

1 **Climatology of mesopause region nocturnal temperature, zonal wind, and sodium**  
2 **density observed by sodium lidar over Hefei, China (32°N, 117°E)**

3 Tao Li<sup>1\*</sup>, Chao Ban<sup>1,2\*</sup>, Xin Fang<sup>1</sup>, Jing Li<sup>1</sup>, Zhaopeng Wu<sup>1</sup>, Wuhu Feng<sup>3,4</sup>, John M. C. Plane<sup>3</sup>,  
4 Jianguang Xiong<sup>5</sup>, Daniel R. Marsh<sup>6</sup>, Michael J. Mills<sup>6</sup>, and Xiankang Dou<sup>1</sup>

5 <sup>1</sup>CAS Key Laboratory of Geospace Environment, School of Earth and Space Sciences,  
6 University of Science and Technology of China, Hefei, Anhui, China

7 <sup>2</sup>Now at Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing,  
8 China<sup>3</sup>School of Chemistry, University of Leeds, Leeds, United Kingdom

9 <sup>4</sup>NCAS, School of Earth and Environment, University of Leeds, Leeds, United Kingdom

10 <sup>5</sup>Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

11 <sup>6</sup>National Center for Atmospheric Research, Boulder, CO, USA

12 *\*To whom correspondence should be addressed: [litao@ustc.edu.cn](mailto:litao@ustc.edu.cn); [banchao@mail.iap.ac.cn](mailto:banchao@mail.iap.ac.cn)*

13

14 **Abstract**

15 The University of Science and Technology of China narrowband sodium temperature/wind  
16 lidar, located in Hefei, China (32°N, 117°E), has made routine nighttime measurements since  
17 January 2012. 154 nights (~1400 hours) of vertical profiles of temperature, sodium density,  
18 and zonal wind, and 83 nights (~800 hours) of vertical flux of gravity wave (GW) zonal  
19 momentum in the mesopause region (80-105 km) have been obtained during the period from  
20 2012 to 2016. In temperature, it is most likely that the diurnal tide dominates below 100 km in  
21 spring, while the semidiurnal tide dominates above 100 km throughout the year. A clear  
22 semiannual variation in temperature is revealed near 90 km, in phase with the tropical  
23 mesospheric semiannual oscillation (MSAO). The variability of sodium density is positively  
24 correlated with temperature below 95 km, suggesting that in addition to dynamics, the  
25 chemistry also plays an important role in the formation of sodium atoms. The seasonal  
26 variability of sodium density observed by both lidar and satellite generally agrees well with a  
27 whole atmosphere model simulation using an updated meteoric input function which includes  
28 different cosmic dust sources. In zonal wind, the diurnal tide dominates in both spring and fall,  
29 while semidiurnal tide dominates in winter. The observed semiannual variation in zonal wind  
30 near 90 km is out-of-phase with that in temperature, consistent with the tropical MSAO. The  
31 lidar observations generally agree with satellite and meteor radar observations as well as

32 model simulations at similar latitude. The 50-70% of zonal momentum flux is induced by  
33 short-period (10 min – 2 hr) GWs. The large zonal momentum flux in summer and winter due  
34 to short-period GWs are clearly anti-correlated with eastward zonal wind maxima below 90  
35 km, suggesting the filtering of short-period GWs by the SAO wind

## 36 1. Introduction

37 The temperature and wind in the mesopause region (80-105 km) are key atmospheric  
38 parameters for studying the dynamics in this region. Ground-based instruments (e.g. lidars,  
39 radars), and space-borne instruments have been widely used to measure these key parameters  
40 over several decades (Vincent and Reid, 1983; She et al., 1998; Wu et al., 2008). Satellites  
41 can provide a near-global view of the mesopause region, but their local coverage is usually  
42 limited to two local times on the ascending and descending orbit. The lack of continuous  
43 coverage in local time makes it difficult to extract information on short period gravity wave  
44 (GW) perturbations from satellite data (Preusse et al., 2009). Ground-based meteor or  
45 medium frequency radars are capable of measuring mesopause wind in a continuous mode,  
46 but do not provide direct temperature measurements with sufficient accuracy and vertical  
47 resolution (Vincent and Reid, 1983). However, a narrowband sodium lidar is able to  
48 simultaneously measure mesopause region temperature and horizontal wind by utilizing the  
49 sodium high resolution spectrum (She et al., 1994; Arnold and She, 2003), which provides a  
50 unique opportunity to study GW perturbations and their breaking process in the mesopause  
51 region (Li et al., 2005; Li et al., 2007).

52 The long-term lidar observations have been used to study the seasonal variability of  
53 mesopause region temperature (She et al., 1998; Gardner et al., 2002; Xu et al., 2006;  
54 Friedman et al., 2007) and horizontal wind (Franke et al., 2005; Gardner et al., 2007), as well  
55 as sodium density (She et al., 2000; Gardner et al., 2005; Ejiri et al., 2010; Yi et al., 2009;  
56 Yuan et al., 2012), iron density (Yi et al., 2009; Lübken et al., 2011) and potassium density  
57 (Friedman et al., 2002; Plane et al., 2015). These datasets are extremely valuable to validate  
58 satellite results (Xu et al., 2006; Fan et al., 2007a; Dawkins et al., 2014) and improve general  
59 circulation models (Yuan et al., 2008; Feng et al., 2013; Marsh et al., 2013). When GWs  
60 break or dissipate in the mesopause region due to increased amplitudes or approaching critical  
61 level (where wave phase speed equal to horizontal background wind), they tend to deposit  
62 wave energy and momentum into the background flow, and further modify the temperature  
63 and wind near the breaking region (Lindzen et al., 1981; Liu and Hagan, 1998; Li et al., 2007).  
64 Therefore, measurements of the GW vertical flux of horizontal momentum and heat are  
65 critical for evaluating the GW contribution to the background state in this region, and their  
66 key roles in the dynamic coupling between lower and middle/upper atmosphere (Li et al.,

67 2013; 2016).

68 The vertical flux of horizontal momentum can be directly derived from the vertical wind  
69 perturbation and associated horizontal wind perturbation. To ensure accuracy of the GW  
70 momentum flux, the wind data must have high temporal and vertical resolutions with good  
71 precision and a long-time average (Kudeki and Franke, 1998; Thorsen et al., 2000). Several  
72 studies of lidar-observed GW momentum flux in the mesosphere/lower thermosphere (MLT)  
73 region have been carried out previously (Espy et al., 2004; Gardner and Liu, 2007; Acott et al.,  
74 2009).

75 In this paper, we present the seasonal variation of sodium density, temperature, zonal  
76 wind and GW zonal momentum flux observed by the University of Science and Technology  
77 of China (USTC) sodium temperature/wind lidar from January 2012 to December 2016 over  
78 Hefei, China (32°N, 117°E). This is the first time simultaneous observations of the seasonal  
79 variability of mesopause region temperature, zonal wind, and GW momentum flux by sodium  
80 lidar over the Eastern Asia region have been reported. We compare the lidar results with  
81 temperature observed by the Sounding of the Atmosphere Using Broadband Emission  
82 Radiometry (SABER) instrument onboard the Thermosphere–Ionosphere–Mesosphere  
83 Energetics and Dynamics (TIMED) satellite (Russell et al., 1999); zonal wind observed by a  
84 nearby meteor radar (Xiong et al., 2004); and sodium density observed by the Optical  
85 Spectrograph and InfraRed Imager System (OSIRIS) onboard the Odin satellite (Llewellyn et  
86 al., 2004). These measurements are then compared with simulations from the Whole  
87 Atmosphere Community Climate Model version 5 (WACCM) (Marsh et al., 2013; Mills et al.,  
88 2016; Feng et al., 2017), using an updated meteoric input function (MIF) for Na  
89 (Cárrillo-Sanchez et al., 2016). The instruments, datasets, and data analysis method are  
90 described in section 2, followed by the results of temperature and sodium density in section 3,  
91 and zonal wind and GW zonal momentum flux in section 4. A summary is provided in section  
92 5.

93

## 94 **2. Instruments, datasets and analysis method**

95 The USTC sodium temperature/wind lidar, located on campus in Hefei, China (32°N,  
96 117°E), utilizes a narrowband three-frequency design and can simultaneously observe sodium  
97 density, zonal wind and temperature in the mesopause region during nighttime clear sky

98 conditions (Li et al., 2012). The system was initially set up in October 2011 with two  
99 receiving telescopes (30-inch diameter) pointing eastward and northward  $30^\circ$  from zenith for  
100 measuring the zonal and meridional wind, respectively. The output laser beam is split into two  
101 beams, each aligned parallel to one telescope. Between December 2012 and May 2014 (total  
102 83 nights), the two receiving telescopes were pointed to eastward and westward, each  $15^\circ$   
103 from zenith. This dual-beam setup allows us to derive the GW zonal momentum flux as well  
104 as the zonal wind. Since June 2014, the westward telescope was pointed to vertical for  
105 measuring the vertical fluxes of heat and sodium atoms, and the eastward telescope to  $30^\circ$   
106 from zenith for measuring zonal wind. Between January 2012 and December 2016, we  
107 obtained 154 nights ( $\sim 1400$  hours) of valid data, which is sufficient to study the seasonal  
108 variations of sodium density, temperature, zonal wind, and GW momentum flux (83 nights) in  
109 the mesopause region over Hefei. Figure 1 shows the number of nights with valid datasets in  
110 each month of the different years. It is clear that Hefei has more clear nights in fall and winter  
111 than in spring and summer.

112 The Wuhan ( $31^\circ\text{N}$ ,  $114^\circ\text{E}$ ) meteor radar, located at  $\sim 300$  km west of Hefei, has  
113 measured mesopause region horizontal wind since January 2002 (Xiong et al., 2004). The  
114 vertical and temporal resolutions of radar wind are 3 km and 2 hr, respectively. The SABER  
115 instrument onboard the TIMED satellite can measure the near-global vertical profile of  
116 temperature from the lower stratosphere to the lower thermosphere (Russell et al., 1999). The  
117 SABER temperature dataset used in this paper is Level2A version 2.0, which has a vertical  
118 resolution of 2 km and accuracies of  $\pm 1\text{-}2$  K between 75 and 95 km, increasing to  $\pm 4$  K at 100  
119 km. The OSIRIS instrument onboard the Odin satellite measures solar-pumped Na resonance  
120 fluorescence from a sun-synchronous polar orbit (Llewellyn et al., 2004), and the datasets can  
121 be used to retrieve the global vertical profiles of sodium density between 75 and 110 km with  
122 a  $\sim 10\%$  uncertainty for 2 km vertical resolution (Gumbel et al., 2007; Fan et al., 2007a).

123 To compare with lidar results, we also use the temperature, zonal wind, and sodium  
124 density simulated by the WACCM, a chemistry-climate model which extends from the  
125 Earth's surface to the lower thermosphere ( $\sim 140$  km) (Garcia et al., 2007; Marsh et al., 2013a).  
126 WACCM uses the framework from the fully coupled global climate model Community Earth  
127 System Model (CESM version 1, e.g., Hurrell et al., 2013). In this paper, we use a version of  
128 WACCM described in Mills et al. (2016), which includes all the detailed physical processes

129 as described in the Community Atmosphere Model, version 5 (CAM5) (Neale et al., 2012).  
130 The current configurations for WACCM are based on a finite volume dynamical core (Lin,  
131 2004) for the tracer advection as well as a new surface topography data from Lauritzen et al.  
132 (2015). WACCM has the fully interactive chemistry described in Mills et al. (2016), and we  
133 have included the Na chemistry scheme listed in Plane et al. (2015) and Gomez Martin et al.  
134 (2015, 2017), with an updated meteoric input function (MIF) for Na (Cárrillo-Sanchez et  
135 al., 2016). The new MIF is calculated for the ablation of cosmic dust particles from Jupiter  
136 Family Comets (80% by mass), Asteroids (8%), and Long Period Comets (12%), and the  
137 injection rate of Na is about 8 times larger than that used in Marsh et al. (2013). The peak Na  
138 ablation rate from Cárrillo-Sanchez et al. (2016) occurs around 87 km, which is ~15 km lower  
139 than the MIF used in Marsh et al. (2013), which was based on meteor head radar  
140 measurements which were biased to the high velocity dust particles which mostly originate  
141 from Long Period Comets (Cárrillo-Sanchez et al., 2016). The absolute Na MIF used in this  
142 paper has been divided by a factor of 5 from that in Cárrillo-Sanchez et al. (2016), in order to  
143 match the observed Na layer density. This most likely reflects the fact that WACCM  
144 underestimates the rate of vertical transport of Na species in the MLT because sub-grid  
145 gravity waves are not resolved in the model (Huang et al., 2015). The horizontal resolution of  
146 WACCM is 1.9° latitude by 2.5° longitude. The vertical model layers and the vertical  
147 resolution are the same as Mills et al. (2017), which is 70 and ~3 km in the MLT region.  
148 Although the model can be nudged by a re-analysis dataset, in the current study we have used  
149 a “free-running” model simulation, which produces a satisfactory Na climatology in the  
150 model. We ran the model for year 2000 condition for 13 years.

151 The lidar raw photon counts are first analyzed to generate hourly mean vertical profiles  
152 of sodium density, temperature and line-of-sight (LOS) wind with 2 km vertical resolution for  
153 each direction. Before and after the dual-beam setup (eastward-westward) between December  
154 2012 and May 2014, we assume that the hourly mean vertical wind is negligible and then  
155 derive the hourly mean zonal wind from the east channel LOS wind (eastward pointing at 30°  
156 from zenith). During the dual-beam setup, we derive the hourly mean zonal wind profiles by  
157 subtracting the hourly westward LOS wind from the eastward LOS wind and then dividing by  
158  $2\sin\theta$  (e.g.  $\theta=20^\circ$ ) (Vincent and Reid, 1983). The uncertainties of the hourly mean zonal wind  
159 and temperature typically range from ~1.0 m/s and ~0.5 K at 92 km (Na peak layer) to ~6 m/s

160 and  $\sim 5$  K at 82 km and 103 km (the edge of Na layer), respectively. We then generate the  
161 nighttime hourly mean composite in each season.

162 Vincent and Reid (1983) presented a method utilizing the dual beam technique to derive  
163 vertical flux of GW horizontal momentum, when two beams are pointed at equal and opposite  
164 angle  $\theta$  from the zenith. The zonal momentum flux  $\overline{w'u'}$  is calculated as follows:

$$165 \quad \overline{w'u'} = \frac{\overline{v^2(\theta, R)} - \overline{v^2(-\theta, R)}}{2\sin(2\theta)} \quad (1)$$

166 where  $\overline{v^2(\theta, R)}$  and  $\overline{v^2(-\theta, R)}$  are the square of the LOS wind perturbations in the east and  
167 west channels respectively, and  $\theta$  is the zenith angle (e.g.  $20^\circ$ ). To derive the momentum flux,  
168 we employed a similar procedure to that of Gardner and Liu (2007). Briefly, we first analyze  
169 lidar raw photon counts to generate the LOS wind with a temporal resolution of 5 min and a  
170 vertical resolution of 2 km. Data points with errors larger than 5 m/s were discarded during  
171 the quality check. We remove the linear trend and nightly mean from the LOS wind to form  
172 wind perturbations for each night. Data where the perturbation variances are smaller than the  
173 corresponding noise variances are also excluded. The seasonal mean vertical profile of  
174 perturbation variance is then obtained by averaging all available perturbation variances in that  
175 season. This process is done separately for each beam. Finally, the seasonal mean momentum  
176 flux is calculated using equation (1). In this way, the results only account for the GW  
177 perturbations with periods of 10 min-20 hr and vertical wavelengths of 4-30 km. We also  
178 apply a high-pass filter with cutoff at 2 hr on raw perturbations to examine the relative  
179 contribution of short-period GWs (10 min – 2 hr) to total momentum flux.

180 Since the meteor radar observed zonal wind is only available in 2013, we then calculate  
181 monthly mean with all available data for comparison. The SABER tracking points within  $\pm 5^\circ$   
182 latitude band ( $27$ - $37^\circ$ N) and longitude band ( $112$ - $122^\circ$ E) of the lidar site are selected first. We  
183 then discard the SABER temperature profiles that are outside of the lidar observation period.  
184 Finally, we average all available SABER temperature profiles within each month to form the  
185 monthly mean for comparison. A similar analysis method is used for the OSIRIS data. In the  
186 case of WACCM, the zonal mean data are first extracted at the coordinates of the lidar site  
187 and then the monthly mean profiles are generated in the same way as the lidar and radar  
188 profiles.

189

### 190 3. Temperature and sodium density

191 Figure 2 shows the hourly mean temperature composite in four different seasons. The  
192 temperatures below 95 km are generally warmer in fall and winter than in spring and summer,  
193 consistent with the mesospheric residual meridional circulation with upwelling in the summer  
194 hemisphere and downwelling in the winter hemisphere (Andrew et al., 1987; Smith, 2012). It  
195 is most likely that the diurnal tide with downward phase progression dominates below 100 km  
196 in spring, although we only have 10-12 hr data. However, the tidal feature is not clear below  
197 95 km in other seasons. The temperature above 100 km in all seasons clearly exhibits two  
198 minima after dusk and before dawn and a maximum near midnight, suggesting dominance  
199 and persistence of the semidiurnal tide in this latitude region throughout the year.

200 The clear downward phase progression of diurnal and semidiurnal tides in mesopause  
201 temperature was previously observed by sodium lidar at the Starfire Optical Range (SOR),  
202 New Mexico (35°N, 107°W) (Chu et al., 2005). However, their observations suggest a clear  
203 dominance of diurnal in April and October and semidiurnal in January below 100 km, while  
204 we see a clear dominance of diurnal only in spring (March-May), and mixed features in other  
205 seasons. In addition, the midnight maximum above 100 km shown in our results is not  
206 observed over SOR. The SABER observations reveal a diurnal amplitude of ~2 K and ~8 K,  
207 and semidiurnal amplitude of ~7 K and ~12 K at 95km for the USTC and SOR lidar sites,  
208 respectively (Zhang et al., 2010). This significant longitudinal variability is likely due to  
209 nonlinear interactions between the migrating tide and non-immigrating tide (Forbes et al.,  
210 2003) and stationary planetary wave number 1 (Lieberman et al., 1991), respectively, and/or  
211 tidal/gravity waves interactions (Lindzen, 1981; Liu and Hagan, 1998; Li et al., 2007; 2009).  
212 The clear longitudinal variability of tides between two lidar sites could thus cause significant  
213 differences in the nocturnal climatology.

214 Figure 3 shows the monthly mean of the nightly mean temperature observed by lidar and  
215 SABER, and simulated by WACCM. All three figures show qualitative agreement in the  
216 general pattern, but difference in absolute values. The mesopause is clearly located near 100  
217 km in winter and below 95 km in summer, indicating a two-level mesopause as previously  
218 observed at mid- and high latitudes (von Zahn et al., 1996; She et al., 1998). The lidar  
219 observed temperature above 95 km is ~10 K lower than SABER, likely due either to the low  
220 signal-to-noise ratio in the lidar return signals above 100 km (Li et al., 2012), or to a non-local



221 thermal equilibrium influence in the SABER analysis (Mertens et al., 2001). The lidar  
222 observed mesopause is also 5-10 K colder than that observed by SABER. The WACCM  
223 simulated temperature is clearly higher than both sets of observations at most altitudes and  
224 months. Yuan et al. (2008) showed a significant monthly mean mesopause region temperature  
225 difference between lidar observations and WACCM simulations over Fort Collins, CO (41°N,  
226 105°W); their comparisons show that the WACCM-simulated winter mesopause is much  
227 warmer than measured by lidar, and the summer mesopause is ~3 km lower than lidar  
228 observations. Another interesting feature in all three figures is that we see a temperature  
229 maximum near ~90 km in March and April, and a second maximum in September and  
230 October, likely related to the mesospheric semiannual oscillation (MSAO) usually dominant  
231 in the equatorial middle atmosphere (Dunkerton, 1982; Burrage et al., 1996; Garcia et al.,  
232 1997).

233 Our measured monthly means of the nightly mean temperatures are also generally  
234 consistent with previously lidar observations at SOR (Gardner and Liu, 2007) and Fort  
235 Collins, CO (She et al., 1998; Yuan et al., 2008). However, the SOR lidar observations were  
236 ~10 K colder below 90 km in summer, and ~10 K warmer between 90 and 95 km in spring,  
237 suggesting significant differences between the two locations likely induced by the significant  
238 longitudinal variability of the diurnal tide (Zhang et al., 2010). The semiannual oscillation  
239 signature is evident over both Hefei and SOR between 90 and 95 km, but not over Fort  
240 Collins. The summer mesopause observed by lidar over Hefei is clearly higher than over the  
241 other two locations.

242 Figure 4 shows the hourly mean sodium density composite during the four different  
243 seasons. The density increases with local time during the night, with a peak height around 92  
244 km. The peak density is overall much higher in fall and winter than in spring and summer,  
245 which is consistent with previous ground-based and satellite observations (She et al., 2000;  
246 Fan et al., 2007a; Fussen et al., 2010). Some peaks above 95 km in summer are likely induced  
247 by sporadic sodium layers (SSLs), which often occur in this season over Hefei (Dou et al.,  
248 2010). The seasonal mean sodium peak density in winter can reach 4000-4500 cm<sup>-3</sup> after  
249 midnight. Figure 5 shows the monthly mean of nightly mean sodium density observed by (a)  
250 lidar and (b) Odin/OSIRIS, and simulated by (c) WACCM. Both observations agree well in  
251 seasonal pattern and absolute sodium density, and are also consistent with the WACCM

252 model simulation. The elevated peak height and enhanced density in summer observed by  
253 lidar is likely due to increased SSL events in summer over Hefei, which is neither frequently  
254 observed by Odin/OSIRIS nor simulated by WACCM. The Odin/OSIRIS did observe SSLs  
255 over China (Fan et al., 2007b), but probably less frequently at 0600 and 1800 local time than  
256 at midnight. The observed sodium density over Hefei is quite consistent with previous  
257 narrowband lidar observations over Fort Collins, CO (She et al., 2000) and Urbana, IL (States  
258 and Gardner, 1998), but ~1.5 times higher than previous broadband sodium lidar observations  
259 over the nearby city of Wuhan, China (Yi et al., 2009).

260 The variability of sodium density is clearly correlated with the temperature variability  
261 shown in Figure 2. This is further demonstrated in Figure 6, where the correlation coefficient  
262 between the composite temperature and relative sodium density perturbations is plotted using  
263 lidar measurements (left) and the WACCM simulation (right). The temporal resolution for  
264 both lidar and WACCM is 1 hr. We also examined the correlation in the four different  
265 seasons and found no significant differences. The lidar observations are clearly consistent  
266 with the WACCM simulation, and both results suggest a positive correlation with coefficient  
267 of 0.5-0.8 between 80-90 km, but a negative correlation with coefficient of less than ~-0.4  
268 above 96 km for lidar and 100 km for WACCM, consistent with lidar observations at Urbana  
269 (40N) (Plane *et al.*, 1999) and in the Arctic (Collins and Smith, 2004). However, our lidar  
270 observations above 95 km are not consistent with the recent sodium lidar observations at  
271 ALOMAR, which showed a positive correlation with temperature above this altitude (Dunker  
272 et al., 2015). This difference may be related to energetic particle precipitation at high latitudes,  
273 but the detailed mechanism is beyond scope of this paper.

274 Our lidar observations suggest that the main chemistry below 95 km is likely dominated  
275 by neutral sodium chemistry, which essentially involves the partitioning of the metal between  
276 atoms and the main reservoir  $\text{NaHCO}_3$ ; the significant activation energy of the reaction  
277  $\text{NaHCO}_3 + \text{H}$  drives the balance towards Na at higher temperatures. In contrast, above 95 km  
278 the source of atomic Na is from  $\text{Na}^+$ , which involves formation of cluster ions that then  
279 undergo dissociative recombination with electrons; the formation of cluster ions is favored at  
280 lower temperatures, hence the negative correlation coefficient between Na and  
281 temperature on the topside of the Na layer (Plane et al., 2015).

282

#### 283 4. Zonal wind and gravity wave momentum flux

284 Figure 7 shows the hourly mean zonal wind composite in 4 different seasons. We see  
285 strong tidal oscillations with downward phase progression in all seasons, much clearer than  
286 those in temperature (Figure 2). The diurnal tide with vertical wavelength of  $\sim 20$  km  
287 dominates in both spring and fall, while the semidiurnal tide with vertical wavelength of  
288 30-40 km dominates in winter. In spring, the diurnal tide in temperature (Figure 2a) leads that  
289 in zonal wind by  $\sim 4$ hr between 90 and 95 km, consistent with earlier mid-latitude  
290 observations (Yuan et al., 2006). There is a strong wave oscillation signature with a period of  
291  $\sim 8$ hr and amplitude of  $\sim 20$  m/s that dominates in summer, possibly related to the terdiurnal  
292 tide. Previous observations by the nearby Wuhan meteor radar show that the diurnal  
293 amplitude near 90 km during equinox is  $\sim 30$  m/s, with a semidiurnal amplitude of  $\sim 10$  m/s  
294 (Xiong et al., 2004; Zhao et al., 2005). The comparable amplitude ( $\sim 10$  m/s) of diurnal and  
295 semidiurnal in winter is also revealed by these radar observations, with which our  
296 observations are generally consistent.

297 We show in Figure 8 the monthly mean of the nightly mean zonal wind observed by (a)  
298 lidar, (b) Wuhan meteor radar, and (c) simulated by WACCM. The radar observed zonal wind  
299 is only available in 2013 for comparison. The general pattern of the lidar observed zonal  
300 winds agrees well with the radar winds, but are 5-10 m/s stronger. This is likely due to the  
301 different vertical and temporal resolutions, signal-to-noise ratio, and the measurement methods,  
302 as well as the different locations. The lidar results exhibit a semiannual variation near 90 km  
303 with minima in March and August/September, and one maximum in May/June, clearly  
304 out-of-phase with the temperature semiannual variation (Figure 3a). The lidar observed  
305 semiannual variation in both wind and temperature is consistent with the tropical MSAO  
306 previously observed by satellites (Garcia et al., 1997), and simulated by WACCM (Richter  
307 and Garcia, 2006). The lidar and radar observations agree with the WACCM simulation  
308 below 90 km in both pattern and magnitude, while disagreeing above. Interestingly, a recent  
309 comparison between lidar measurements over Fort Collins, CO and several general  
310 circulation models also reveals significant differences (Yuan et al., 2008).

311 The USTC lidar telescopes were pointed  $15^\circ$  from zenith in eastward and westward  
312 directions between December 2012 and May 2014. This setup allows us to derive the vertical  
313 flux of GW zonal momentum. A total of 83 nights of GW momentum flux measurements

314 were obtained with 21, 12, 23, and 27 nights in spring, summer, fall, and winter respectively.  
315 Figure 9 shows vertical profiles of the seasonal mean GW zonal momentum flux for period  
316 10min – 16hr (blue) and 10min – 2hr (green), and zonal wind (red) in (a) spring, (b) summer,  
317 (c) fall, and (d) winter. The zonal momentum flux is mostly eastward in spring, positively  
318 correlated with the eastward zonal wind. However, the zonal momentum flux is mostly  
319 westward in other seasons, clearly anti-correlated with the eastward zonal wind, suggesting  
320 zonal wind filtering of GWs below 80 km. It is also clear that the zonal momentum flux  
321 induced by short-period (10 min – 2 hr) GWs clearly dominates total momentum flux in all  
322 seasons except summer.

323 The seasonal variation of zonal momentum flux is consistent with previous sodium lidar  
324 observation at SOR, NM (Gardner and Liu, 2007). However, MU radar observations near  
325 Kyoto, Japan (35°N, 136°E) shows a clear eastward flux in summer and westward flux in  
326 winter between 65 and 85 km (Tsuda et al., 1990). MF radar observations in Adelaide,  
327 Australia (35°S, 138°E) suggest an eastward flux of  $\sim 3 \text{ m}^2/\text{s}^2$  in winter (Reid and Vincent,  
328 1987). We note here that part of the differences between our lidar results and other published  
329 work is likely due to different vertical and temporal resolutions and thus sensitivity to  
330 different portions of the GW spectrum. Table 1 compares the GW zonal momentum flux  
331 measured at different mid-latitude lidar and radar stations. The results from other locations are  
332 estimated from the following studies: Gardner and Liu (2007) for the SOR lidar results; Acott  
333 et al. (2009) for the Fort Collins, CO lidar results; and Tsuda et al. (1990) for the Japan MU  
334 radar results. This comparison demonstrates that all observations report a clear westward GW  
335 zonal momentum flux in winter. In spring, both the USTC and SOR lidars observed an  
336 eastward momentum flux of  $1.4\text{-}2 \text{ m}^2/\text{s}^2$ .

337 The short-period (10 min – 2 hr) GWs clearly contribute 50%-70% of the total  
338 momentum flux, consistent with previously medium frequency (MF) radar observations  
339 (Fritts and Vincent, 1987). The large westward momentum fluxes of  $-0.9$  and  $-0.6 \text{ m}^2/\text{s}^2$  for  
340 short-period GWs in summer and winter respectively are clearly anti-correlated with eastward  
341 zonal wind maxima below 90 km (Figure 8a), suggesting the filtering of short-period GWs by  
342 the SAO wind. However, this SAO variation is not clear in the total momentum flux. For the  
343 annual mean, our lidar result is clearly smaller than the SOR lidar result, mainly due to  
344 significant difference in summer. Our results also show that the annual mean zonal wind

345 averaged between 87-95 km is  $\sim 10$  m/s eastward, and anti-correlated with the westward  
346 momentum flux of  $\sim -0.15$  m<sup>2</sup>/s<sup>2</sup> induced by short-period GWs. This anti-correlation suggests  
347 that the GW momentum flux observed in the mesopause region is generally consistent with  
348 the wind filtering theory proposed by Lindzen (1981), and adopted by general circulation  
349 models (e.g. Richter et al., 2010).

350

## 351 **5. Summary**

352 Between 2012 and 2016, the USTC sodium temperature/wind lidar observed mesopause  
353 region nighttime temperature, zonal wind, and sodium density over 150 nights, and the  
354 vertical flux of zonal momentum during 83 nights. The seasonal nighttime hourly composites  
355 of temperature and zonal wind show clear diurnal and/or semidiurnal tidal signatures. In  
356 temperature, the diurnal tide with clear downward phase progression dominates only in spring,  
357 while the semidiurnal tide dominates above 100 km throughout the year. In zonal wind, the  
358 diurnal tide with vertical wavelength of  $\sim 20$  km dominates in both spring and fall, while the  
359 semidiurnal tide with vertical wavelength of 30-40 km dominates in winter. Between 90 and  
360 95 km, the diurnal tide in temperature in spring leads that in zonal wind by  $\sim 4$  hr, consistent  
361 with previous observations and model simulations. The monthly mean results show a  
362 signature of semiannual variation in both temperature and zonal wind near 90 km but with  
363 clear out-of-phase feature, consistent with the tropical MSAO. Comparison of the USTC lidar  
364 results with observations by satellite and meteor radar, and simulated by WACCM show  
365 generally good agreement, although there are some differences among them, with pronounced  
366 disagreement between the observed zonal wind and the model above 90 km.

367 The seasonal mean of zonal momentum flux is mostly westward in summer, fall and  
368 winter, clearly anti-correlated with the eastward zonal wind, which suggests zonal wind  
369 filtering of GWs below 80 km. However, during spring the zonal momentum flux is mostly  
370 eastward, positively correlated with the eastward zonal wind. The short-period GWs clearly  
371 contribute 50%-70% of total momentum flux averaged over 87-95 km. The large westward  
372 momentum fluxes in summer and winter for short-period GWs are clearly anti-correlated with  
373 eastward zonal wind maxima below 90 km (Figure 8a), suggesting the filtering of  
374 short-period GWs by the SAO wind. The annual mean flux averaged over 87-95 km is  $\sim -0.15$   
375 m<sup>2</sup>/s<sup>2</sup> (westward) induced by the short-period GWs, anti-correlated with the zonal wind of

376 ~10 m/s (eastward), suggesting that the GW momentum flux observed in the mesopause  
377 region is generally consistent with the wind filtering theory.

378 The sodium density increases with local time during the night, with a peak height near 92  
379 km. The peak density is overall much higher in fall and winter than in spring and summer.  
380 The seasonal mean sodium peak density in winter can reach 4000-4500 cm<sup>-3</sup> after mid-night.  
381 The variability of sodium density is positively correlated with temperature variability,  
382 suggesting that chemistry plays a dominant role in the formation of sodium atoms in the  
383 mesopause region below 95 km. The lidar observations agree well with Odin/OSRIS satellite  
384 observations in both seasonal pattern and absolute monthly mean sodium density, consistent  
385 with WACCM simulations using a new Na meteoric input function.

386

### 387 **Acknowledgments**

388 The work described in this paper was carried out at the University of Science and  
389 Technology of China (USTC), under support of the National Natural Science Foundation of  
390 China grant 41674149 and the Open Research Project of Large Research Infrastructures of  
391 CAS - "Study on the interaction between low/mid-latitude atmosphere and ionosphere based  
392 on the Chinese Meridian Project. WF and JMCP were supported by the European Research  
393 Council (project 291332-CODITA). The National Center for Atmospheric Research (NCAR)  
394 is sponsored by the National Science Foundation. We thank Chengyun Yang, Shengyang Gu,  
395 Xianyu Wang, Yetao Cen, Feng Li, and Huazhi Ge for help to take lidar data. TL would like  
396 to thank Alan Liu for helpful discussion. The SD-WACCM model was obtained from the  
397 NCAR and run at the University of Leeds and is available for contacting the co-authors FW or  
398 JMCP. We would like to thank Francis Vitt at NCAR for the WACCM model support. The  
399 SABER data is downloaded from <http://saber.gats-inc.com/>. We thank Richard Collins and  
400 another anonymous reviewer for their constructive comments.

401 **Reference:**

- 402 Acott, P. E., C. Y. She, D. A. Krueger, Z. A. Yan, T. Yuan, J. Yue, and S. Harrell (2011),  
403 Observed nocturnal gravity wave variances and zonal momentum flux in mid-latitude  
404 mesopause region over Fort Collins, Colorado, USA, *J. Atmos. Sol. Terr. Phys.*, 73(4),  
405 449–456, doi:10.1016/j.jastp.2010.10.016.
- 406 Andrews, D. G., J. R. Holton, and C. B. Leovy (1987), *Middle Atmosphere Dynamics*, 489  
407 pp., Elsevier, New York.
- 408 Arnold, K., and C. She (2003), Metal fluorescence lidar (light detection and ranging) and the  
409 middle atmosphere, *Contemporary Physics*, 44(1), 35–49,  
410 doi:10.1080/0010751021000019157.
- 411 Burrage, M. D., R. A. Vincent, H. G. Mayr, W. R. Skinner, N. F. Arnold, and P. B. Hays  
412 (1996), Long-term variability in the equatorial middle atmosphere zonal wind, *J.*  
413 *Geophys. Res.*, 101(D), 12–, doi:10.1029/96JD00575.
- 414 Carrillo-Sánchez, J. D., D. Nesvorný, P. Pokorný, D. Janches, and J. M. C. Plane (2016),  
415 Sources of cosmic dust in the Earth’s atmosphere, *Geophys. Res. Lett.*, 43, 11,979–  
416 11,986, doi:10.1002/2016GL071697.
- 417 Chu, X., C. S. Gardner, and S. J. Franke (2005), Nocturnal thermal structure of the  
418 mesosphere and lower thermosphere region at Maui, Hawaii (20.7°N), and Starfire  
419 Optical Range, New Mexico (35°N), *J. Geophys. Res.*, 110(D), D09S03,  
420 doi:10.1029/2004JD004891.
- 421 Collins, R. L. and Smith, R. W.: Evidence of damping and overturning of gravity waves in the  
422 Arctic mesosphere: Na lidar and OH temperature observations, *J. Atmos. Sol. Terr. Phys.*,  
423 66(10), 867–879, doi:10.1016/j.jastp.2004.01.038, 2004.
- 424 Dou, X. - K., X. - H. Xue, T. Li, T. - D. Chen, C. Chen, and S. - C. Qiu (2010), Possible  
425 relations between meteors, enhanced electron density layers, and sporadic sodium layers,  
426 *J. Geophys. Res.*, 115, A06311, doi:10.1029/2009JA014575.
- 427 Dawkins, E. C. M., J. M. C. Plane, M. P. Chipperfield, W. Feng, J. Gumbel, J. Hedin, J.  
428 Hoffner, and J. S. Friedman (2014): First global observations of the mesospheric  
429 potassium layer, *Geophys. Res. Lett.*, 41, 5653-5661.
- 430 Dunker, T., U.-P. Hoppe, W. Feng, J. M. C. Plane, and D. R. Marsh (2015), Mesospheric  
431 temperatures and sodium properties measured with the ALOMAR Na lidar compared

432 with WACCM, *J. Atmos. Sol. Terr. Phys.*, 127, 111–119,  
433 doi:10.1016/j.jastp.2015.01.003.

434 Dunkerton, T. J. (1982), Theory of the Mesopause Semiannual Oscillation, *J. Atmos. Sci.*,  
435 39(12), 2681–2690, doi:10.1175/1520-0469(1982)039<2681:TOTMSO>2.0.CO;2.

436 Ejiri, M. K., T. Nakamura, and T. D. Kawahara (2010), Seasonal variation of nocturnal  
437 temperature and sodium density in the mesopause region observed by a resonance scatter  
438 lidar over Uji, Japan, *J. Geophys. Res.*, 115, D18126, doi:10.1029/2009JD013799.

439 Espy, P. J., G. O. L. Jones, G. R. Swenson, J. Tang, and M. J. Taylor (2004), Seasonal  
440 variations of the gravity wave momentum flux in the Antarctic mesosphere and lower  
441 thermosphere, *J. Geophys. Res.*, 109, D23109, doi:10.1029/2003JD004446.

442 Fan, Z. Y., J. M. C. Plane, J. Gumbel, J. Stegman, and E. J. Llewellyn (2007a), Satellite  
443 measurements of the global mesospheric sodium layer, *Atmospheric Chemistry and*  
444 *Physics*, 7, 4107-4115.

445 Fan, Z. Y., J. M. C. Plane, and J. Gumbel (2007b), On the global distribution of sporadic  
446 sodium layers, *Geophysical Research Letters*, 34, Article number L15808

447 Feng, W., Marsh, D. R., Chipperfield, M. P., Janches, D., Hoffner, J. Yi, F., and Plane, J. M.  
448 C. (2013): A global atmospheric model of meteoric iron, *Journal of Geophysical*  
449 *Research*, 118, 9456–9474.

450 Feng, W., B. Kaifler, D. R. Marsh, J. Höffner, U.-P. Hoppe, B. P. Williams, and J. M. C.  
451 Plane (2017), Impacts of a sudden stratospheric warming on the mesospheric metal layers,  
452 *J. Atmos. Sol. Terr. Phys.*, 1–10, doi:10.1016/j.jastp.2017.02.004.

453 Forbes, J. M., X. Zhang, W. Ward, and E. Talaat (2003), Nonmigrating diurnal tides in the  
454 thermosphere, *J. Geophys. Res.*, 108(A1), 1033, doi:10.1029/2002JA009262.

455 Franke, S. J., X. Chu, A. Z. Liu, and W. K. Hocking (2005), Comparison of meteor radar and  
456 Na Doppler lidar measurements of winds in the mesopause region above Maui, Hawaii, *J.*  
457 *Geophys. Res.*, 110, D09S02, doi:10.1029/2003JD004486.

458 Friedman, J. S., S. C. Collins, R. Delgado, and P. A. Castleberg (2002), Mesospheric  
459 potassium layer over the Arecibo Observatory, 18.3°N 66.75°W, *Geophys. Res. Lett.*,  
460 29(5), 1071, doi:10.1029/2001GL013542.

461 Friedman, J.S., Chu,X. (2007) Nocturnal temperature structure in the mesopause region over  
462 the Arecibo Observatory (18.351N, 66.751W): seasonal variations. *J. Geophys. Res.*,



463 112(D11), D14107.

464 Fritts, D. and Vincent, R.: Mesospheric Momentum Flux Studies at Adelaide, Australia:  
465 Observations and a Gravity Wave-Tidal Interaction Model, *Journal of the Atmospheric*  
466 *Sciences*, 44(3), 605–619, 1987.

467 Fussen, D., Vanhellemont, F., Tétard, C., Mateshvili, N., Dekemper, E., Loodts, N., et al.  
468 (2010). A global climatology of the mesospheric sodium layer from GOMOS data during  
469 the 2002-2008 period. *Atmospheric Chemistry and Physics*, 10(1), 9225–9236,  
470 doi:10.5194/acp-10-9225-2010.

471 Garcia, R. R., T. J. Dunkerton, R. S. Lieberman, and R. A. Vincent (1997), Climatology of  
472 the semiannual oscillation of the tropical middle atmosphere, *J. Geophys. Res.*, 102(D),  
473 26–, doi:10.1029/97JD00207.

474 Garcia, R. R., D. Marsh, D. E. Kinnison, B. Boville, and F. Sassi, Simulations of secular  
475 trends in the middle atmosphere, 1950-2003, *J. Geophys. Res.*, 112, D09301,  
476 doi:10.1029/2006JD007485, 2007.

477 Gardner, C. S., Y. Zhao, and A. Z. Liu (2002), Atmospheric stability and gravity wave  
478 dissipation in the mesopause region, *J. Atmos. Sol. Terr. Phys.*, 64, 923– 929,  
479 doi:10.1016/S1364-6826(1002)00047-00040.

480 Gardner, C. S., J. M. C. Plane, W. Pan, T. Vondra, B. J. Murray, and X. Chu (2005), Seasonal  
481 variations of the Na and Fe layers at the South Pole and their implications for the  
482 chemistry and general circulation of the polar mesosphere, *J. Geophys. Res.*, 110,  
483 D10302, doi:10.1029/2004JD005670.

484 Gardner, C. S., and Liu A. Z. (2007), Seasonal variations of the vertical fluxes of heat and  
485 horizontal momentum in the mesopause region at Starfire Optical Range, New Mexico, *J.*  
486 *Geophys. Res.*, 112, D09113, doi:10.1029/2005JD006179.

487 Gómez Martín, J.C., et al., Reaction Kinetics of Meteoric Sodium Reservoirs in the Upper  
488 Atmosphere, *J. Phys. Chem. A*, 2015, DOI: 10.1021/acs.jpca.5b00622

489 Gómez Martín, J.C., et al., The Reaction Between Sodium Hydroxide and Atomic Hydrogen  
490 in Atmospheric and Flame Chemistry, *J. Phys. Chem. A*, 2017,  
491 doi:10.1021/acs.jpca.7b07808.

492 Huang, W.; Chu, X. Z.; Gardner, C. S.; Carrillo-Sanchez, J. D.; Feng, W.; Plane, J. M. C.;  
493 Nesvorny, D. (2015): Measurements of the vertical fluxes of atomic Fe and Na at the

494 mesopause: Implications for the velocity of cosmic dust entering the atmosphere,  
495 *Geophysical Research Letters*, 42, 169-175.

496 Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.  
497 F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald,  
498 N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins,  
499 W. D., Hack, J. J., Kiehl, J. and Marshall, S.: The Community Earth System Model: A  
500 Framework for Collaborative Research, *Bulletin of the American Meteorological Society*,  
501 94(9), 1339–1360, doi:10.1175/BAMS-D-12-00121.1, 2013.

502 Kudeki, E., and S. J. Franke (1998), Statistics of momentum flux estimation, *J. Atmos. Sol.*  
503 *Terr. Phys.*, 60, 1549– 1553.

504 Lauritzen, P. H., Bacmeister, J. T., Callaghan, P. F., and Taylor, M. A.: NCAR global model  
505 topography generation software for unstructured grids, *Geosci. Model Dev.*, 8, 1-12,  
506 doi:10.5194/gmd-8-1-2015, 2015

507 Li, T., C. She, B. Williams, T. Yuan, R. Collins, L. Kieffaber, and A. Peterson (2005),  
508 Concurrent OH imager and sodium temperature/wind lidar observation of localized  
509 ripples over northern Colorado, *J. Geophys. Res.*, 114, D06106,  
510 doi:10.1029/2008JD011089.

511 Li, T., C. She, H. Liu, and M. Montgomery (2007), Evidence of a gravity wave breaking  
512 event and the estimation of the wave characteristics from sodium lidar observation over  
513 Fort Collins, CO (41°N, 105°W), *Geophys. Res. Lett.*, 34, L05815,  
514 doi:10.1029/2006GL028988.

515 Li, T., C.-Y. She, H.-L. Liu, J. Yue, T. Nakamura, D. A. Krueger, Q. Wu, X. Dou, and S.  
516 Wang (2009), Observation of local tidal variability and instability, along with dissipation  
517 of diurnal tidal harmonics in the mesopause region over Fort Collins, Colorado (41°N,  
518 105°W), *J. Geophys. Res.*, 114, D06106, doi:10.1029/2008JD011089.

519 Li, T., X. Fang, W. Liu, S. Y. Gu, and X. K. Dou (2012), Narrowband sodium lidar for the  
520 measurements of mesopause region temperature and wind, *Appl. Optics*, 51(22),  
521 5401-5411, doi:10.1364/ao.51.005401.

522 Li, T., N. Calvo, J. Yue, X. Dou, J. M. Russell III, M. G. Mlynczak, C.-Y. She, and X. Xue  
523 (2013), Influence of El Niño-Southern Oscillation in the mesosphere, *Geophys. Res. Lett.*,  
524 40(12), 3292–3296, doi:10.1002/grl.50598.

525 Li, T., N. Clavo, J. Yue, J. Russel III, A. Smith, M. Mlynczak, A. Chandran, X. Dou, and A.  
526 Liu (2016), Southern Hemisphere summer mesopause responses to El Niño–Southern  
527 Oscillation, *J. Clim.*, 29, 6319–6328, doi:10.1175/JCLI-D-15-0816.1.

528 Lieberman, R. S. (1991), Nonmigrating diurnal tides in the equatorial middle atmosphere, *J.*  
529 *Atmos. Sci.*, 48, 1112–1123.

530 Lin, S.–J., A “vertically-Lagrangian” finite-volume dynamical core for global atmospheric  
531 models, *Mon. Wea. Rev.*, 132, 2293-2307, 2004.

532 Lindzen, R. S. (1981), Turbulence and stress owing to gravity-wave and tidal breakdown, *J.*  
533 *Geophys. Res.*, 86(NC10), 9707-9714, doi:10.1029/JC086iC10p09707.

534 Liu, H. L., and M. E. Hagan (1998), Local heating/cooling of the mesosphere due to gravity  
535 wave and tidal coupling, *Geophys. Res. Lett.*, 25(15), 2941-2944,  
536 doi:10.1029/98gl02153.

537 Lübken F, Höffner J, Viehl TP, Kaifler B, Morris RJ (2011), First measurements of thermal  
538 tides in the summer mesopause region at Antarctic latitudes. *Geophys. Res. Lett.*, 38,  
539 L24806. doi:10.1029/ 2011GL0500458.

540 Llewellyn, E. J., et al. (2004). The OSIRIS instrument on the Odin spacecraft, *Can. J. Phys.*,  
541 82, 411–422.

542 Marsh, D. R., M. J. Mills, D. E. Kinnison, J.-F. Lamarque, N. Calvo, and L. M. Polvani  
543 (2013a), Climate Change from 1850 to 2005 Simulated in CESM1(WACCM), *Journal of*  
544 *Climate*, 26(19), 7372–7391, doi:10.1175/JCLI-D-12-00558.1.

545 Marsh, D. R., Janches, D., Feng, W., and Plane, J. M. C. (2013b). A global model of meteoric  
546 sodium. *J. Geophys. Res.*, 118(1), 11,442–11,452, doi:10.1002/jgrd.50870.

547 Mertens, C. J., M. G. Mlynczak, M. López-Puertas, P. P. Wintersteiner, R. H. Picard, J. R.  
548 Winick, L. L. Gordley, and J. M. I. Russell (2001), Retrieval of mesospheric and lower  
549 thermospheric kinetic temperature from measurements of CO<sub>2</sub> 15 μm Earth Limb  
550 Emission under non-LTE conditions, *Geophys. Res. Lett.*, 28(7), 1391–1394,  
551 doi:10.1029/2000GL012189.

552 Mills, M. J. et al. (2016), Global volcanic aerosol properties derived from emissions,  
553 1990-2014, using CESM1(WACCM), *J Geophys Res-Atmos*, 121(5), 2332–2348,  
554 doi:10.1002/2015jd024290.

555 Mills, M. J., Richter, J. H., Tilmes, S., Kravitz, B., MacMartin, D. G., Glanville, A. A.,

556 Tribbia, J. J., Lamarque, J.-F., Vitt, F., Schmidt, A., Gettelman, A., Hannay, C.,  
557 Bacmeister, J. T. and Kinnison, D. E.: Radiative and Chemical Response to Interactive  
558 Stratospheric Sulfate Aerosols in Fully Coupled CESM1(WACCM), *Journal of*  
559 *Geophysical Research-Atmospheres*, 6(3), 541, doi:10.1002/2017JD027006, 2017.

560 Neale, R.B., C.C. Chen, A. Gettelman and Coauthors, 2012: Description of the NCAR  
561 Community Atmosphere Model (CAM 5.0). NCAR Tech. Note NCAR-TN-486+STR,  
562 274 pp.

563 Plane, J. M. C., C. S. Gardner, J. Yu, C.Y. She, R. R. Garcia and H. C. Pumphrey (1999), The  
564 Mesospheric Na layer at 40°N: Modelling and Observations. *Journal of Geophysical*  
565 *Research*, 104, 3773-3788.

566 Plane, J. M. C., W. Feng, and E. C. M. Dawkins (2015), The Mesosphere and Metals:  
567 Chemistry and Changes, *Chem. Rev.*, 115(10), 4497–4541, doi:10.1021/cr500501m.

568 Preusse, P., S. D. Eckermann, M. Ern, J. Oberheide, R. H. Picard, R. G. Roble, M. Riese, J. M.  
569 Russell, and M. G. Mlynczak (2009), Global ray tracing simulations of the SABER  
570 gravity wave climatology, *J. Geophys. Res.*, 114(D), D08126,  
571 doi:10.1029/2008JD011214.

572 Reid, I. M.: Measurements of mesospheric gravity wave momentum fluxes and mean flow  
573 accelerations at Adelaide, Australia, *Journd of Atmospheric and Terresfrial Physrcs*, 1–  
574 18, 1987.

575 Richter, J. H., F. Sassi, and R. R. Garcia (2010), Toward a Physically Based Gravity Wave  
576 Source Parameterization in a General Circulation Model, *Journal of the Atmospheric*  
577 *Sciences*, 67, 136, doi:10.1175/2009JAS3112.1.

578 Russell, J. M., III, M. G. Mlynczak, L. L. Gordley, J. Tansock, and R. Esplin (1999), An  
579 overview of the SABER experiment and preliminary calibration results, *Proc. SPIE*, 3756,  
580 277– 288.

581 She, C. Y., and J. R. Yu (1994), Simultaneous three-frequency Na lidar measurements of  
582 radial wind and temperature in the mesopause region, *Geophys. Res. Lett.*, 21(1), 1771–  
583 1774, doi:10.1029/94GL01417.

584 She, C.Y., S. W. Thiel, D. A. Krueger (1998), Observed Episodic Warming at 86 and 100 km  
585 Between 1990 and 1997: Effects of Mount Pinatubo Eruption, *Geophys. Res. Lett.*, 25(4),  
586 497-500, doi: 10.1029/98GL00178

587 She, C. Y. (2000), Eight-year climatology of nocturnal temperature and sodium density in the  
588 mesopause region (80 to 105 km) over Fort Collins, Co (41°N, 105°W), *Geophys. Res.*  
589 *Lett.*, 27(20), 3289-3292, doi: 10.1029/2000GL003825.

590 Smith, A. K. (2012), Global Dynamics of the MLT, *Surv. Geophys.*, 33(6), 1177–1230,  
591 doi:10.1007/s10712-012-9196-9.

592 States, R. J., & Gardner, C. S. (1999). Structure of the mesospheric Na layer at 40°N latitude:  
593 Seasonal and diurnal variations. *J. Geophys. Res.*, 104(D), 11,783-11,798. doi:  
594 10.1029/1999JD900002.

595 Thorsen, D., S. J. Franke, and E. Kudeki (2000), Statistics of momentum flux estimation  
596 using the dual coplanar beam technique, *Geophys. Res. Lett.*, 27, 3193–3196.

597 Tsuda, T., Y. Murayama, and M. Yamamoto (1990), Seasonal variation of momentum flux in  
598 the mesosphere observed with the MU radar, *Geophys. Res. Lett.*, 17, 725–728.

599 Vincent, R. A., and I. M. Reid (1983), HF doppler measurements of mesospheric  
600 gravity-wave momentum fluxes, *J. Atmos. Sci.*, 40(5), 1321-1333,  
601 doi:10.1175/1520-0469(1983)040<1321:hdmomg>2.0.co;2.

602 Wu, Q., D. A. Ortland, T. L. Killeen, R. G. Roble, M. E. Hagan, H. L. Liu, S. C. Solomon, J.  
603 Xu, W. R. Skinner, and R. J. Niciejewski (2008), Global distribution and interannual  
604 variations of mesospheric and lower thermospheric neutral wind diurnal tide: 1.  
605 Migrating tide, *J. Geophys. Res.*, 113(A), A05308, doi:10.1029/2007JA012542.

606 Xiong, J. G., W. Wan, B. Ning, and L. Liu (2004), First results of the tidal structure in the  
607 MLT revealed by Wuhan Meteor Radar (30 degrees 40 ' N, 114 degrees 30 ' E), *J. Atmos.*  
608 *Sol.-Terr. Phys.*, 66(6-9), 675-682, doi:10.1016/j.jastp.2004.01.018.

609 Xu, Jiyao, She, C. Y., Yuan Wei, Mertens Chris, Mlynczak Marty, Russell, James (2006),  
610 Comparison between the temperature measurements by TIMED/SABER and lidar in the  
611 midlatitude, *J. Geophys. Res.*, 11(A10), doi:10.1029/2005JA011439

612 Yi, F., C. Yu, S. Zhang, X. Yue, Y. He, C. Huang, Y. Zhang, and K. Huang (2009), Seasonal  
613 variations of the nocturnal mesospheric Na and Fe layers at 30°N, *J. Geophys. Res.*, 114,  
614 D01301, doi:10.1029/2008JD010344.

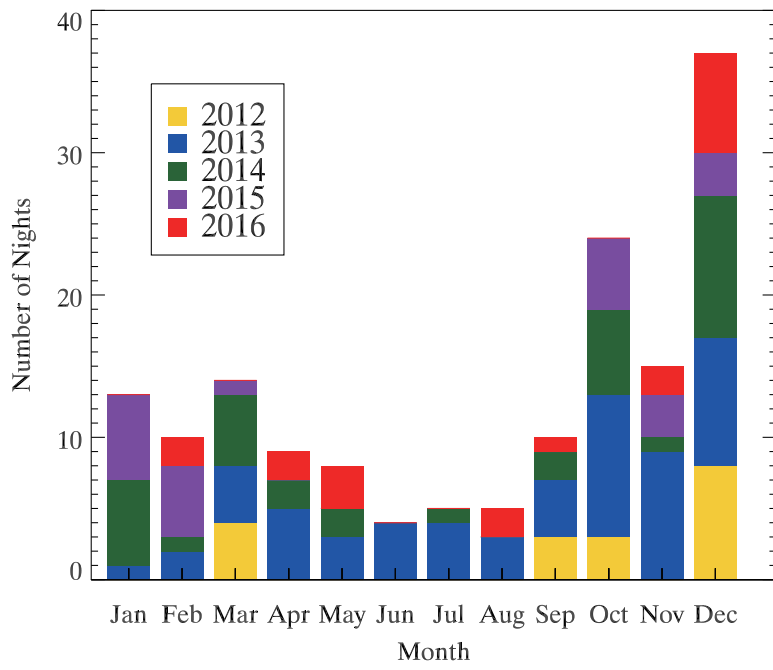
615 Yuan, T., et al. (2006), Seasonal variation of diurnal perturbations in mesopause region  
616 temperature, zonal, and meridional winds above Fort Collins, Colorado (40.6°N, 105°W),  
617 *J. Geophys. Res.*, 111, D06103, doi:10.1029/2004JD005486.

- 618 Yuan, T., She, C. Y., Kawahara Takuya D., Krueger, D. A. (2012), Seasonal variations of  
619 midlatitude mesospheric Na layer and their tidal period perturbations based on full  
620 diurnal cycle Na lidar observations of 2002–2008, *J. Geophys. Res.*, 117(D11),  
621 doi:10.1029/2011JD017031.
- 622 Zahn, von, U., J. Hoffner, V. Eska, and M. Alpers (1996), The mesopause altitude: Only two  
623 distinctive levels worldwide? *Geophys. Res. Lett.*, 23(2), 3231–3234,  
624 doi:10.1029/96GL03041.
- 625 Zhang, X., J. M. Forbes, and M. E. Hagan (2010), Longitudinal variation of tides in the MLT  
626 region: 1. Tides driven by tropospheric net radiative heating, *J. Geophys. Res.*, 115,  
627 A06316, doi:10.1029/2009JA014897.
- 628 Zhao, G., L. Liu, W. Wan, B. Ning, and J. Xiong (2005), Seasonal behavior of meteor radar  
629 winds over Wuhan, *Earth Planets and Space*, 57(1), 61–70, doi:10.1186/BF03351806.

630 **Table 1.** Comparison of the GW zonal momentum flux ( $\text{m}^2/\text{s}^2$ ) measured at different middle  
 631 latitude lidar and radar stations.

Stations	Altitude/filter	Annual	Spring	Summer	Fall	Winter
USTC lidar (32°N, 117°E)	87 – 95 km 10min – 16hr	-0.08	1.4	-0.2	-0.3	-0.9
	87 – 95 km 10min – 2hr	-0.15	0.8	-0.9	-0.16	-0.6
SOR lidar (35°N, 107°W)	85 – 100 km 3min – 14hr	-1.2	~2	1.8	N/A	-1.7
CSU lidar (41°N, 105°W)	85 – 95 km 6min – 4hr	N/A	~0.1	N/A	~0.1	-0.7
MU Radar (35°N, 136°E)	65 – 85km 5min – 2 hr	N/A	~0	2.0	~0	-1.5

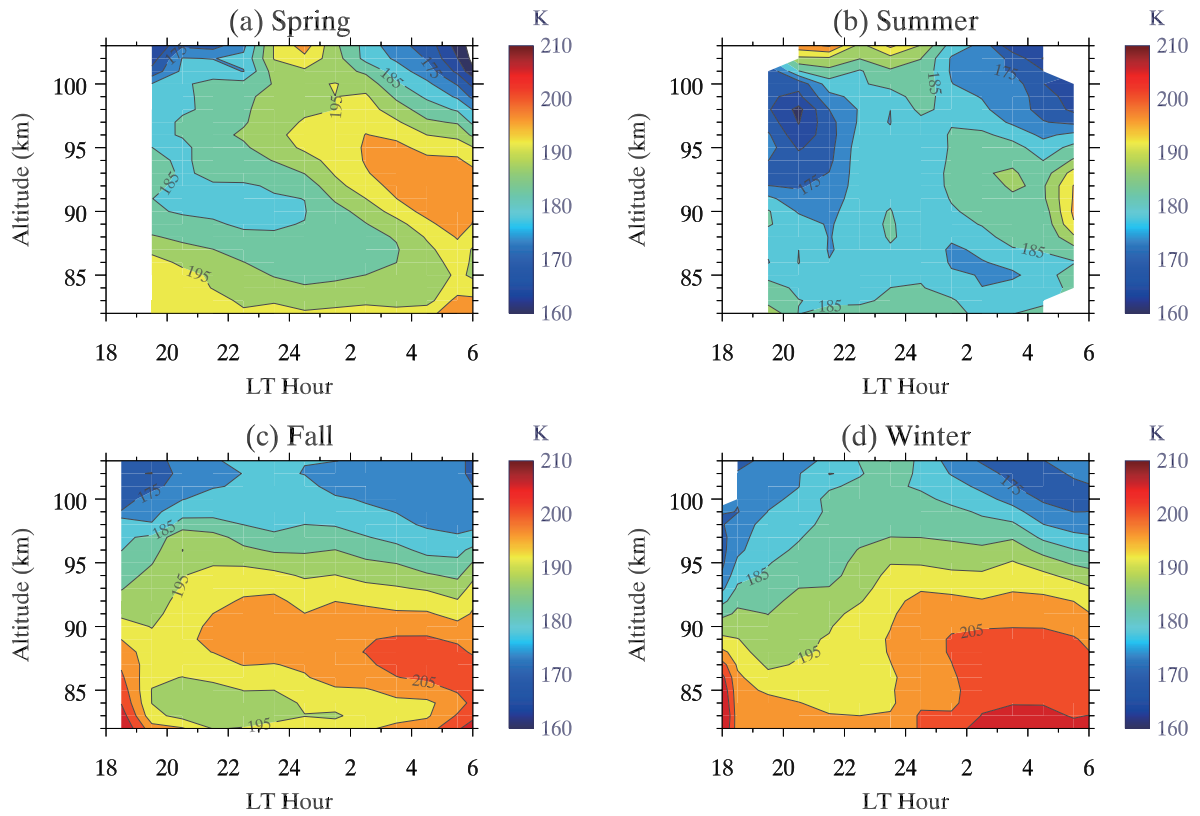
632



633

634 **Figure 1.** Histogram of number of nights with valid data observed by the USTC sodium lidar.

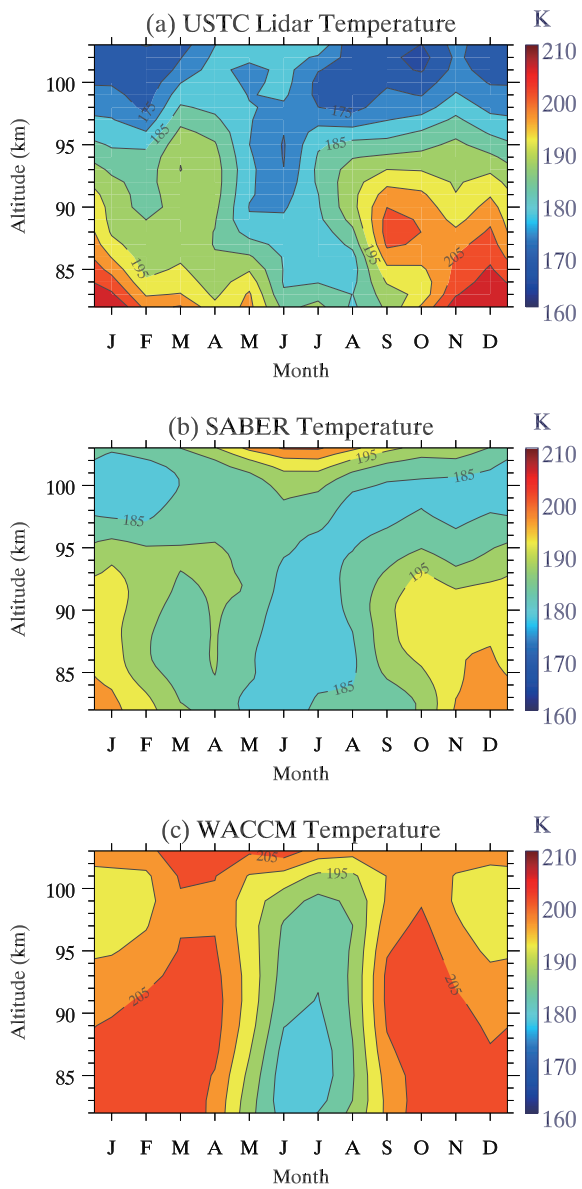




635

636 **Figure 2.** Lidar observed nighttime hourly mean temperature composite in (a) spring, (b)

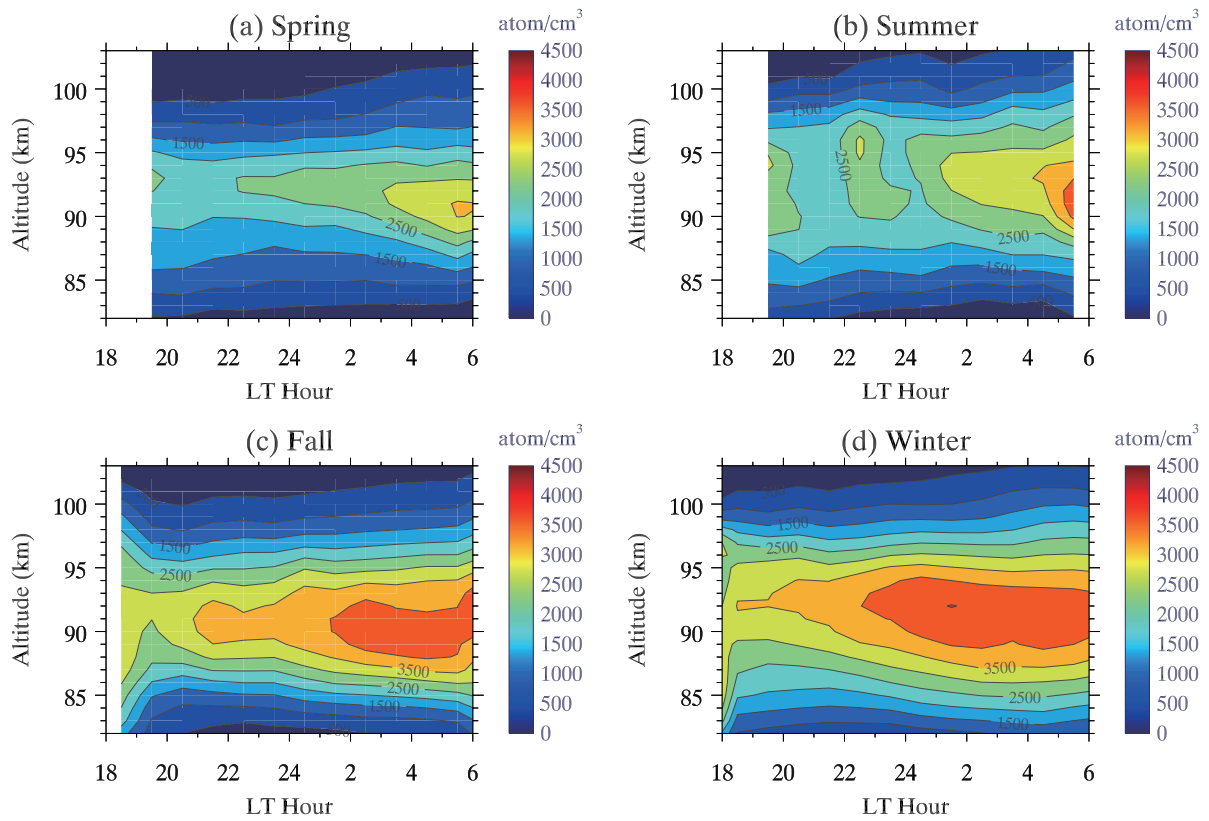
637 summer, (c) fall, and (d) winter.



638

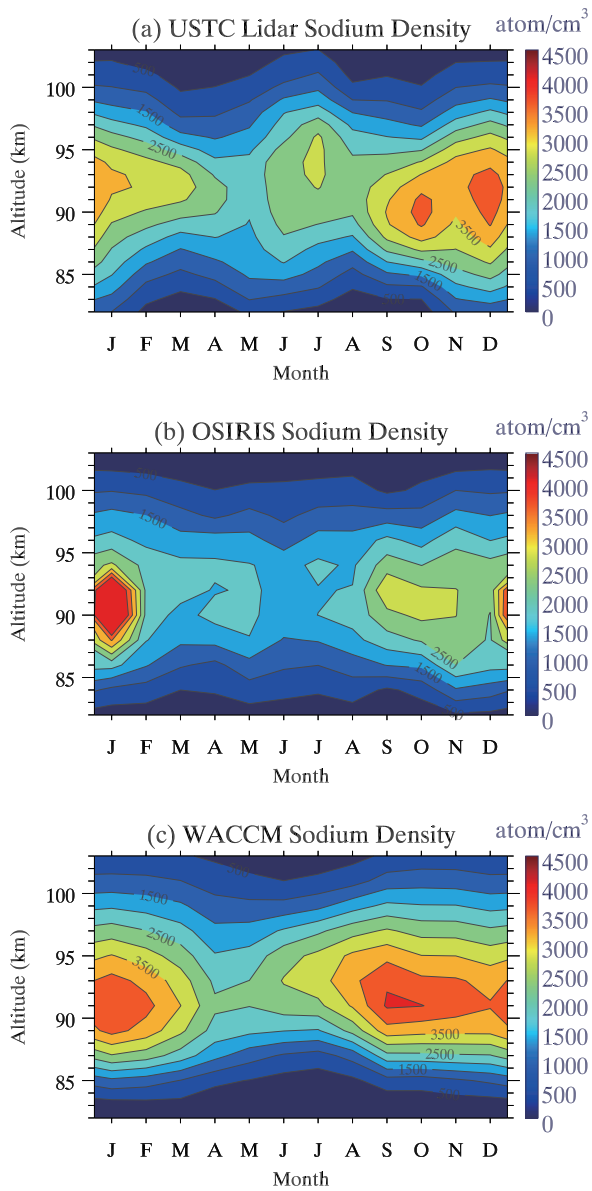
639 **Figure 3.** Monthly mean of mean temperature observed by (a) lidar, (b) SABER, and

640 simulated by (c) WACCM.



641

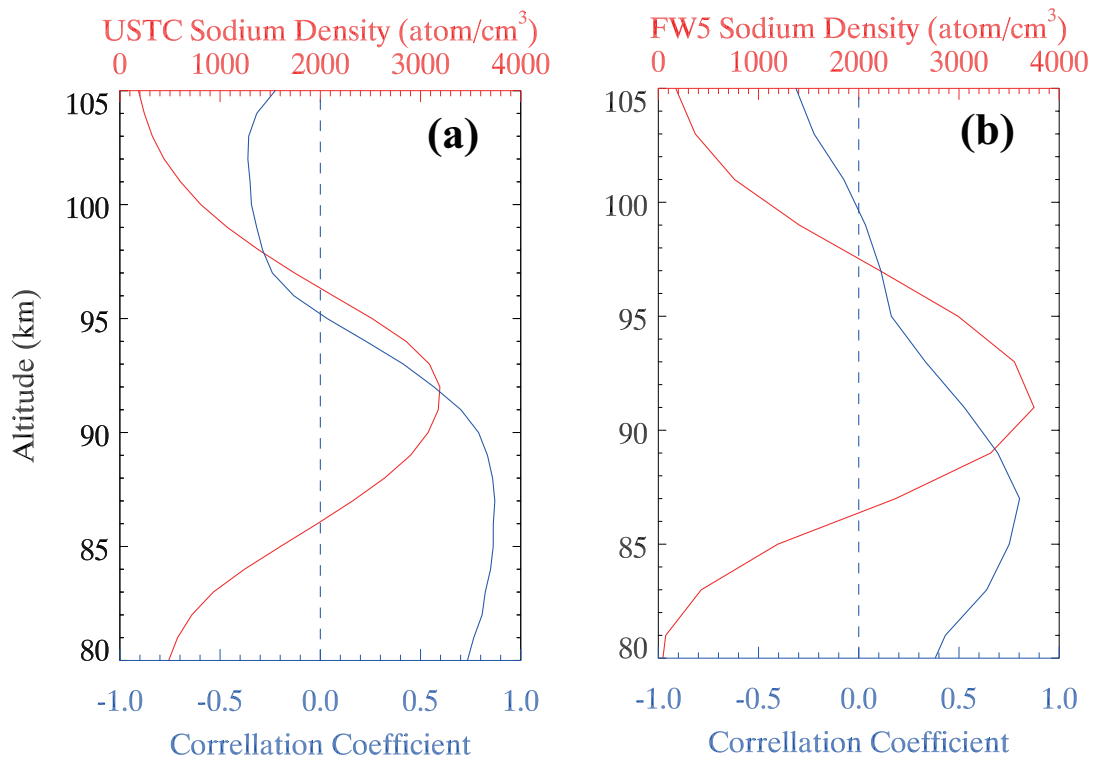
642 **Figure 4.** Same as Figure 2, but for sodium number density.



643

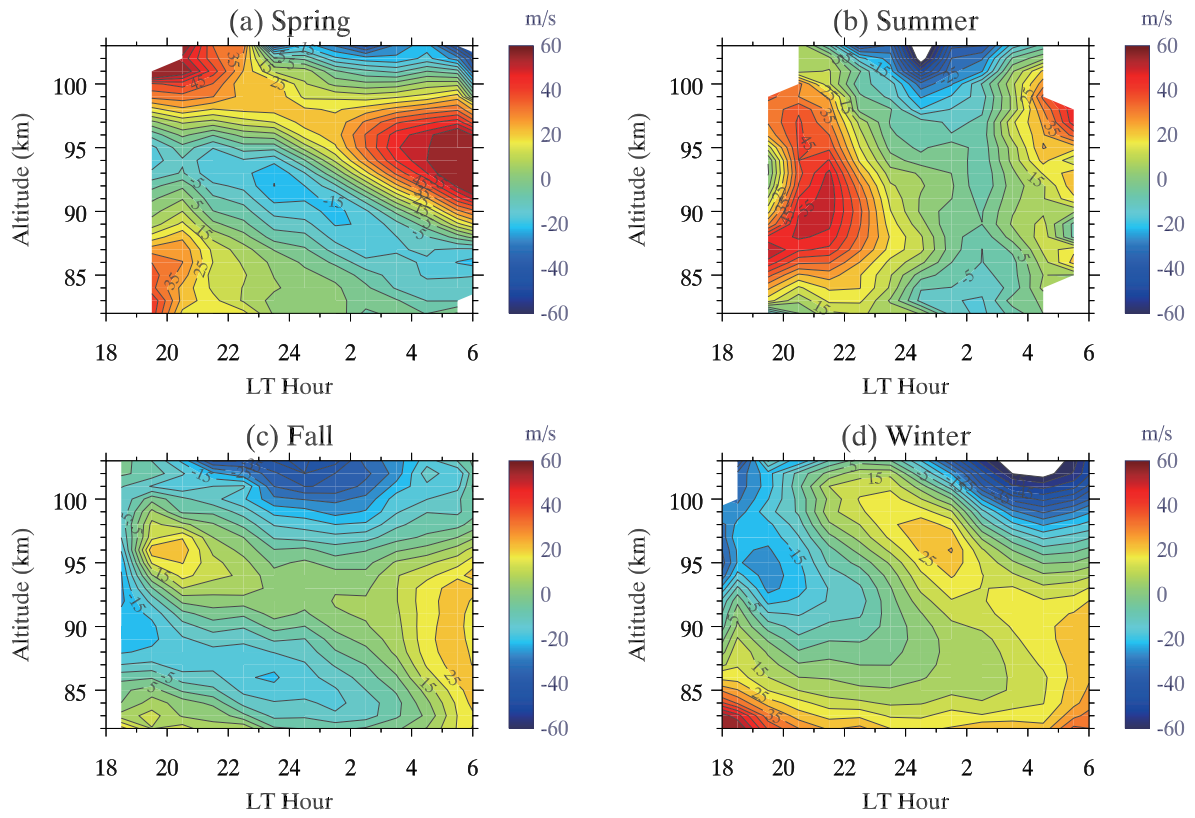
644 **Figure 5.** Monthly mean of nightly mean sodium density observed by (a) lidar and (b) Odin/

645 OSIRIS, and simulated by (c) WACCM.



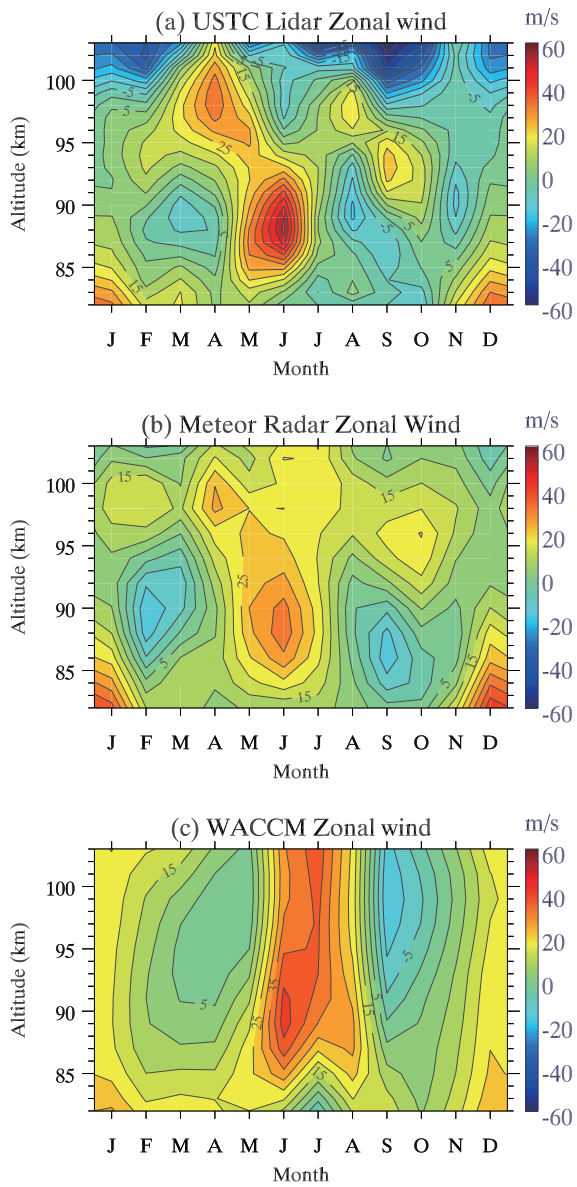
646

647 **Figure 6.** The vertical profiles of correlation coefficient (blue) between composite temperature  
 648 and relative sodium density perturbations, and annual mean sodium density (red), observed by  
 649 lidar (left) and simulated by WACCM (right).



650

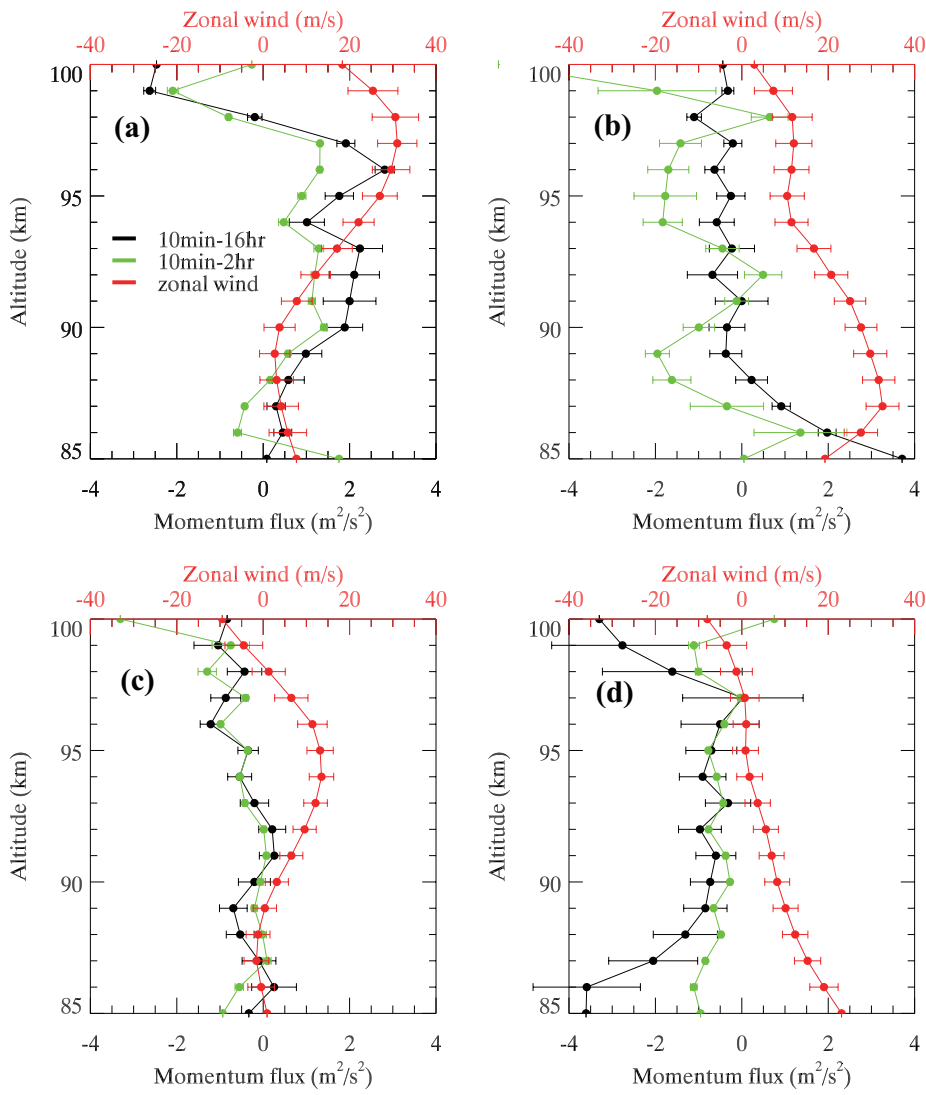
651 **Figure 7.** Same as Figure 2, but for zonal wind.



652

653 **Figure 8.** Monthly mean of nightly mean zonal wind observed by (a) lidar, (b) meteor radar,

654 and simulated by (c) WACCM.



655

656 **Figure 9.** Comparison of seasonal mean of nightly mean zonal wind (red) and zonal  
 657 momentum flux for 10min - 16hr (blue) and 10min - 2hr (green) observed by lidar in (a)  
 658 spring, (b) summer, (c) fall, and (d) winter.