plumb  
 152 flux and its divergence ( $\nabla \cdot \mathbf{F}$ ) are defined as follows:

$$153 \quad F^{(\lambda)} = \rho_0 \cos \varphi \left( \frac{1}{2a^2 \cos^2 \varphi} \left[ \left( \frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \right) \quad (4)$$

$$154 \quad F^{(\varphi)} = \rho_0 \cos \varphi \left( \frac{1}{2a^2 \cos^2 \varphi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \varphi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \varphi} \right] \right) \quad (5)$$

$$155 \quad F^{(z)} = \rho_0 \cos \varphi \left( \frac{2\Omega^2 \sin^2 \varphi}{N^2 a \cos \varphi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial z} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial z} \right] \right) \quad (6)$$

$$156 \quad \nabla \cdot \mathbf{F} = \frac{\partial F^{(\lambda)}}{\partial \lambda} + \frac{\partial F^{(\varphi)}}{\partial \varphi} + \frac{\partial F^{(z)}}{\partial z} \quad (7)$$

157 where  $\lambda$  is longitude,  $\Omega$  is the Earth's angular velocity,  $N$  is the Brunt–Väisälä  
 158 frequency,  $\psi = \Phi/2\Omega \sin \varphi$ , and  $\Phi$  is potential height.

### 159 **3. Temperature Trends Near the Stratopause in**

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## 160 **NH during the Northern Winter**

161 Figs. 1a and 1c present the spatial patterns of the 3 hPa temperature trends over the NH  
162 during January from 1980-2003 and from 2003-2020 derived from MERRA-2  
163 reanalysis data, respectively. A noticeable feature is that there is a zonally asymmetric  
164 pattern in temperature trends at mid-high latitudes shown in Fig. 1a, with a cooling  
165 trend in the western hemisphere and a warming trend in the eastern hemisphere. In  
166 contrast, a reversal temperature trend in the east-west direction can be noted in Fig. 1c,  
167 with a warming (cooling) trend in the western (eastern) hemisphere. Note that the  
168 results here are not sensitive to slight changes in the starting/ending year of the time  
169 series. Thompson et al. (2012) indicated that due to ozone depletion and increasing  
170 well-mixed GHGs in recent decades, the stratospheric cooling in the upper stratosphere  
171 is more robust than that in the lower-middle stratosphere. Hence, although these  
172 warming trends in Figs. 1a and 1c are statistically insignificant at the 95% confidence  
173 level, they contrast with the overall cooling trend in the upper stratosphere. To  
174 understand the unusual warming near the stratopause, we separate the temperature into  
175 two components, i.e., zonal mean and deviations from the zonal mean (hereafter zonal  
176 temperature deviations). The zonal mean temperature denotes the background field,  
177 which is dominated by chemical and radiative balances. The temperature deviations  
178 denote the disturbed field, which is largely controlled by adiabatic/diabatic  
179 thermodynamic processes.

180 Figs. 1b and 1d show the spatial patterns of trends in zonal temperature deviations  
181 at 3 hPa over the NH during January from 1998 to 2003 and from 2003 to 2020 derived

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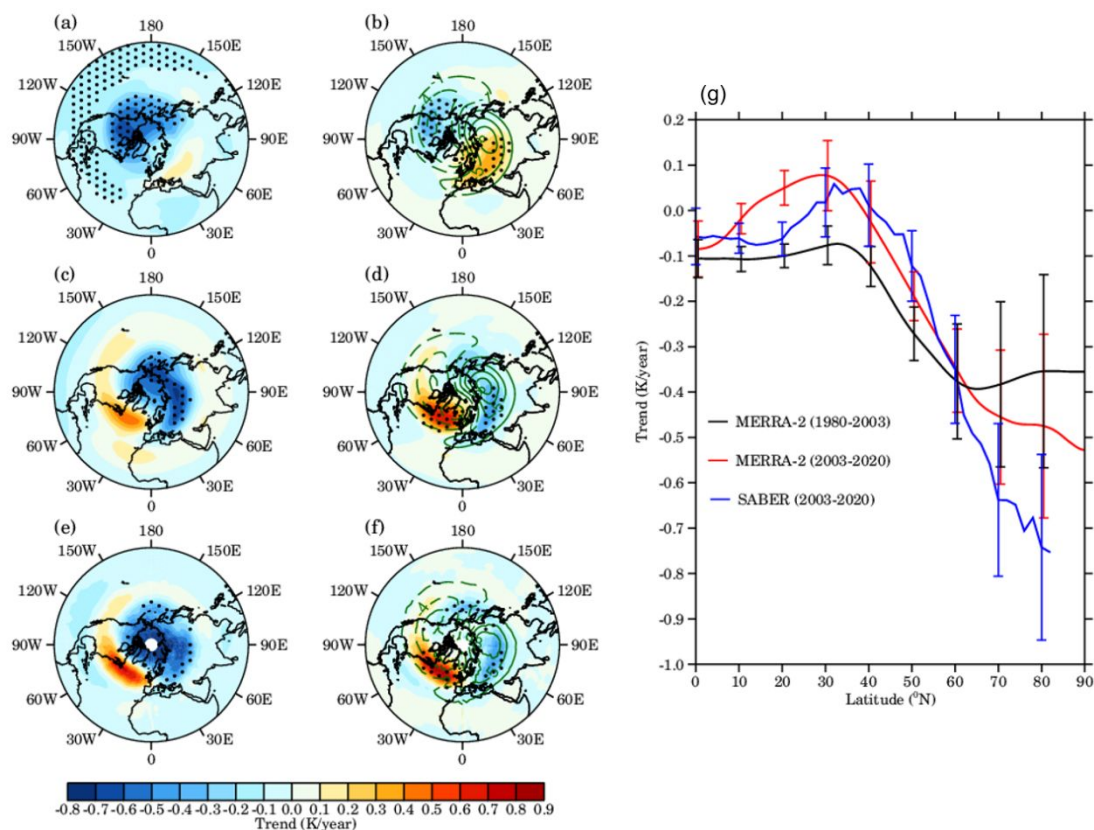
182 from MERRA-2 reanalysis data, respectively. The trends in zonal temperature  
183 deviations also present zonally asymmetric patterns at mid-high latitudes, with a  
184 statistically significant cooling (warming) trend in the western (eastern) hemisphere in  
185 Fig. 1b, and a reversal temperature trend in the east-west direction in Fig. 1d. The  
186 warming (cooling) trends in the zonal temperature deviations are stronger (weaker)  
187 compared to those in the original temperature. The green contours superimposed on  
188 Figs. 1b and 1d are the climatology of the zonal temperature deviations, which are  
189 likewise zonally asymmetric at mid-high latitudes, with negative (positive) anomalies  
190 in the western (eastern) hemisphere. The climatology of the zonal temperature  
191 deviations is generally in phase (out of phase) with the trends of the zonal temperature  
192 deviations in Fig. 1b (1d), suggesting that the zonal asymmetry of temperature  
193 variations was strengthened (weakened) before (after) the 2000s, and there was a  
194 transition in the zonally asymmetric temperature trend pattern around the 2000s.

195 The latitudinal variations in the 3 hPa zonal mean temperature trends over the NH  
196 during January from 1980 to 2003 and from 2003 to 2020 derived from MERRA-2  
197 reanalysis data are shown in Fig. 1g, respectively. The morphology of zonal mean  
198 temperature trend before the 2000s is similar to that after the 2000s. The zonal mean  
199 temperature trend is close to zero at lower latitudes but decreases with increasing  
200 latitudes at mid-high latitudes. Overall, the zonal mean temperature trend before/after  
201 the 2000s is cooling in the NH, which is consistent with the increase in well-mixed  
202 GHGs in recent decades. The results shown in Fig. 1 as derived from MERRA-2  
203 reanalysis data suggest that the zonal asymmetry of the temperature trends near the

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204 stratopause is the product of changes in disturbed fields.

205 To further verify the trends exhibited in Fig. 1 derived from MERRA-2 reanalysis  
206 data, TIMED/SABER satellite temperature observations (from 2003-2020) are  
207 analyzed. Figs. e, f, and g (blue line) are the same as Figs. c, d, and g (red line),  
208 respectively, but the data is derived from TIMED/SABER observations. It is seen that  
209 the zonally asymmetric temperature trend pattern is also apparent in TIMED/SABER  
210 observations, and the corresponding results derived from MERRA-2 reanalysis data  
211 agree well with those derived from TIMED/SABER observations in both morphology  
212 and magnitude. Since the temperature trends near the stratopause in MERRA-2  
213 reanalysis data are in good agreement with those from the TIMED/SABER temperature  
214 observations, the MERRA-2 dataset is utilized to investigate the possible factors  
215 responsible for the zonally asymmetric variations in the temperature. Note that the  
216 spatial pattern of 3 hPa temperature shows an almost uniform cooling trend over the  
217 NH during January from 1980 to 2020 derived from MERRA-2 reanalysis data (not  
218 shown).



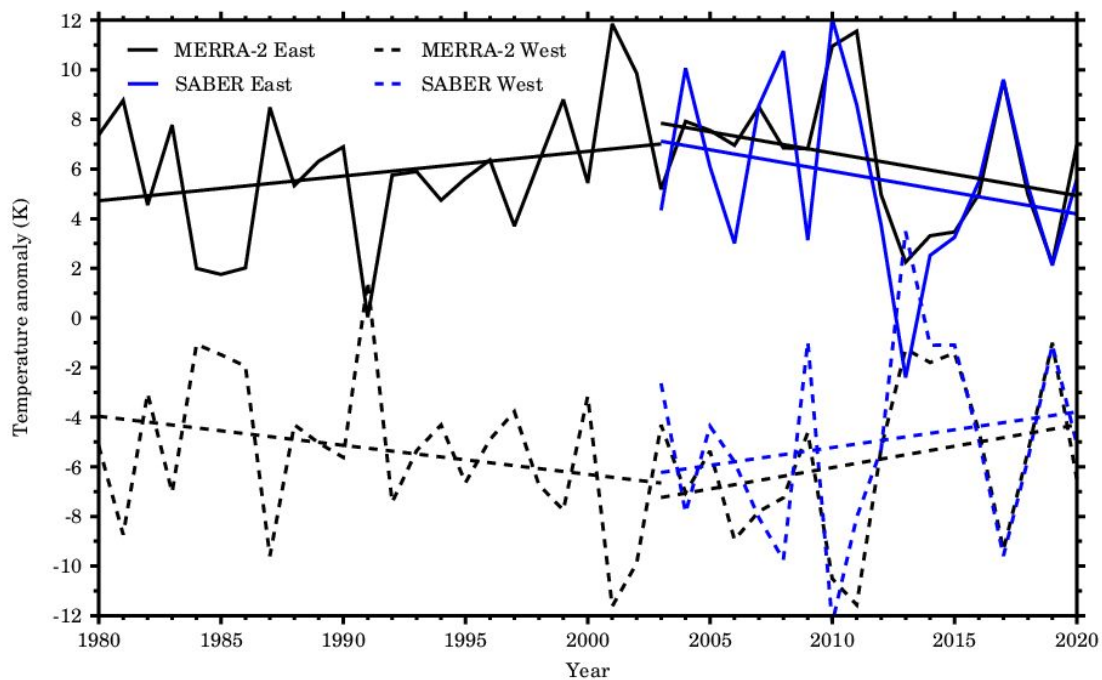
219

220 **Fig. 1.** Spatial pattern of trends in (a) temperature and (b) zonal temperature deviations  
 221 over the NH at 3 hPa during January from 1980 to 2003 derived from MERRA-2  
 222 reanalysis data. (c) and (d) are the same as (a) and (b), respectively, but the time period  
 223 is from 2003 to 2020. (e) and (f) are the same as (c) and (d), respectively, but the data  
 224 is derived from TIMED/SABER observations. The values over the stippled areas are  
 225 statistically significant at the 95% confidence level according to Student's t test. The  
 226 green contour lines denote the climatology of the zonal temperature deviations (the  
 227 contour interval is 3 K, solid and dashed lines indicate positive and negative values,  
 228 respectively). (g) Latitude variations in the zonal mean temperature trends over the NH  
 229 at 3 hPa during January from 1980 to 2003 derived from MERRA-2 reanalysis dataset  
 230 (black line), from 2003 to 2020 derived from MERRA-2 reanalysis dataset (red line),  
 231 and from 2003 to 2020 derived from TIMED/SABER observations (blue line). Error

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232 bars show the  $2\sigma$  statistical uncertainty.

233 Fig. 2 presents the time series of the zonal temperature deviations averaged over  
234 the climatological high-temperature lobe (hereafter East) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ )  
235 (solid lines) and the climatological low-temperature lobe (hereafter West) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  
236  $0$ - $150^{\circ}\text{W}$ ) (dashed lines) at 3 hPa during January from 1980 to 2020 derived from  
237 MERRA-2 reanalysis data (black lines) and from 2003 to 2020 derived from  
238 TIME/SABER observations (blue lines), respectively. The straight lines represent the  
239 linear fits of the zonal temperature deviations before and after 2003, respectively. The  
240 time series of the zonal temperature deviations derived from MERRA-2 agree well with  
241 those derived from the TIMED/SABER observations in both magnitudes and variations.  
242 The East underwent a statistically significant increasing trend ( $0.1$  K/year) from 1980  
243 to 2003 and a statistically significant decreasing trend ( $-0.17$  K/year) from 2003 to 2020.  
244 The West has similar magnitudes but opposite signs in both interannual variations and  
245 long-term trends compared to the East, indicating a close negative correlation in the  
246 zonal temperature deviations between the two lobes. The correlation coefficients  
247 between the East and West are  $-0.89$  ( $-0.90$ ) derived from the MERRA-2 reanalysis  
248 data (TIMED/SABER observations). Note that the results here are not sensitive to slight  
249 changes in the latitude/longitude bounds used for averaging the data.



250

251 **Fig. 2.** Time series of the zonal temperature deviations averaged over the climatological  
 252 high-temperature lobe (hereafter East) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ ) (solid lines) and the  
 253 climatological low-temperature lobe (hereafter West) ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $0$ - $150^{\circ}\text{W}$ ) (dashed  
 254 lines) at 3 hPa during January from 1980 to 2020 derived from the MERRA-2 reanalysis  
 255 data (black lines) and from 2003 to 2020 TIME/SABER observations (blue lines),  
 256 respectively. The straight lines represent the linear fits of the zonal temperature  
 257 deviations before and after 2003, respectively.

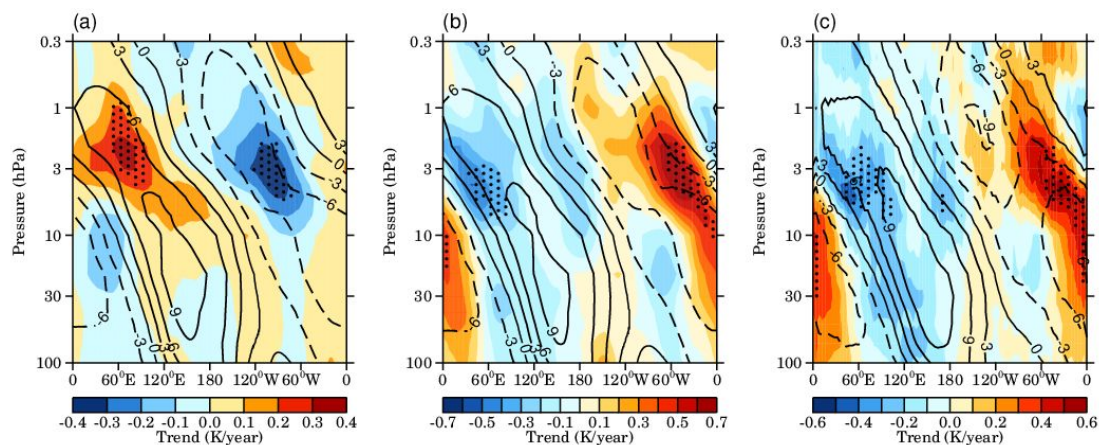
258 To depict the zonally asymmetric temperature trend variations with heights, Fig.  
 259 3 shows the longitude-height cross sections of the trends in zonal temperature deviation  
 260 at  $70^{\circ}\text{N}$  during January (a) from 1980 to 2003 derived from MERRA-2 reanalysis data  
 261 (a), (b) from 2003 to 2020 derived from MERRA-2 reanalysis data (b), and (c) from  
 262 2003 to 2020 derived from TIMED/SABER observations (c). The black contours  
 263 superimposed on Fig. 3 denote the climatology of the zonal temperature deviations. The  
 264 climatology of the zonal temperature deviations in the upper stratosphere and lower

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265 mesosphere (hereinafter USLM) also present a zonally asymmetric pattern, with the  
266 climatological high-temperature (low-temperature) lobe mainly located in the eastern  
267 (western) hemisphere. The climatology of the zonal temperature deviations tilts  
268 westward with heights, exhibiting a pattern analogous to that of the quasi-stationary  
269 planetary wavenumber 1 (wave 1).

270 As shown in Fig. 3a, the trend in the zonal temperature deviation is generally in  
271 phase with the climatology of the zonal temperature deviation in the USLM, with a  
272 statistically significant warming (cooling) trend in the eastern (western) hemisphere  
273 near the stratopause before the 2000s. In contrast, Fig. 3b shows the trend in the zonal  
274 temperature deviation is generally out of phase with the climatology of the zonal  
275 temperature deviation in the USLM, with a statistically significant cooling (warming)  
276 trend mainly located in the eastern (western) hemisphere near the stratopause after the  
277 2000s. The longitude-height cross section of the zonal temperature deviation derived  
278 from MERRA-2 reanalysis data (Fig. 3b) is comparable to that derived from  
279 TIMED/SABER observations (Fig. 3c). The results in Fig. 3 further support that the  
280 zonally asymmetric temperature trend pattern undergoes a transition in the east-west  
281 direction around the 2000s and is most pronounced near the stratopause.





282

283 **Fig. 3.** Longitude-height cross sections of the trends (color shading) and climatology  
 284 (black contours, the contour interval is 3 K, solid and dashed lines indicate positive and  
 285 negative values, respectively) of zonal temperature deviations at 70°N during January  
 286 (a) from 1980 to 2003 derived from MERRA-2 reanalysis dataset, (b) from 2003 to  
 287 2020 derived from MERRA-2 reanalysis dataset, and (c) from 2003 to 2020 derived  
 288 from TIMED/SABER observations. The values over the stippled areas are statistically  
 289 significant at the 95% confidence level according to Student's t test.

#### 290 4. Factors Responsible for the Temperature Trends

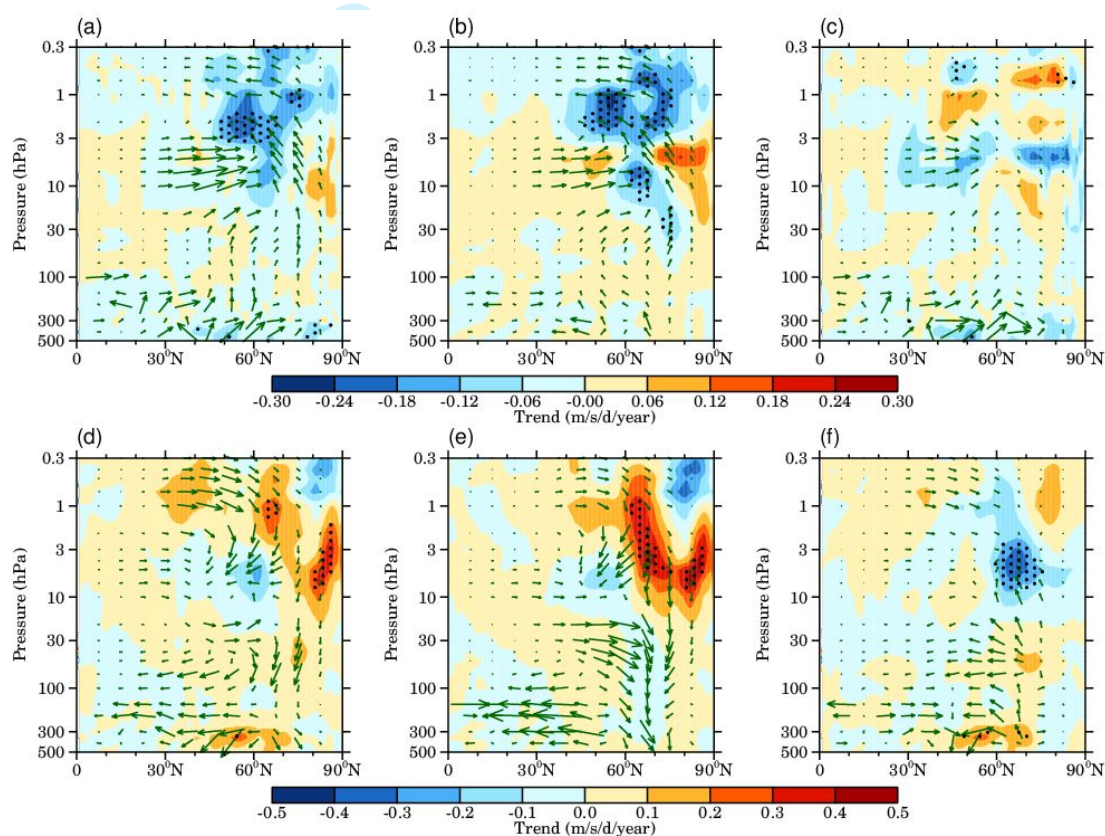
291 The previous section mentioned that the zonally asymmetric temperature trends  
 292 near the NH stratopause result from changes in the zonal temperature deviations and  
 293 may be controlled by thermodynamic factors. France et al. (2012) reported that the  
 294 advection and dissipation of quasi-stationary planetary waves could largely influence  
 295 the spatial structure of temperatures at mid-high latitudes in the upper stratosphere.  
 296 Therefore, the contributions of wave activities to the zonally asymmetric temperature  
 297 trends are first examined here. Figs. 4a and 4d shows the latitude-height distributions  
 298 of the trends in the EP flux (green vectors) and its divergence (color shading) during  
 299 January from 1980 to 2003 and from 2003 to 2020 derived from MERRA-2 reanalysis

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300 datasets, respectively. The signs of trends in EP flux are upward (downward) from the  
301 troposphere to the lower mesosphere at mid-high latitudes, indicating enhanced  
302 (weakened) wave activities throughout the troposphere and stratosphere before (after)  
303 the 2000s. In particular, the magnitudes of EP flux trends are robust in the mid-high  
304 latitude USLM, where the zonally asymmetric temperature trends exist. The negative  
305 (positive) trend in EP flux divergence is robust and statistically significant near the mid-  
306 high latitudes stratopause, supporting the enhanced (weakened) wave activities are  
307 most pronounced near the mid-high latitudes stratopause before (after) the 2000s. The  
308 trends of EP flux and its divergence in Fig. 4a are generally opposite to those in Fig.  
309 4d, indicating the intensity of wave activities also underwent a transition around the  
310 2000s from the troposphere to the lower mesosphere at mid-high latitudes.

311 According to Fig. 3, the climatology and trends of the zonal temperature deviations  
312 in the mid-high latitude USLM display a wave 1 pattern, suggesting that wave 1  
313 activities may play a key role in modulating zonal temperature deviations. Therefore,  
314 we separate total waves into wave 1 and residual waves. Figs. 4b and 4e are the same  
315 as Figs. 4a and 4d, but for the EP flux and its divergence associated with wave 1,  
316 respectively. Figs. 4c and 4f are the same as Figs. 4a and 4d, but for the EP flux and its  
317 divergence associated with residual waves, respectively. The morphology and  
318 magnitude shown in Fig. 4b (4e) are much similar to those in Fig. 4a (Fig. 4d),  
319 confirming that the intensity of wave 1 are enhanced (weakened) before (after) the  
320 2000s, and the changes in wave activities are dominated by changes in wave 1 activities.  
321 Besides, Fig. 4c depicts that the EP flux and its divergence associated with residual

322 waves do not show statistically significant changes in the USLM from 1980 to 2003.  
 323 Fig. 4f presents a statistically significant negative trend in EP flux divergence in the  
 324 high latitude upper stratosphere, along with the upward sign of the EP flux trend, which  
 325 indicates that the intensity of residual waves is enhanced in this region from 2003 to  
 326 2020 but is contrary to that of wave 1 (Fig. 4e). The combine effects of enhanced  
 327 residual waves and weakened wave 1 result in slightly weakened total waves in this  
 328 region (Fig. 4d).



329

330 **Fig. 4.** (a) Latitude-height distribution of trends in Eliassen-Palm (EP) fluxes (green  
 331 vectors, units in the horizontal and vertical components are  $10^{-2}$  and  $10^{-4}$   $m^2/s^2/year$ ,  
 332 respectively) and the EP flux divergence (color shading) in January during the period  
 333 from 1980 to 2003. (b) The same as (a), but for the EP flux and its divergence associated

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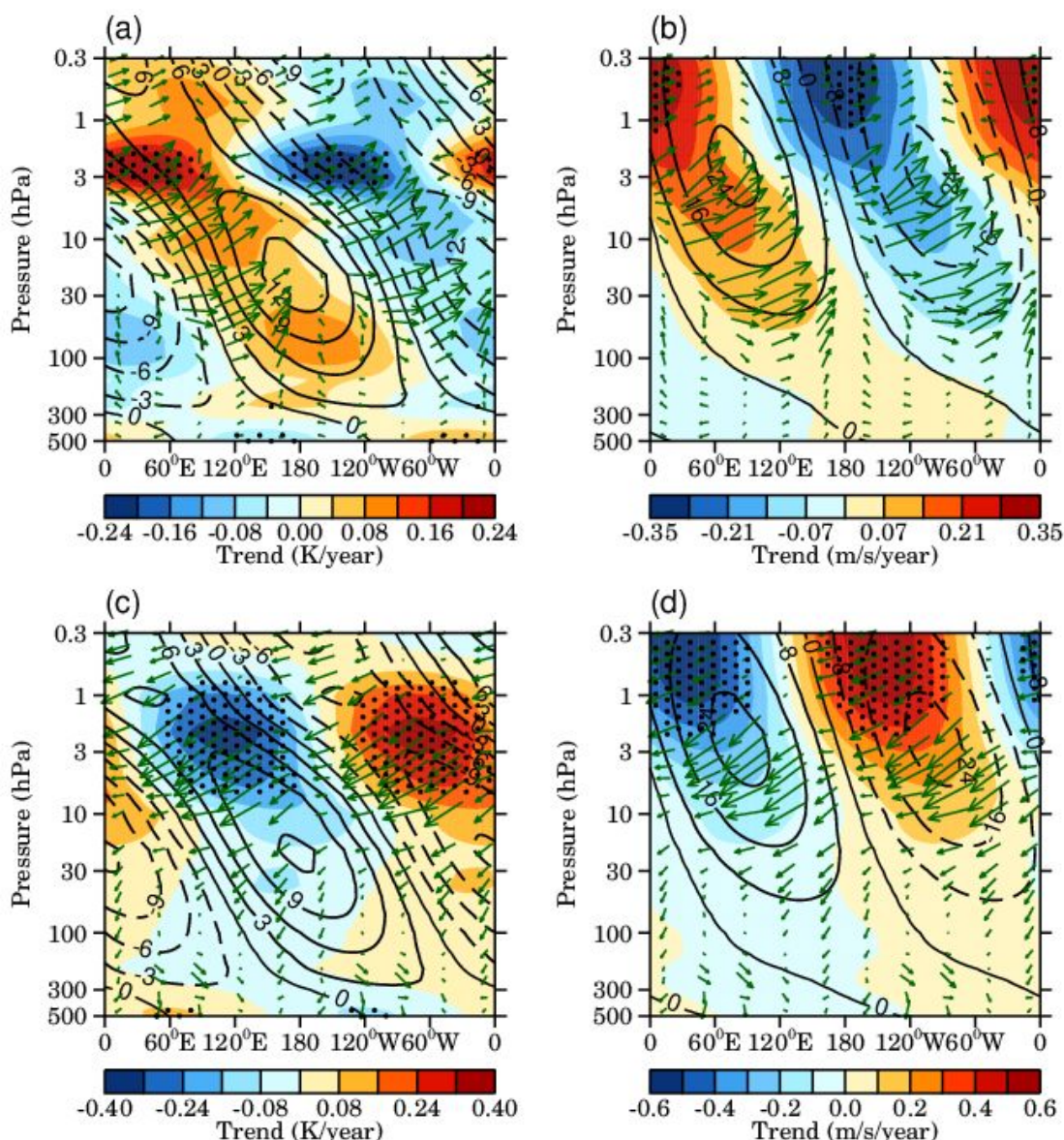
334 with wave 1. (c) The same as (a), but for the EP flux and its divergence associated with  
335 residual waves. (d), (e), and (f) are the same as (a), (b), and (c), respectively, but the  
336 time period is from 2003 to 2020. The EP fluxes are multiplied by the square root of  
337  $1000/\text{pressure}$  (hPa). The trends over stippled areas are statistically significant at the 95%  
338 confidence level according to Student's t test. The results are derived from the  
339 MERRA-2 reanalysis dataset.

340 Since the changes in zonal mean wave 1 activities underwent a transition around  
341 the 2000s, which is coincident with the changes in the zonally asymmetric temperature  
342 trend pattern, we further examine the zonal variations in wave 1 and the effects of wave  
343 1 on the zonally asymmetric temperature variations. Figs. 5a and 5c present the  
344 longitude-height cross sections of the trends (color shading) and climatology (black  
345 contours) of temperature associated with wave 1 at 70°N during January from 1980 to  
346 2003 and from 2003 to 2020 derived from the MERRA-2 reanalysis dataset,  
347 respectively. The temperature trends associated with wave 1 tilt westward with heights  
348 and are generally in phase (out of phase) with their climatology throughout the  
349 stratosphere, indicating enhanced (weakened) wave 1 activities before (after) the 2000s.  
350 In particular, the temperature trends associated with wave 1 are robust and statistically  
351 significant near the stratopause. The results in Fig. 5 are comparable to those in Fig. 3  
352 in the USLM, indicating the changes in wave 1 are responsible for the changes in zonal  
353 temperature deviations. Moreover, Both Figs. 5a and 5c show statistically significant  
354 temperature trends associated with wave 1 in the troposphere, suggesting significant  
355 changes in the tropospheric wave 1 before and after the 2000s, respectively. The green

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356 vectors superimposed on Figs. 5a and 5c are the trends of Plumb fluxes associated with  
357 wave 1. The signs of the trends of Plumb flux associated with wave 1 are upward  
358 (downward) from the troposphere and the lower mesosphere, which further supports  
359 enhanced (weakened) wave 1 activities from the troposphere and the lower mesosphere  
360 within the whole latitudinal band before (after) the 2000s.

361 Figs. 5b and 5d are the same as Figs. 5a and 5c, respectively, but for the meridional  
362 wind associated with wave 1. Likewise, the trend of the meridional wind associated  
363 with wave 1 is in phase (out of phase) with the climatology of the meridional wind  
364 associated with wave 1 from the troposphere to the lower mesosphere before (after) the  
365 2000s. The strongest amplitude of the meridional wind associated with wave 1 is near  
366 the stratopause and dominates the meridional wind there (Andrews et al, 1987). The  
367 poleward (equatorward) meridional wind associated with wave 1 induces warm (cold)  
368 meridional temperature advection in the eastern (western) hemispheres near the  
369 stratopause, resulting in the climatological high-temperature (low-temperature) mainly  
370 located in the eastern (western) hemispheres. Since the intensity of wave 1 is  
371 strengthened (weakened) before (after) the 2000s, it enhances (reduces) the meridional  
372 temperature advection near the stratopause; consequently, the zonally asymmetric  
373 trends in zonal temperature deviations are in phase (out of phase) with their climatology  
374 near the stratopause. Gabriel et al. (2007, 2011a) also noted that the wave 1 structure  
375 of temperature near the stratopause is controlled by zonally asymmetric transport by  
376 geostrophically balanced winds.



377

378 **Fig. 5.** Longitude-height cross sections of the trends (color shading) and climatology  
 379 (black contours, the contour interval is 3 K, solid and dashed lines indicate positive and  
 380 negative values, respectively) of (a) the temperature associated with wave 1 and (b) the  
 381 meridional wind associated with wave 1 at 70°N from 1980 to 2003, respectively. (c)  
 382 and (d) are the same as (a) and (b), respectively, but the time period is from 2003 to  
 383 2020. The green vectors denote Plumb flux trends associated with wave 1 (units in the  
 384 horizontal and vertical components are  $10^{-2}$  and  $10^{-4}$   $\text{m}^2/\text{s}^2/\text{year}$ , respectively). The  
 385 vertical and horizontal wave fluxes are multiplied by the square root of  $1000/\text{pressure}$

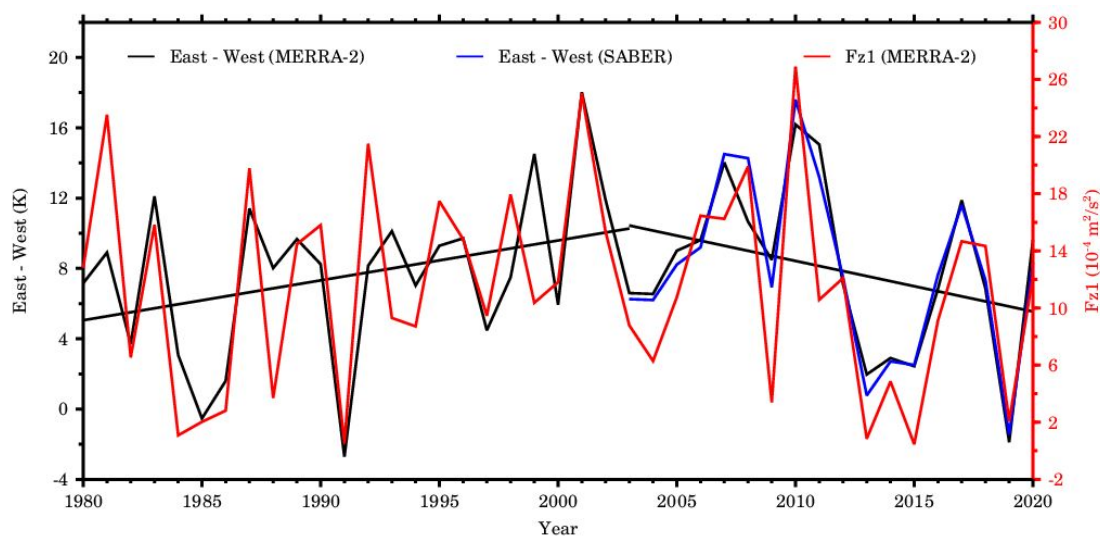
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386 (hPa). The stippled areas are statistically significant at the 95% confidence level  
387 according to Student's t test. The results are derived from the MERRA-2 dataset.

388 The long-term correlations between the zonally asymmetric temperature variations  
389 and the corresponding wave 1 component are shown in Fig. 6. The black line denotes  
390 the time series of the temperature differences between the climatology high-  
391 temperature region (50°N-70°N, 30°E-180°E) and climatology low-temperature region  
392 (50°N-70°N, 0-150°W) at 3 hPa (hereafter referred to as East–West) during January  
393 from 1980 to 2020 derived from the MERRA-2 reanalysis dataset. The red line denotes  
394 the time series of the vertical wave flux associated with wave 1 averaged between 40°N-  
395 70°N at 3 hPa (hereafter referred to as Fz1) during January from 1980 to 2020 derived  
396 from the MERRA-2 reanalysis dataset. It is seen that there is a strong correlation  
397 between wave 1 and hemispheric temperature differences near the stratopause. The  
398 correlation coefficient between Fz1 and East–West is 0.79 (0.77 when removing their  
399 linear trends), which is statistically significant at the 99% confidence level. Moreover,  
400 there is an apparent transition in the East–West (Fz1) around the 2000s, with a  
401 statistically significant increasing (decreasing) trend from 1980 to 2003 (2003 to 2020)  
402 during January. The increasing trend in East–West (Fz1) is 0.24 K/year ( $2.1 \times 10^{-5}$   
403  $\text{m}^2/\text{s}^2/\text{year}$ ), and the decreasing trend in East–West (Fz1) is -0.30 K/year ( $-2.7 \times 10^{-5}$   
404  $\text{m}^2/\text{s}^2/\text{year}$ ). Furthermore, Fz1 can explain 61% (64%) of the East–West variance and  
405 has a 60% (62%) contribution to the East–West trend from 1980 to 2003 (from 2003 to  
406 2020) during January, as estimated from the linear regression method. Overall, the  
407 changes in the intensity of wave 1 can adequately explain the zonally asymmetric

408 temperature trends near the stratopause.

409 The East–West time series during January from 2003 to 2020 derived from  
 410 TIMED/SABER observations is shown by the green line in Fig. 6. The East–West time  
 411 series derived from TIMED/SABER observations agrees well with that derived from  
 412 the MERRA-2 reanalysis dataset, with a 0.96 correlation coefficient.



413

414 **Fig. 6.** Time series of the differences between the climatology of the high-temperature  
 415 region ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $30^{\circ}\text{E}$ - $180^{\circ}\text{E}$ ) and the climatology of the low-temperature region  
 416 ( $50^{\circ}\text{N}$ - $70^{\circ}\text{N}$ ,  $0$ - $150^{\circ}\text{W}$ ) at 3 hPa (East–West) during January derived from the  
 417 MERRA-2 reanalysis data (black line) and TIMED/SABER observations (green line),  
 418 respectively, as well as the vertical wave flux associated with wave 1 (Fz1) averaged  
 419 between  $50^{\circ}\text{N}$  -  $70^{\circ}\text{N}$  at 3 hPa (red line). The black straight lines are linear fits of the  
 420 East–West during 1980–2003 and 2003–2020 derived from MERRA-2 reanalysis  
 421 dataset.

422 It should be noted that the downwelling of the Brewer-Dobson circulation (BDC)  
 423 may also affect the stratospheric temperature via adiabatic processes. Lin et al. (2009)

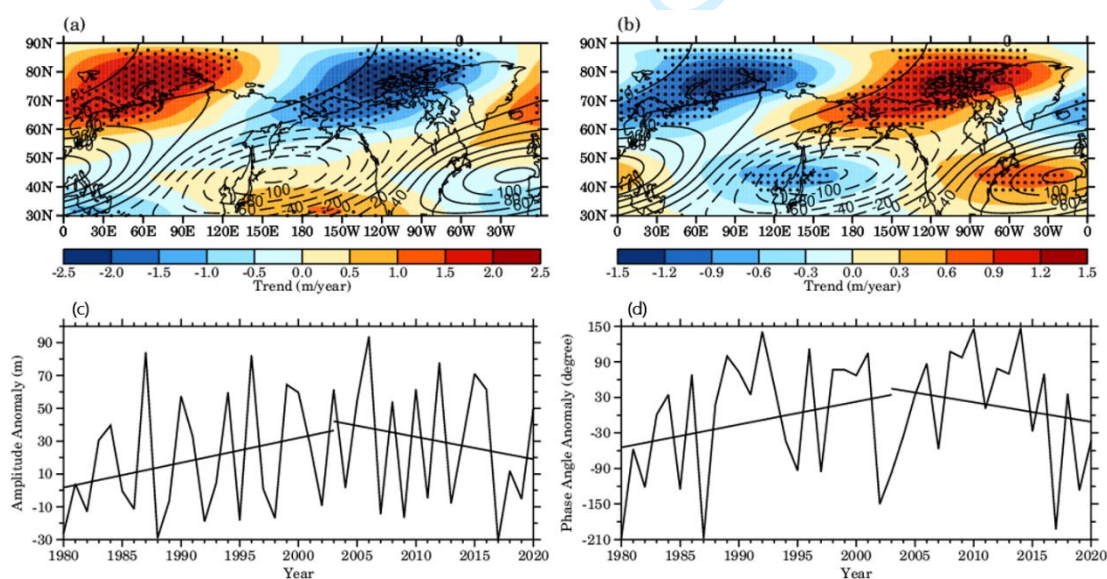


424 noted that enhanced BDC led to dynamic warming and produced a zonally  
425 ~~symmetric~~asymmetric structure along with ozone-induced radiative cooling in the  
426 lower and middle stratosphere during September and October from 1979 to 2007. Thus,  
427 a zonally ~~symmetric~~asymmetric pattern in temperature near the stratopause may be  
428 induced not only by the meridional advection of wave 1 but also by the effects of BDC.  
429 However, our analysis reveals that the residual vertical velocity in the stratosphere (i.e.,  
430 the downwelling of BDC) does not have statistically significant changes, which agrees  
431 with Fu et al. (2019, Fig. 3). Therefore, the BDC contributes slightly to the zonally  
432 ~~symmetric~~asymmetric temperature trends during the study period.

433 The intensity of the stratospheric stationary planetary waves is affected by the  
434 tropospheric wave source (e.g., Matsuno, 1970). Thus, the shift in the intensity of wave  
435 1 near the stratopause may also induced by the shift in intensity of tropospheric wave 1  
436 source. Figs. 7a and 7b present the spatial map of trends in 500-hPa geopotential height  
437 associated with wave 1 during January from 1980-2003 and from 2003-2020 derived  
438 from MERRA-2 reanalysis dataset, respectively. Black contour lines overlapped in Figs.  
439 7a and 7b denote the climatology of 500-hPa geopotential height associated with wave  
440 1. It is seen that a transition in the intensity of the tropospheric wave 1 around the 2000s.  
441 There is a statistically significant increasing (decreasing) trend in the geopotential  
442 height over the eastern European and a statistically significant decreasing (increasing)  
443 trend in the geopotential height over North Pacific at mid-high latitude before (after)  
444 the 2000s, which is generally in phase (out of phase-) with the climatological eastern  
445 European high and the North Pacific low, respectively, indicating an enhanced

446 (weakened) wave 1 in the mid-high latitude troposphere before (after) the 2000s.  
 447 Garfinkel et al. (2010) noted that the in phase (out of phase) of geopotential height  
 448 anomalies in the eastern European high and the North Pacific low in the troposphere  
 449 can constructively (destructively) interfere with the tropospheric wave 1 and thus  
 450 enhance (weaken) the stratospheric wave 1.

451 Figs. 7c and 7d show the time series of the amplitude and phase anomaly of 500-  
 452 hPa geopotential height associated with wave 1 at 70°N, respectively. The trend in wave  
 453 1 amplitude also underwent a transition before (1.6 m/year) and after (-1.1 m/year) the  
 454 2000s, which agrees with the results in Figs 7a and 7b. According to Smith et al. (2010),  
 455 The increasing trend in phase of wave 1 before the 2000s (3.9 degree/year) and  
 456 decreasing trend in phase of wave 1 after the 2000s (-3.3 degree/year), further  
 457 supporting the constructively and destructively interfere with the tropospheric wave 1  
 458 before and after the 2000s, respectively.



459

460 **Fig. 7.** (a) The spatial map of trends (color shading) and climatology (black contours,  
 461 the contour interval is 20 m, solid and dashed lines indicate positive and negative values,

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462 respectively) of 500-hPa geopotential height associated with wave 1 during January  
463 from 1980 to 2003 derived from MERRA-2 reanalysis data. (b) The same as (a), but  
464 the time period is from 2003 to 2020. The values over stippled areas are statistically  
465 significant at the 90% confidence level according to Student's t test. (c) Time series of  
466 the amplitude of 500-hPa geopotential height associated with wave 1 at 70°N. The black  
467 straight lines are linear fits of the amplitude during 1980–2003 and 2003–2020,  
468 respectively. (d) is the same as (c), but for the phase of 500-hPa geopotential height  
469 associated with wave 1.

## 470 **5. Conclusion and Discussion**

471 In this study, TIMED/SABER satellite observations and the MERRA-2 reanalysis  
472 dataset were used to investigate the spatial variations in the temperature trend near the  
473 NH stratopause during January from 1980 to 2020 and the possible factors responsible  
474 for these trends. We find that there is a zonally asymmetric temperature trend pattern  
475 near the northern mid-high latitude stratopause during January. There was a warming  
476 (cooling) trend in the eastern (western) hemisphere near the stratopause before the  
477 2000s. However, a reversed zonally asymmetric temperature trend in the east-west  
478 direction was identified after the 2000s. Although the warming trends are statistically  
479 insignificant, they contrasted with the overall cooling trend in the upper stratosphere  
480 due to ozone depletion and increasing well-mixed GHGs in recent decades. Both  
481 datasets reveal that the zonal mean temperature has an overall cooling trend during the  
482 NH northern winter near the stratopause. The temperature deviations from the zonal  
483 mean have similar zonally asymmetric trends and are in phase (out of phase) with the

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484 climatology of the zonal temperature deviations before (after) the 2000s. Moreover, the  
485 zonally asymmetric trend in zonal temperature deviations tilts westward with height in  
486 the USLM and is most pronounced near the stratopause. The results derived from the  
487 MERRA-2 reanalysis dataset agree well with those derived from TIMED/SABER  
488 temperature observations in both morphology and magnitude during the  
489 TIMED/SABER satellite era.

490 Further analysis reveals that the meridional perturbation of wave 1 dominates the  
491 meridional wind near the stratopause, resulting in the zonally asymmetric pattern of the  
492 zonal temperature deviations. The increasing (decreasing) trend in the strength of wave  
493 1 enhances (reduce) its meridional temperature advection near the stratopause before  
494 (after) the 2000s. Consequently, zonally asymmetric temperature trends alter in the  
495 east-west direction after (before) the 2000s. The effects of meridional temperature  
496 advection of wave 1 on the temperature in the USLM have also been reported in  
497 previous studies (e.g., Gabriel et al., 2011a). The results derived from the MERRA-2  
498 reanalysis dataset indicate that wave 1 has a close correlation with the zonally  
499 asymmetric temperature pattern, with a statistically significant correlation coefficient  
500 of 0.79 (0.77 when removing their linear trends). The temperature variations associated  
501 with wave 1 can explain 61% (64%) of the variance in the zonally asymmetric  
502 temperature variations and contribute 60% (62%) to the zonally asymmetric  
503 temperature trend during January from 1980 to 2003 (from 2003 to 2020).

504 The tropospheric wave 1 at mid-high latitudes shows a strengthening (weakening)  
505 trend during January from 1980 to 2003 (from 2003 to 2020), which is in accordance

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506 with the transition in the trend of stratospheric wave 1 intensity around the 2000s. The  
507 in phase (out of phase) of 500-hPa geopotential height anomalies in the eastern  
508 European high and the North Pacific low can constructively (destructively) interfere  
509 with the tropospheric wave 1 and thus enhance (weaken) the stratospheric wave 1  
510 before (after) the 2000s. In addition, some studies have reported that the zonally  
511 asymmetric temperature variations near the stratopause can be modulated by 11-year  
512 solar cycles via their impact on wave 1 (Kodera and Kudora, 2002; Gabriel et al., 2011b;  
513 Liu et al., 2023). The effects of 11-year solar cycles on the zonally asymmetric  
514 temperature pattern will be investigated in future work.

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516 Jiankai Zhang and Jinlong Huang for their helpful discussions and remarks. We would  
517 like to acknowledge the scientific teams at MERRA-2 and TIMED/SABER for  
518 providing the datasets.

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