

1 **Impact of low-pressure systems on winter heavy air pollution in the northwest Sichuan Basin, China**

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13 **Abstract**

14 The cities of Chengdu, Deyang, and Mianyang in the northwest Sichuan Basin are part of a rapidly developing
15 urban agglomeration adjoining the eastern slopes of the Tibetan Plateau. Heavy air pollution events have frequently
16 occurred over the cities in recent decade, but the effects of meteorological conditions on these pollution events are
17 unclear. We explored the effects of weather systems on winter heavy air pollution from 1 January 2006 to 31
18 December 2012 and from 1 January 2014 to 28 February 2017. Ten heavy air pollution events occurred during the
19 research period and eight of these took place while the region was affected by a dry low-pressure system at 700 hPa.
20 When the urban agglomeration was in front of the low-pressure system and the weather conditions were controlled
21 by a warm southerly air flow, and a strong temperature inversion appeared above the atmospheric boundary layer
22 acting as a lid. Forced by this strong inversion layer, the local secondary circulation was confined within the
23 atmospheric boundary layer and the horizontal wind speed in the lower troposphere was low. As a result, vertical
24 mixing and horizontal dispersion in the atmosphere were poor, favoring the formation of heavy air pollution events.
25 After the low-pressure system had transited over the region, the weather conditions in the urban agglomeration were
26 controlled by a dry and cold air flow from the northwest at 700 hPa. The strong inversion layer gradually dissipated,

27 the secondary circulation enhanced and uplifted, and the horizontal wind speed in the lower troposphere also
28 increased, resulting in a sharp decrease in the concentration of air pollutants. The strong inversion layer above the
29 atmospheric boundary layer induced by the low-pressure system at 700 hPa thus played a key role in the formation
30 of heavy air pollution during the winter months in this urban agglomeration. This study provides scientific insights
31 for forecasting heavy air pollution in this region of China.

32 **1 Introduction**

33 Air quality, especially the occurrence of heavy air pollution events, is not only strongly affected by excessive
34 emission of air pollutants, but is also closely associated with meteorological conditions, including atmospheric
35 circulations, weather systems, structures of atmospheric boundary layer, and the corresponding meteorological
36 parameters (**Deng et al., 2014;Gu and Yim, 2016;Li et al., 2015;Wei et al., 2011;Ye et al., 2016;Zhang et al.,**
37 **2012a**). The total amount of pollutants emitted in a particular period of time is usually stable in China (**Wu et al.,**
38 **2017**), but there are large differences in the concentrations of air pollutants, indicating that the meteorological
39 conditions have an important role in modulating concentrations of ambient air pollutants (**Gao et al., 2011;Hu et al.,**
40 **2014;Ji et al., 2014;Ji et al., 2012;Wang et al., 2010;Wang et al., 2009;Yang et al., 2011**).

41 Weather systems control the ability of the atmosphere to disperse pollutants and thus provide the primary
42 driving force for variations in regional air pollution (**Chen et al., 2008;Ye et al., 2016**). Leśniok et al. (2010)
43 reported that the atmosphere was stagnant and that the concentrations of near-ground air pollutants increased
44 significantly in Upper Silesia, Poland during periods with an anticyclonic circulation. By contrast, when a cyclonic
45 circulation prevailed, causing an inflow of fresh air masses from regions with lower levels of pollution, the
46 concentrations of air pollutants decreased. As synoptic-scale high-pressure ridges at 500 hPa transit across Utah,
47 accompanied by warm advection above valleys, the stability of the atmosphere is increased and favors the formation
48 of persistent pools of cold air, resulting in deterioration in air quality (**Whiteman et al., 2014**).

49 Many studies have been carried out on the impact of weather systems on air quality in China. Bei et al. (2016)

50 classified typical synoptic situations and evaluated their contributions to air quality in the Guanzhong Basin, China.
51 They found that an inland high-pressure system at 850 hPa resulted in temperature inversion, low horizontal wind
52 speed and a shallow atmospheric boundary layer, which favor the formation of heavy air pollution. Weather systems
53 have significantly impact on the transport of air pollutants. Luo et al. (2018) reported that the trans-boundary air
54 pollution and the pollutant concentration in Hong Kong increased when a tropical cyclones is approaching. During
55 winter, floating dust particles over northwestern China can be carried downstream to northern China by the
56 prevailing northwesterly winds at 700 hPa, where they mix with anthropogenic pollution to form a regional haze
57 (**Tao et al., 2012;Tao et al., 2014**). Changes in weather systems also significantly influence air quality. Shallowing
58 of the East Asian trough and weakening of the Siberian high-pressure in winter can induce weak horizontal
59 advection and vertical convection in the lower troposphere, reducing the height of the boundary layer in the
60 Beijing–Tianjin–Hebei region and favoring the formation of haze (**Zhang et al., 2016**).

61 The deep Sichuan Basin to the east of the Tibetan Plateau has a maximum elevation difference >2000 m, and is
62 ranked fourth in China for heavy air pollution after the Beijing–Tianjin–Hebei region, the Yangtze River Delta, and
63 the Pearl River Delta (**Tian et al., 2017;Zhang et al., 2012b**). The complex terrain leads to unique weather systems
64 that affect air quality in this region (**Chen et al., 2014;Huang et al., 2017**). Low-pressure systems, such as a
65 southwest vortex and low trough, are often formed at 700 hPa due to the dynamic and thermodynamic effects of the
66 Tibetan Plateau (**Wang and Tan, 2014;Yu et al., 2016**) and have different characteristics in different seasons. They
67 are warm and moist low-pressure systems in summer and autumn and have crucial effects on local precipitation
68 (**Feng et al., 2016;Peng and Cheng, 1992**); much work has been carried out in an attempt to understand the impacts
69 of these low-pressure systems on precipitation (**Chen et al., 2015;Fu et al., 2011;Kuo et al., 1986;Kuo et al.,**
70 **1988;Ni et al., 2017**). In winter and spring, however, these low-pressure systems are both dry and cold (**Feng et al.,**
71 **2016**). No attempt has previously been made to investigate the association between air quality and these dry and cold
72 low-pressure systems.

73 Chengdu, Deyang, and Mianyang, have undergone rapid development to form an urban agglomeration in the
74 northwest Sichuan Basin. This urban agglomeration lies close to the eastern slopes of Tibetan Plateau, and is affected
75 by low-pressure systems moving east from the plateau (Feng et al., 2016). Heavy air pollution events have
76 frequently occurred over there in recent decade. Number of days with exceedance of Grade II standards (MEP, 2012)
77 is more than 150 days each year in Chengdu (Ning et al., 2018). Most previous studies have investigated the basic
78 characteristics of air pollution (Chen and Xie, 2012; Chen et al., 2014; Luo et al., 2001; Ning et al., 2018; Tao et al.,
79 2013a; Tao et al., 2013b; Zhang et al., 2017) and the related meteorological parameters (He et al., 2017; Li et al.,
80 2015; Liao et al., 2017; Zeng and Zhang, 2017). However, the influencing mechanism of dry low-pressure system
81 on heavy air pollution events has yet to be comprehensively explored. The main purpose of this study was to
82 statistically analyze the relationships between low-pressure systems and winter heavy air pollution events in this
83 urban agglomeration, and to explore the physical mechanisms involved in the formation of winter heavy air pollution.
84 This study can deepen our understanding of the meteorological causes of heavy air pollution events in winter, and
85 provide scientific insights that can be used by local governments to take effective measures to mitigate air pollution.

86 This paper is organized as follows. The data and methods are described in Section 2. Section 3 provides a
87 statistical analysis of the relationships between the low-pressure systems and winter heavy air pollution. Section 4
88 illustrates the physical mechanisms of the effect of weather systems on air pollution and our conclusions are
89 summarized in Section 5.

90 **2 Data and methods**

91 **2.1 Air quality data**

92 Air pollution in the Sichuan Basin during the winter months is mainly caused by particulate matter (Ning et al.,
93 2018). The Chinese Ministry of Environmental Protection (MEP) currently monitors particles with diameters ≤ 2.5
94 μm ($\text{PM}_{2.5}$) and particles with diameters $\leq 10 \mu\text{m}$ (PM_{10}). We studied heavy air pollution events occurring during the
95 winter months in Chengdu, Deyang, and Mianyang in the northwest Sichuan Basin (Fig. 1). We selected pollution

96 events with a daily PM_{10} mean concentration $\geq 350 \mu g m^{-3}$ from 1 January 2006 to 31 December 2012 and from 1
97 January 2014 to 28 February 2017. The third revision of the “Ambient Air Quality Standard” (AAQS)
98 (GB3095-2012) was released on February 29th, 2012, replacing the old “Ambient Air Quality Standard” (AAQS)
99 (GB3095-1996) and $PM_{2.5}$ was adopted into the AAQS in China since 2013. The air quality monitoring stations
100 needed to be updated and the data of air pollutants monitored in the three cities existed missing measurement during
101 2013. Thus, the winter heavy pollution events during 2013 have not been analyzed in this paper. Moreover, the PM_{10}
102 daily mean concentration from 1 January 2014 to 28 February 2017 refers to the 24-hour average concentration of
103 PM_{10} from 00:00 BST (Beijing Standard Time, i.e., Coordinate Universal Time (UTC) +8 h) to 24:00 BST on the
104 current day based on the new “Ambient Air Quality Standard” (AAQS) (GB3095-2012). However, based on the old
105 “Ambient Air Quality Standard” (AAQS) (GB3095-1996), the PM_{10} daily mean concentration from 1 January 2006
106 to 31 December 2012 refers to the 24-hour average concentration of PM_{10} from 12:00 BST on the previous day to
107 12:00 BST on the current day. Hourly concentrations of $PM_{2.5}$, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon
108 monoxide (CO), and ozone (O_3) were also measured in the three cities from 1 January 2014 to 28 February 2017.
109 These above air quality data were collected from the MEP website (<http://datacenter.mep.gov.cn/index>).

110 **2.2 Meteorological data**

111 **(1) ERA-Interim daily data**

112 To analyze the weather systems at 700 hPa, and the dynamic and thermodynamic conditions in the lower
113 troposphere, the temperature, the geopotential, the vertical velocity, and the u and v components of wind during the
114 study period were obtained from the ERA-Interim daily dataset ($0.125^\circ \times 0.125^\circ$ grids) from 950 to 500 hPa for a
115 total of 14 vertical layers (with a vertical separation of 25 hPa from 950 to 775 hPa and a vertical separation of 50
116 hPa from 750 to 500 hPa). These meteorological data are available for 00:00, 06:00, 12:00, and 18:00 UTC and were
117 collected from the website (<http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/>). The height of the
118 atmospheric boundary layer was obtained from the ERA-Interim daily dataset at the surface with a 3 h temporal

119 resolution (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC)
120 (<http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/>) to explore the structure of the atmospheric
121 boundary layer. This boundary layer height was defined as the level where the bulk Richardson number, based on the
122 difference between quantities at that level and the lowest model level, reaches the critical value $Ri_{cr} = 0.25$ (Beljaars,
123 2006).

124 (2) Sounding data

125 Radiosonde measurements from launches at Wenjiang station (see Fig. 1) in Chengdu city (30.70 °N, 103.83 °E,
126 elevation 541.0 m) at 08:00 and 20:00 BST were obtained from the University of Wyoming website
127 (<http://weather.uwyo.edu/upperair/sounding.html>) and included the temperature, potential temperature, and
128 horizontal wind. These data were used to investigate the dynamic and thermodynamic structure of the lower
129 troposphere.

130 2.3 Quantitative measures of meteorological conditions

131 2.3.1 Lower tropospheric stability

132 The lower tropospheric stability (LTS) is defined as the difference in the potential temperature between 700 hPa
133 and the surface (Slingo, 1987), and can be used to describe the thermodynamic state of the lower troposphere (Guo
134 et al., 2016a; Guo et al., 2016b). The LTS can be used to quantitatively evaluate the vertical mixing of air pollutants
135 in the lower troposphere:

$$136 \quad LTS = \theta_{700\text{hPa}} - \theta_{\text{surface}} \quad (1)$$

137 A large LTS represents a high degree of stability in the lower troposphere and indicates the potential for the weak
138 vertical mixing of air pollutants.

139 2.3.2 The mean wind speed in the lower troposphere

140 Sichuan Basin belongs to a low wind speed zone in China due to its deep mountain-basin topography, and the
141 wind speed in the mixing layer is often low and with less changed (Chen and Xie, 2012; Huang et al., 2017; Wang

142 **et al., 2018**). For analyzing air quality in Sichuan Basin, the meteorological conditions contributing to the
143 atmospheric ventilation should be taken into consideration. To quantitatively evaluate the horizontal dispersion of air
144 pollutants in Sichuan Basin, the mean wind speed (MWS) in the lower troposphere was constructed based on the
145 concept of ventilation coefficient (VC is a product of mixing layer height multiplied by average wind speed through
146 the mixing height). In the eastern plains of China, the ventilation coefficient has been widely used to measure the
147 capability of air pollutants' dispersion (**Deng et al., 2014; Lu et al., 2012; Tang et al., 2015**). The mean wind speed
148 (MWS) in the lower troposphere was defined as:

$$149 \quad \text{MWS} = \frac{1}{h} \int_0^h V(z) dz \quad (2)$$

150 where h is the height above the ground at 700 hPa and $V(z)$ is the wind speed in the lower troposphere. This can
151 be simplified as follows:

$$152 \quad \text{MWS} = \frac{1}{h} \sum_{i=1}^n [V_i(z_i) + V_{i-1}(z_{i-1})] \cdot 0.5 \cdot \Delta z_i \quad (3)$$

153 where n is the number of vertical layers from the ground surface to 700 hPa isobaric layer (including the 700 hPa
154 isobaric layer, and n is greater than 6 in general), $V_i(z_i)$ is the wind speed in a vertical layer (when $i=0$ represents
155 the wind speed at the ground surface and $i=n$ represents the wind speed at 700 hPa), and Δz_i is the difference in
156 height between the two adjacent vertical layers. A large value of MWS suggests strong horizontal dispersion of air
157 pollutants.

158 **3 Heavy air pollution events and weather conditions**

159 **3.1 Overview of the heavy air pollution events**

160 A total of ten heavy winter air pollution events occurred from 1 January 2006 to 31 December 2012 and from 1
161 January 2014 to 28 February 2017 in the urban agglomeration of Chengdu, Deyang, and Mianyang. Nine events

162 were accompanied by a low-pressure system at 700 hPa, and the low-pressure systems in eight events were dry and
163 didn't induce precipitation. This paper explores the impacts of dry low-pressure systems on the eight winter heavy
164 air pollution events (see **Table 1** for a summary of these eight events).

165 **Table 1** shows that particulate matter was the primary pollutants during these eight heavy air pollution events.
166 Six of the eight events were classified as persistent air pollution events. A “persistent” pollution event was defined
167 by two or more consecutive days with daily PM₁₀ mean concentration $\geq 250 \mu\text{g m}^{-3}$, which is reported to be harmful
168 to the health of local residents (**Chow et al., 2006;Guo et al., 2016c;Langrish et al., 2012;Lim et al., 2012**), and
169 the longest duration was 10 days. Most of the heavy air pollution events had the characteristics of regional pollution,
170 with five pollution events occurring in multiple cities. Two heavy air pollution events (events 6 and 7) occurred
171 during the Spring Festival, with maximum daily mean PM₁₀ concentrations up to 403 and 562 $\mu\text{g m}^{-3}$ on the Chinese
172 New Year Day. This suggests that the centralized letting-off of fireworks during the traditional Chinese Spring
173 Festival, accompanied by poor conditions for the dispersion of air pollution, may lead to a sharp increase in the
174 concentration of particulate pollutants near ground level within a short period of time (**Huang et al., 2012;Liao et al.,**
175 **2017;Shi et al., 2011;Wang et al., 2007**).

176 **3.2 Weather systems and meteorological conditions during heavy air pollution events**

177 An analysis of the synoptic conditions showed that the urban agglomeration was affected by low-pressure
178 systems (low vortex or low trough) at 700 hPa during periods of deteriorating air quality in the eight heavy air
179 pollution events (**Fig. 2**). These studied areas were all located in front of low-pressure systems (east of low-pressure
180 systems) and were controlled by a southerly warm air flow (**Fig. 2**). To explore the differences between these
181 low-pressure systems and the background of winter atmospheric circulation, composite anomalies of wind vectors
182 and geopotential heights at 700 hPa were calculated (**Fig. S1**). The calculation method is as follows: the averaged
183 wind vectors and geopotential heights at 700 hPa during periods of deteriorating air quality in the above eight events
184 subtracted from their winter mean values from 1 January 2006 to 31 December 2012 and from 1 January 2014 to 28

185 February 2017. As illustrated in **Fig. S1**, the anomalies of geopotential heights were negative in the northwest of the
186 urban agglomeration during periods of deteriorating air quality in these heavy air pollution events. As a result, this
187 urban agglomeration was located in front of an anomalous cyclone and was controlled by a strong southerly anomaly
188 wind (**Fig. S1**).

189 Weather systems can be characterized by their relative vorticity. A positive relative vorticity usually
190 corresponds to a low-pressure system, whereas a negative relative vorticity usually represents a high-pressure system.
191 Thus the relative vorticity at 700 hPa was analyzed during periods of both deteriorating and improving air quality
192 (**Table 2**). As shown in **Table 2**, the relative vorticities at 700 hPa during periods of deteriorating air quality were all
193 positive. This indicated that the study areas were located in front of low-pressure systems at 700 hPa. As a result, a
194 southerly warm air flow dominated at 700 hPa and led to an increase in temperature above the atmospheric boundary
195 layer, which increased atmospheric stability and favored the formation of an air pollution event. During periods of
196 improving air quality, the relative vorticities at 700 hPa of six heavy air pollution events (except for events 6 and 7)
197 were negative, showing that the low-pressure systems had transited across the study areas. These areas were thus
198 controlled by a northerly dry, cold air flow at 700 hPa. As a consequence, the temperature above the atmospheric
199 boundary layer decreased and the stability of the atmosphere weakened, which favored the vertical mixing of air
200 pollutants.

201 To explore the impacts of low-pressure systems on the structure of the atmospheric boundary layer, the
202 boundary layer height during periods of deteriorating and improving air quality were analyzed for each heavy air
203 pollution event (**Table 3**). In most of the heavy air pollution events, the height of the boundary layer increased after
204 the low-pressure system had passed across the study area. However, the increase in the height of the boundary layer
205 was not as significant as that seen in Eastern China (**He et al., 2015; Ji et al., 2012; Leng et al., 2016; Qu et al.,**
206 **2017; Quan et al., 2013**) and the boundary layer heights in air pollution events 3, and 4 decreased after transit of the
207 low-pressure system. These results show that the effects of the transit of low-pressure systems at 700 hPa on the

208 height of the boundary layer were weak, and the causes for the formation of these features will be discussed later. It
209 is therefore difficult to explain the variations in the concentrations of air pollutants in the study areas by considering
210 only the meteorological conditions within the boundary layer.

211 Previous studies have shown that the meteorological conditions above the boundary layer should also be
212 considered (Guo et al., 2016a;Guo et al., 2016b;Slingo, 1987). Therefore an index of the MWS in the lower
213 troposphere was proposed and this index, together with the LTS of the eight heavy air pollution events, were further
214 investigated (Table 3). The differences in the potential temperature between 700 hPa and the surface during periods
215 of deteriorating air quality in the eight events were all ≥ 18.54 K and the maximum value was 29.45 K, indicating that
216 the lower troposphere was very stable. The MWS was ≤ 4.22 m s⁻¹ for all eight events, with a minimum of 1.91 m s⁻¹.
217 These results show that the low-pressure systems resulted in the stagnation of air in the lower troposphere. After the
218 low-pressure systems had transited the study area, the lower tropospheric stability significantly decreased, with a
219 maximum decrease in the LTS of up to -11.23 K, and the MWS increased. This showed that the arrival of a dry, cold
220 air flow induced by the transit of the low-pressure system significantly weakened the stability of the lower
221 troposphere and increased the wind speed, improving air quality.

222 In events 6 and 7, however, although the study areas were still located in front of the low-pressure system and
223 the capacity for dispersion had not yet improved, the concentrations of particulate matter began to sharply decrease
224 before the transit of the low-pressure system. Both of these events occurred during the Chinese Spring Festival. After
225 the Chinese New Year Day, the letting-off of fireworks stopped and the emission of air pollutants was significantly
226 reduced, resulting in a sharp decrease in the concentration of particulate matter (Liao et al., 2017;Shi et al.,
227 2011;Wang et al., 2007). The decrease in the magnitude of the daily mean concentration of PM₁₀ in event 7 was up
228 to 350 $\mu\text{g m}^{-3}$. These eight heavy air pollution events in the northwest Sichuan Basin can therefore be categorized
229 into two types based on their date of occurrence. The two heavy air pollution events (6 and 7) occurring during the
230 Chinese Spring Festival were categorized as Spring Festival excessive emission heavy air pollution events. The other

231 six events (events 1–5 and 8) were categorized as normal heavy air pollution events.

232 **4 Impacts of low-pressure systems on heavy air pollution events**

233 To further explore the mechanism involved in the formation of heavy air pollution events, with a particular
234 emphasis on the effect of low-pressure systems on air quality, a typical event was selected from the eight events
235 described in the preceding section. The variations in air quality and the dynamic and thermodynamic conditions in
236 the lower troposphere of the selected event were analyzed. Additionally, the impacts of Spring Festival excessive
237 emission on heavy air pollution events were also investigated.

238 **4.1 The influencing mechanism of low-pressure systems on heavy air pollution events**

239 Heavy air pollution event 8 occurred from 1 January 2017 to 6 January 2017 (Table 3) and the most polluted
240 area was Chengdu. The maximum daily mean concentrations of PM_{2.5} and PM₁₀ occurred on 5 January 2017. The
241 maximum PM₁₀ daily mean concentration in Chengdu was up to 480 $\mu\text{g m}^{-3}$. The concentrations of particulate
242 matter increased sharply (**Fig. 3**) from 00:00 BST on 3 January 2017 to 00:00 BST on 5 January 2017 and the
243 concentrations of nitrogen dioxide and carbon monoxide also showed an increasing trend. Since 12:00 BST on 5
244 January 2017, the concentrations of particulate matter decreased significantly (**Fig. 3**).

245 **Fig. 4** shows the weather maps at 700 hPa during event 8. **Fig. 4a** shows that there was no low-pressure system
246 at 700 hPa over the urban agglomeration at 02:00 BST on 2 January and there was a dry, cold air flow from the
247 northwest. As shown in **Fig. 4b**, a low trough was subsequently generated at 700 hPa on the west side of the urban
248 agglomeration at 14:00 BST on 2 January 2017, which showed the beginning of low-pressure system causing air
249 pollution. This trough later developed and was enhanced, and the lifespan of this low-pressure system was about 3
250 days. The urban agglomeration was still located at the front of the trough and was controlled by a warm, moist air
251 flow from the southwest until 02:00 BST on 5 January 2017 (**Fig. 4b** and **4c**). The concentrations of particulate
252 matter in the urban agglomeration increased sharply and the air quality deteriorated. The trough developed further
253 and a low vortex was formed, which transited across over the study area at 02:00 BST on 5 January 2017 (**Fig. 4d**).

254 The urban agglomeration was then located behind the low vortex and was controlled by a northerly dry, cold air flow
255 (**Fig. 4d**), which illustrated the meteorological conditions in the end of air pollution event. As a result, the air
256 pollutants were rapidly dispersed.

257 The west–east vertical cross-sections of the 24-hour change in temperature and wind vectors (u and w) in the
258 most polluted area (30.75 °N) (**Fig. 5**) and the vertical profiles of temperature and horizontal wind speed (**Fig. 6**)
259 were analyzed to investigate the effects of the low-pressure system on the dynamic and thermodynamic dispersion of
260 air pollutants in the lower troposphere.

261 **Fig.4b** and **4c** shows that the urban agglomeration was located in front of the low-pressure system and was
262 controlled by a southerly warm air flow. There was a descending motion between the top of the boundary layer and
263 500 hPa (**Fig. 5a** and **5b**). Under the effects of warm advection and descending motion, a warming center appeared
264 between 800 and 650 hPa (**Fig. 5a–c**) and the maximum increase in the 24-hour temperature was up to 10 °C (**Fig.**
265 **6a**). Weak cooling occurred below 800 hPa, a strong temperature inversion appeared between 775 and 650 hPa (**Fig.**
266 **6a**), and the stability of the lower troposphere increased. The urban agglomeration was dominated by the
267 low-pressure system for a long time and a long-lasting strong temperature inversion was therefore induced and
268 maintained above the boundary layer. This was different from the temperature inversion that is often seen within the
269 boundary layer in Eastern China (**Ji et al., 2012;Li and Chan, 2016;Li et al., 2012;Wang et al., 2014;Zhang and**
270 **Niu, 2016**). The temperature inversion acted as a lid over the boundary layer, suppressing the dispersion of air
271 pollutants. This lid effect restrained vertical mixing in the atmosphere and the local secondary circulation was
272 therefore confined in the boundary layer, with its center located at about 850 hPa (**Fig. 5a–c**). The horizontal wind
273 speed below 800 hPa was $\leq 2 \text{ m s}^{-1}$ (**Fig. 6b**). These results indicate that vertical mixing and horizontal dispersion
274 were weak, causing accumulation of air pollutants at the ground level. The concentrations of particulate matter then
275 sharply increased to their peak value (**Fig. 3**), generating a heavy air pollution event.

276 A low vortex and trough at 700 hPa transited across the urban agglomeration and a northwesterly dry, cold air

277 flow prevailed (**Fig. 4d**). Under the influence of the cold air flow, a cooling center appeared between 800 and 650
278 hPa (**Fig. 5d**), whereas the air temperature increased below 800 hPa (**Fig. 5d**). As a result, the stability in the lower
279 troposphere was weakened and the strong inversion layer gradually disappeared (**Fig. 6a**). The lid effect above the
280 boundary layer also disappeared, resulting in an increase in the local secondary circulation, the center of which was
281 uplifted to 700 hPa (**Fig. 5d**). The horizontal wind speed below 800 hPa also increased (**Fig. 6b**). The air pollutants
282 were able to disperse over a larger space and the vertical mixing and horizontal dispersion were significantly
283 improved. The air quality improved and the heavy air pollution event ended.

284 To verify whether the mechanism involved in the formation of event 8 is used for the others heavy air pollution
285 events, the vertical profiles of temperature and horizontal wind speed in events 1-7 (**Fig. 7**) were explored during the
286 periods of both the low-pressure system controlling and transited over this urban agglomeration. Similar to the event
287 8, a strong temperature inversion appeared over the study area between 800 and 650 hPa (**Fig. 7a**) when the urban
288 agglomeration was located in the front of low-pressure system and was controlled by a southerly warm air flow at
289 700 hPa. Meanwhile, the horizontal wind speed was low below 800 hPa; the wind speed at all levels below 850 hPa
290 was $\leq 2 \text{ m s}^{-1}$ (**Fig. 7c**). After the low-pressure system had transited across the urban agglomeration, the strong
291 inversion layer above the boundary layer gradually disappeared (**Fig. 7b**), and the horizontal wind speed in the lower
292 troposphere increased (**Fig. 7d**). Therefore, the influencing mechanism of low-pressure system on heavy air pollution
293 events is common in this urban agglomeration.

294 Additionally, composite anomalies of west-to-east vertical cross-section of 24-hour temperature change and
295 wind vectors (synthesized by u and w) (**Fig. S2**), and the anomalies of temperature vertical profiles (**Fig. S3**) were
296 also analyzed to further investigate the influencing mechanism of low-pressure system on heavy air pollution events.
297 **Fig. S2** shows that anomalous warming appeared above the atmospheric boundary layer, while anomalous cooling
298 was observed within the boundary layer when the urban agglomeration was located in front of low-pressure system
299 and was controlled by a southerly warm air flow at 700 hPa. This vertical structure of the anomalies of 24-hour

300 temperature change (**Fig. S2**) led to an increase in the stability of the lower troposphere. As illustrated in **Fig. S3**, the
301 positive anomalies of temperature between 1500 m and 3000 m above the ground level increased significantly with
302 height. The maximum value of positive anomalies appeared at about 3000 m and was up to 9 °C. These features
303 revealed that a strong temperature inversion existed above the boundary layer and suppressed the vertical exchange
304 of atmosphere. As a result, the anomalous secondary circulation was also confined in the boundary layer, with its
305 center located at about 925 hPa (**Fig. S2**). These results of anomalies analysis were consistent with the above
306 analysis for real-time data, and further proved that the influencing mechanism of low-pressure system on heavy air
307 pollution events is credible.

308 From **Fig.6** and **Fig.7**, we also found some interesting features characterized by the weak effects of the transit of
309 low-pressure systems at 700 hPa on the meteorological factors within the boundary layer. These features may be
310 related to its deep mountain-basin topography (**Fig. 1**). Under the effects of the deep mountain-basin topography,
311 wind speed in the boundary layer is often low and less altered (**Chen and Xie, 2012;Huang et al., 2017;Wang et al.,**
312 **2018**), and cold air induced by the transit of low-pressure systems is usually difficult to reach in the ground layer
313 faster (**Fig. 5**). As a result, the increase wind speed (**Fig. 6b, Fig. 7 c and 7d**) and the degree of change in
314 temperature (**Fig. 6a, Fig. 7a and 7b**) were very small in the boundary layer after the low-pressure system at 700 hPa
315 passed. Especially for events 3 and 4, the wind speed decreased and a temperature inversion formed in the boundary
316 layer. These characteristics of the wind and temperature profiles in the boundary layer were the key factors leading
317 to the evolution of boundary layer height as shown in **Table 3**.

318 **4.2 Impacts of Spring Festival excessive emission on heavy air pollution events**

319 **Table 1** shows that events 6 and 7 occurred during the Chinese Spring Festival when the concentration of
320 particulate matter increased sharply. Low concentrations of gaseous pollutants were found throughout these two
321 events, however, which may be related to a reduction in production or the shut-down of factories, as well as lower
322 numbers of vehicles during the week-long Spring Festival (**Liao et al., 2017**). The centralized letting-off of fireworks

323 during the Chinese Spring Festival played an important part in the sharp increase in the concentrations of particulate
324 matter (**Huang et al., 2012;Liao et al., 2017;Shi et al., 2011;Wang et al., 2007**). We investigated the impacts of
325 Spring Festival excessive emission on events 6 and 7.

326 It's noteworthy that the emission of air pollutants increased sharply during this period of deteriorating air
327 quality for events 6 and 7 due to the centralized letting-off of fireworks during the Chinese Spring Festival. What's
328 more, under the effects of low-pressure system, the strong temperature inversion appeared above the atmospheric
329 boundary layer (**Fig. 7a**) and the horizontal wind speed was low below 800 hPa (**Fig. 7c**). The combination of
330 excessive emissions with poor dispersion conditions resulted in the maximum daily concentrations of PM₁₀ occurring
331 on the Chinese New Year Day (**Table 1**). The maximum daily mean PM₁₀ concentration of eight heavy air pollution
332 events occurred in event 7 and was up to 562 μg m⁻³ (**Table 1**). This shows that the excessive emissions during the
333 short Chinese Spring Festival were able to increase the peak concentrations of particulate matter. Thus, the
334 centralized letting-off of fireworks in the Chinese Spring Festival combined with the impacts of low-pressure system
335 were the main causes of these two events in this region of China.

336 Unlike the normal heavy air pollution events, the concentrations of particulate matter began to decrease sharply
337 in event 6 and 7 before the low-pressure system transited over the urban agglomeration (**Fig. 8a** and **8b**), when the
338 strong temperature inversion was still present above the atmospheric boundary layer (**Fig. 10**), the local secondary
339 circulation was still confined in the atmospheric boundary layer (**Fig. 9a** and **9b**) and the capacity for dispersion has
340 not yet improved significantly (**Table 3**). To explore the causes of the sharp decrease in PM₁₀ concentration for these
341 two events, the effects of fireworks on air quality in Chengdu during Chinese New Year (CNY) from 2013 to 2017
342 have been investigated. As illustrated in **Fig. S4**, it is a common phenomenon that PM₁₀ concentrations decreased
343 sharply after the letting-off of fireworks stopped during CNY. During 5 days after the letting-off of fireworks stopped,
344 production was reduced, factories were shut-down and the numbers of vehicles were lower due to the week-long
345 holiday of CNY (**Liao et al., 2017**). As a result, the maximum decrease in the magnitude of PM₁₀ concentration was

346 more than $220 \mu\text{g m}^{-3}$ and occurred at night from 00:00 BST to 06:00 BST (**Fig. S5**) which corresponded to the
347 period of the centralized letting-off of fireworks on the Eve of CNY. Based on the above analysis results, we
348 concluded that the sharp decreases in PM_{10} concentration for events 6 and 7 were mainly attributable to the
349 significant reduction in emissions induced by the letting-off of fireworks stopped and the week-long holiday of CNY.

350 **5 Conclusions and discussions**

351 We investigated the relationships between low-pressure systems and winter heavy air pollution events in the
352 urban agglomeration of Chengdu, Deyang, and Mianyang in the northwest Sichuan Basin and explored the influence
353 of dry and cold low-pressure systems on winter air quality.

354 A total of ten heavy winter air pollution events occurred in the urban agglomeration from 1 January 2006 to 31
355 December 2012 and from 1 January 2014 to 28 February 2017. The meteorological causes of eight of these air
356 pollution events were attributed to dry low-pressure systems (trough and low vortex) at 700 hPa. The schematic
357 diagram in **Fig. 11** shows that a strong temperature inversion appeared above the atmospheric boundary layer
358 because the urban agglomeration was located in front of low-pressure system at 700 hPa and was controlled by a
359 warm southerly air flow. This strong inversion layer acted as a lid over the boundary layer and suppressed the
360 dispersion of air pollutants, confining the local secondary circulation within the atmospheric boundary layer. The
361 horizontal wind speed in the lower troposphere was low. As a result, the space available for the vertical and
362 horizontal dispersion of air pollutants was small. The concentrations of air pollutants increased to their peak values,
363 resulting in heavy air pollution events.

364 After the low-pressure system had transited across the urban agglomeration, the strong inversion layer above the
365 boundary layer gradually disappeared, resulting in an increase and uplift of the secondary circulation and an increase
366 in the horizontal wind speed in the lower troposphere. The space available for the vertical and horizontal dispersion
367 of air pollutants increased and the concentrations of air pollutants decreased sharply, ending the heavy air pollution
368 event. The centralized letting-off of fireworks during the Chinese Spring Festival was one of the main causes of the

369 heavy air pollution events in this region of China.

370 The urban agglomeration studied here, which is flanked by the eastern slopes of the Tibetan Plateau, is sensitive
371 to low-pressure systems moving east from the plateau (**Feng et al., 2016**). The complex terrain forms local
372 secondary circulations, which have a significant impact on air quality (**Chen et al., 2009; Liu et al., 2009; Miao et al.,**
373 **2015**). We found that the intensity and altitude of the local secondary circulations were markedly affected by the
374 low-pressure system and changes in circulation affected the local air quality. The mechanism of influence of the
375 low-pressure system on the local secondary circulation requires further elaboration using numerical simulation. The
376 centralized letting-off of fireworks during the Chinese Spring Festival significantly affected the air quality (**Huang**
377 **et al., 2012; Liao et al., 2017; Shi et al., 2011; Wang et al., 2007**), especially during some of the heavy air pollution
378 events in the urban agglomeration, although the impact of fireworks on air quality was remarkably different
379 depending on the dispersion conditions (**Li et al., 2006**). Sensitivity research should therefore be carried out using
380 models coupled with detailed meteorological and chemical processes to quantitatively examine the impacts of the
381 centralized emission of air pollutants from the Chinese Spring Festival on local air quality.

382 **Competing interests**

383 The authors declare that they have no conflict of interest.

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609 **Table 1.** Overview of the eight heavy air pollution events affected by dry low-pressure systems.
 610

Event	Most polluted city	Heavy air pollution event		Most polluted day		End date of heavy air pollution event		Other cities with heavy air pollution
		Start and end dates of air pollution event	PM ₁₀ concentration range in this period ($\mu\text{g m}^{-3}$)	Date	PM ₁₀ concentration ($\mu\text{g m}^{-3}$)	Date	PM ₁₀ concentration ($\mu\text{g m}^{-3}$)	
1	Mianyang	13–14 Jan 2006	284–442	13 Jan 2006	442	15 Jan 2006	166	Chengdu
2	Chengdu	29 Jan 2006	407	29 Jan 2006	407	30 Jan 2006	190	None
3	Chengdu	19–23 Dec 2006	348–385	23 Dec 2006	385	24 Dec 2006	246	None
4	Chengdu	21–24 Dec 2007	260–529	23 Dec 2007	529	25 Dec 2007	174	Mianyang
5	Chengdu	18–20 Jan 2009	264–381	19 Jan 2009	381	21 Jan 2009	220	Mianyang
6	Chengdu	3 Feb 2011	403	3 Feb 2011	403	4 Feb 2011	190	None
7	Chengdu	22–31 Jan 2014	282–562	31 Jan 2014	562	1 Feb 2014	207	Deyang
8	Chengdu	1–6 Jan 2017	294–480	5 Jan 2017	480	7 Jan 2017	118	Deyang

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613 **Table 2.** Relative vorticity at 700 hPa during the periods of deteriorating and improving air quality in each of the
 614 eight heavy air pollution events.
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Event	Deteriorating air quality		Improving air quality	
	Time (BST)	Relative vorticity ($1 \times 10^{-5} \text{ s}^{-1}$)	Time (BST)	Relative vorticity ($1 \times 10^{-5} \text{ s}^{-1}$)
1	02:00 on 13 Jan 2006	2.58	20:00 on 13 Jan 2006	-0.94
2	02:00 on 29 Jan 2006	4.15	08:00 on 30 Jan 2006	-3.36
3	20:00 on 22 Dec 2006	4.64	14:00 on 23 Dec 2006	-1.09
4	14:00 on 22 Dec 2007	0.59	14:00 on 23 Dec 2007	-0.82
5	02:00 on 19 Jan 2009	1.75	08:00 on 19 Jan 2009	-2.48
6	02:00 on 3 Feb 2011	2.96	14:00 on 3 Feb 2011	3.16
7	02:00 on 31 Jan 2014	9.12	02:00 on 1 Feb 2014	5.49
8	20:00 on 4 Jan 2017	6.49	08:00 on 5 Jan 2017	-5.74

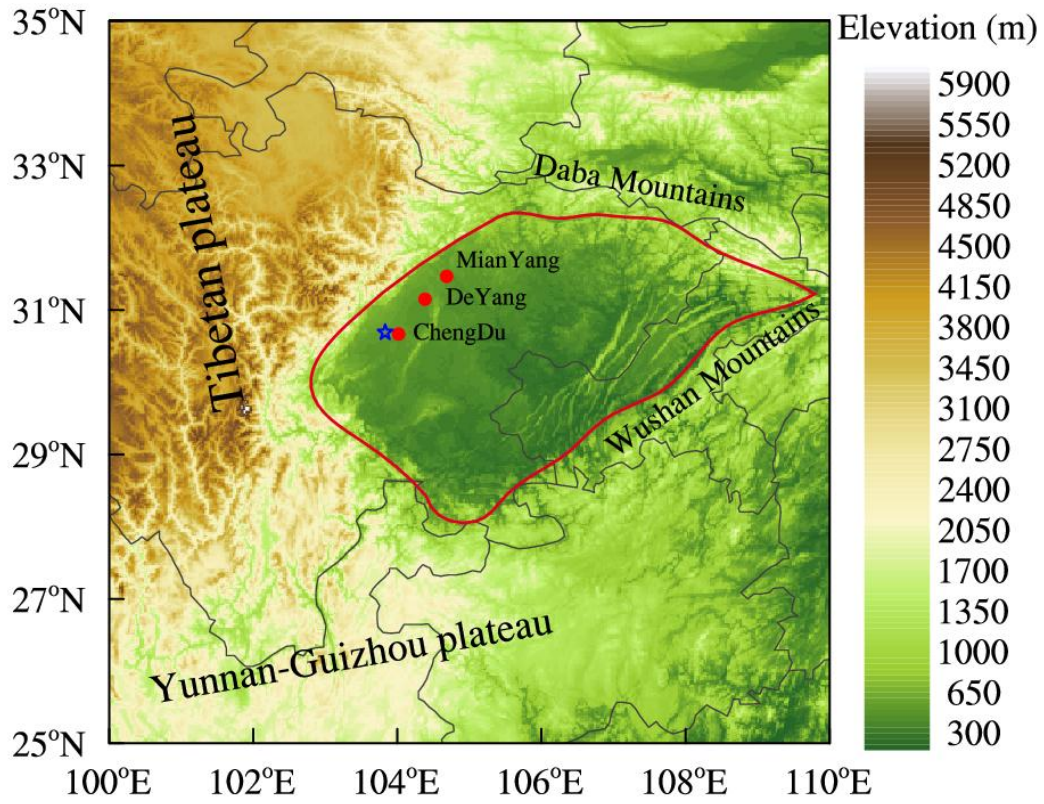
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618 **Table 3.** Height of the atmospheric boundary layer (BLH), lower tropospheric stability (LTS), and mean wind speed
619 (MWS) in the lower troposphere during periods of deteriorating air quality in each of the eight heavy air pollution
620 events, and the differences of them between periods of improving and deteriorating air quality in each event.
621

Event	Deteriorating air quality			Differences between periods of improving and deteriorating air quality		
	BLH (m)	LTS (K)	MWS (m s^{-1})	BLH (m)	LTS (K)	WMS (m s^{-1})
1	278.16	23.13	2.86	144.75	-11.23	0.41
2	375.42	29.45	4.12	139.08	-10.2	1.93
3	279.50	18.54	2.99	-16.45	-5.61	0.34
4	282.61	18.58	1.91	-39.62	-7.23	1.04
5	251.53	19.63	3.11	51.17	-7.88	0.85
6	282.16	25.80	4.22	-16.87	0.55	1.91
7	232.57	25.95	4.21	30.77	-1.97	-1.07
8	266.23	18.88	2.59	107.57	-8.4	0.27

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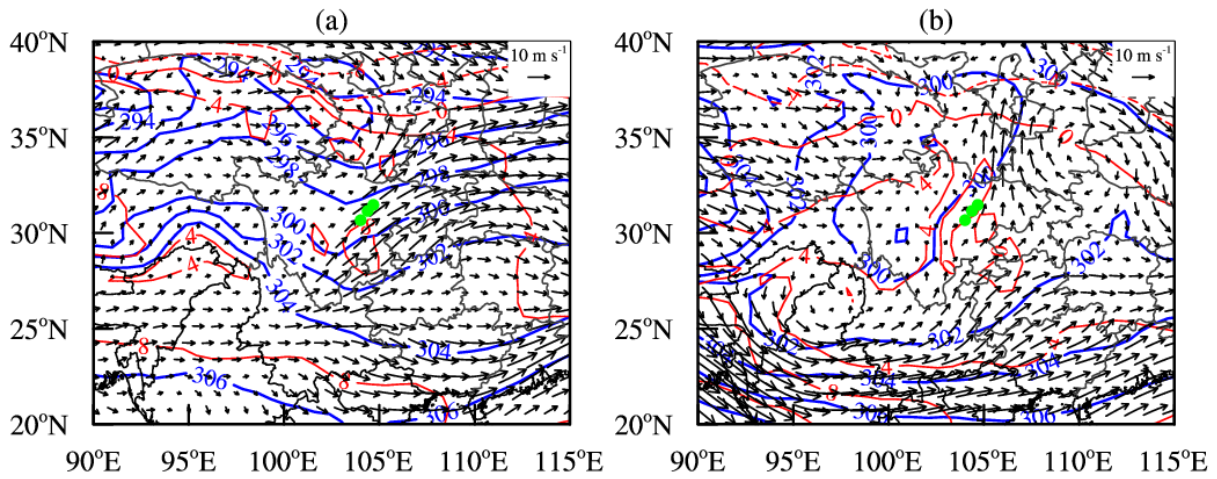
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Fig. 1 Topographic map (shading, units: m) of the Sichuan Basin (delineated in red) and surrounding areas showing the location of the cities of Chengdu, Deyang, and Mianyang (red dots). The Wenjiang station is marked with blue five-pointed stars. For interpretation of the colors, see web version of this article.

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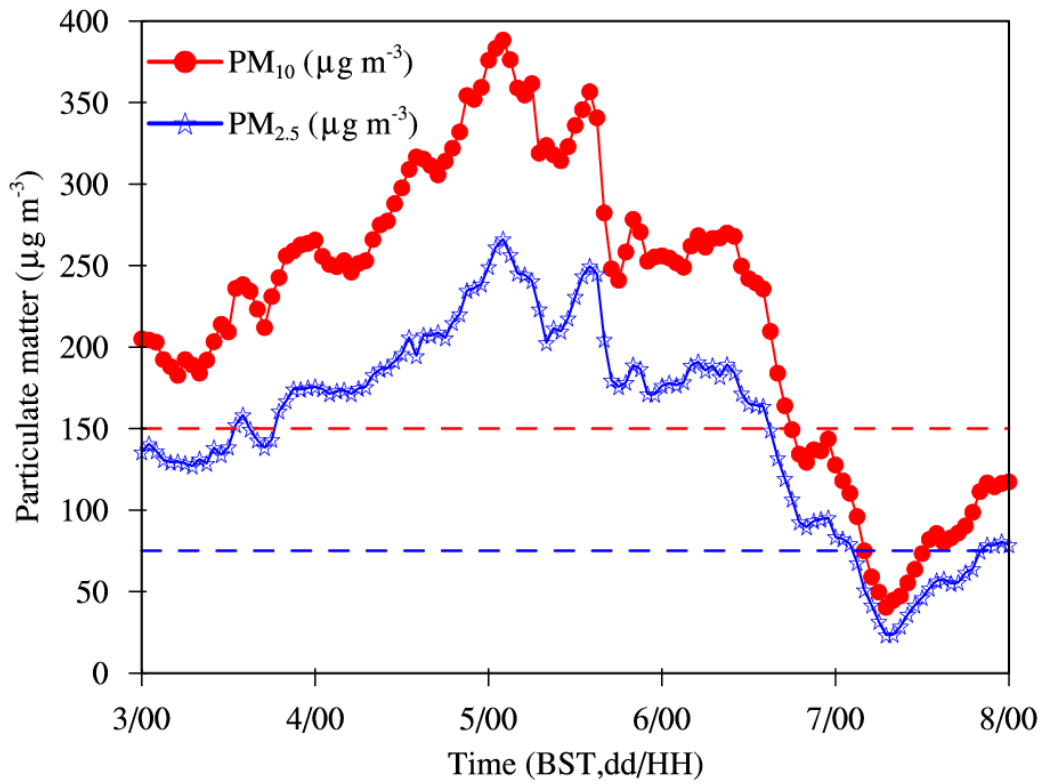
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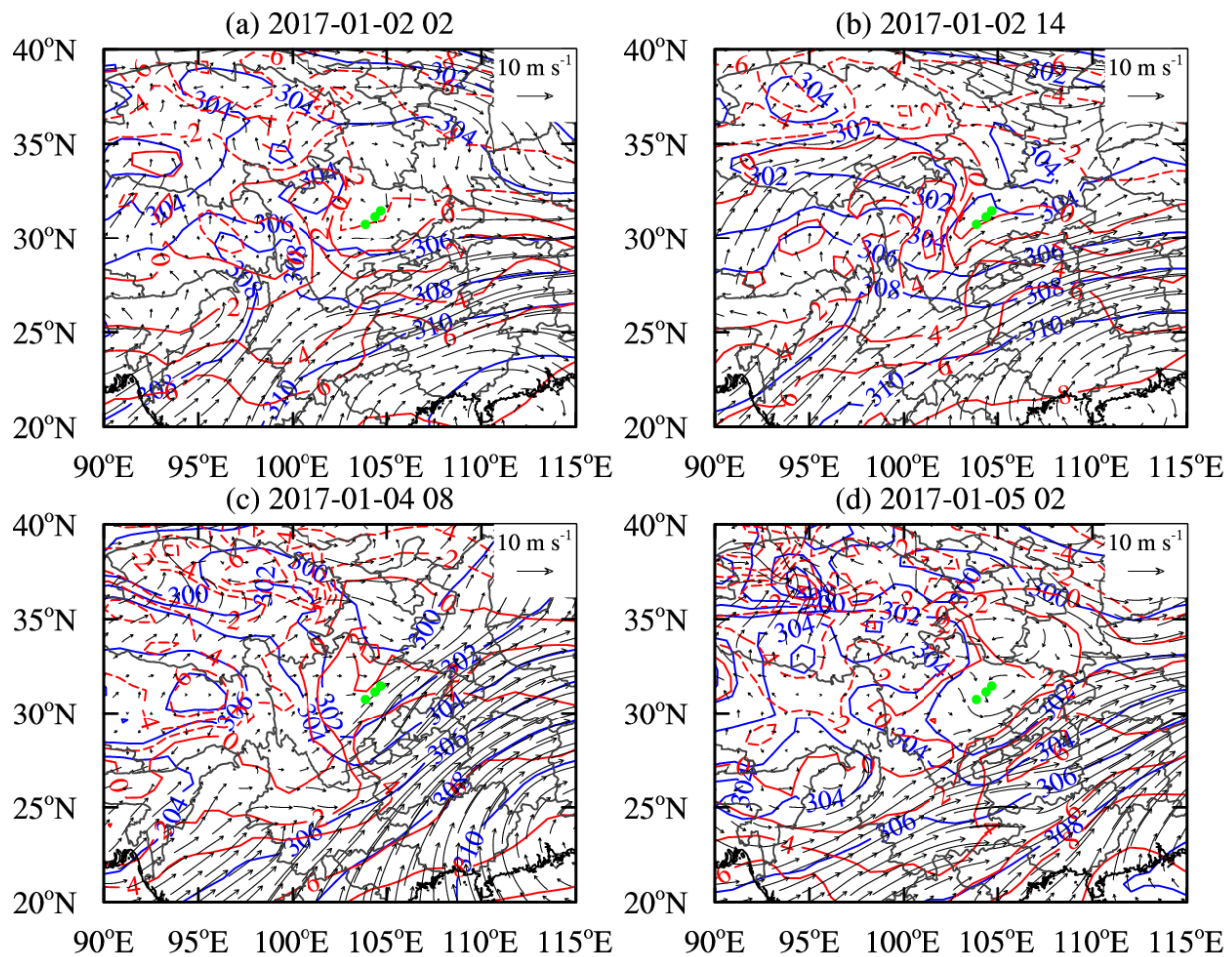
632 **Fig. 2** Weather maps at 700 hPa based on ERA-Interim daily data showing (a) a trough from event 2 at 20:00 BST
 633 on 28 January, 2006 and (b) a low vortex from event 4 at 14:00 BST on 22 December, 2007. The blue lines are
 634 isopleths of geopotential height, the red lines are isotherms and the black arrows are wind vectors. The green dots
 635 show the location of the urban agglomeration.

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639 **Fig. 3** Average hourly concentrations of surface PM₁₀ (red solid line) and PM_{2.5} (blue solid line) in the urban
 640 agglomeration from 00:00 BST on 3 January 2017 to 00:00 BST on 8 January 2017 during event 8. The dashed red
 641 line represents Grade II standard of PM₁₀ daily concentration ($150 \mu\text{g m}^{-3}$), the dashed blue line represents Grade II
 642 standard of PM_{2.5} daily concentration ($75 \mu\text{g m}^{-3}$).
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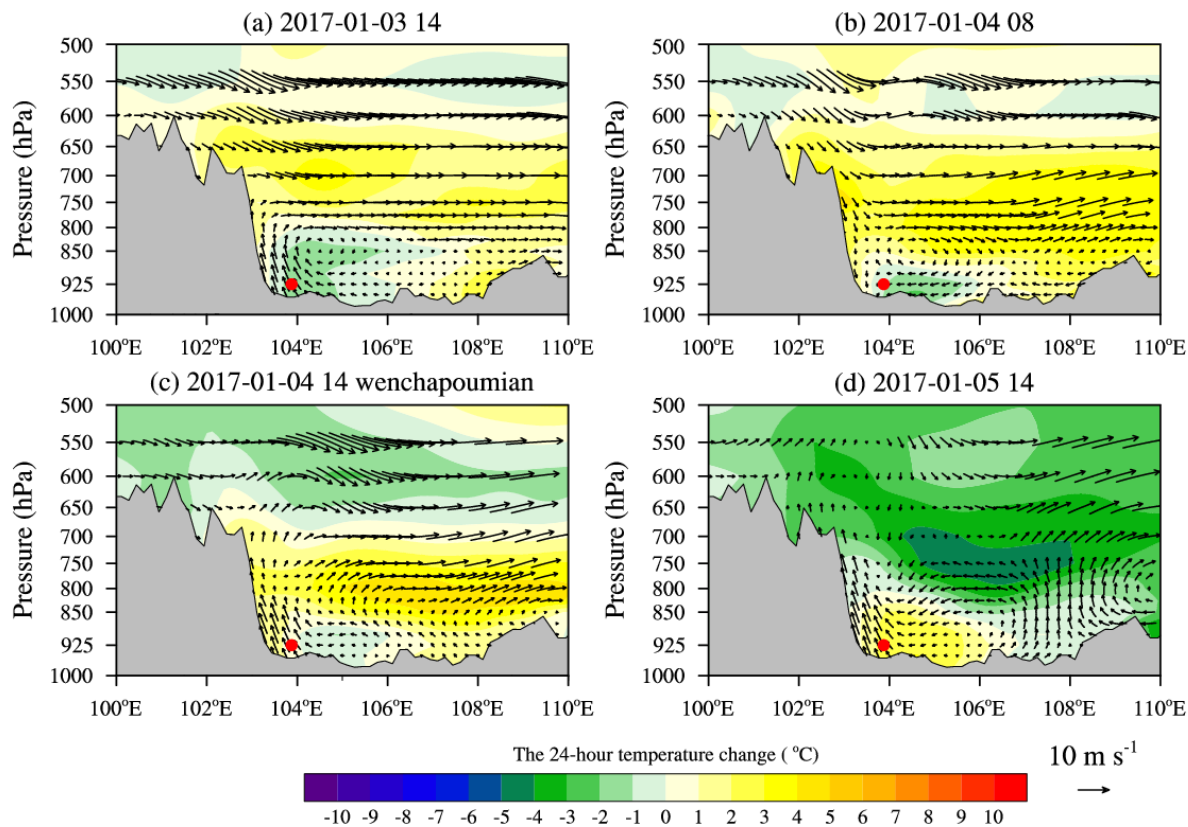
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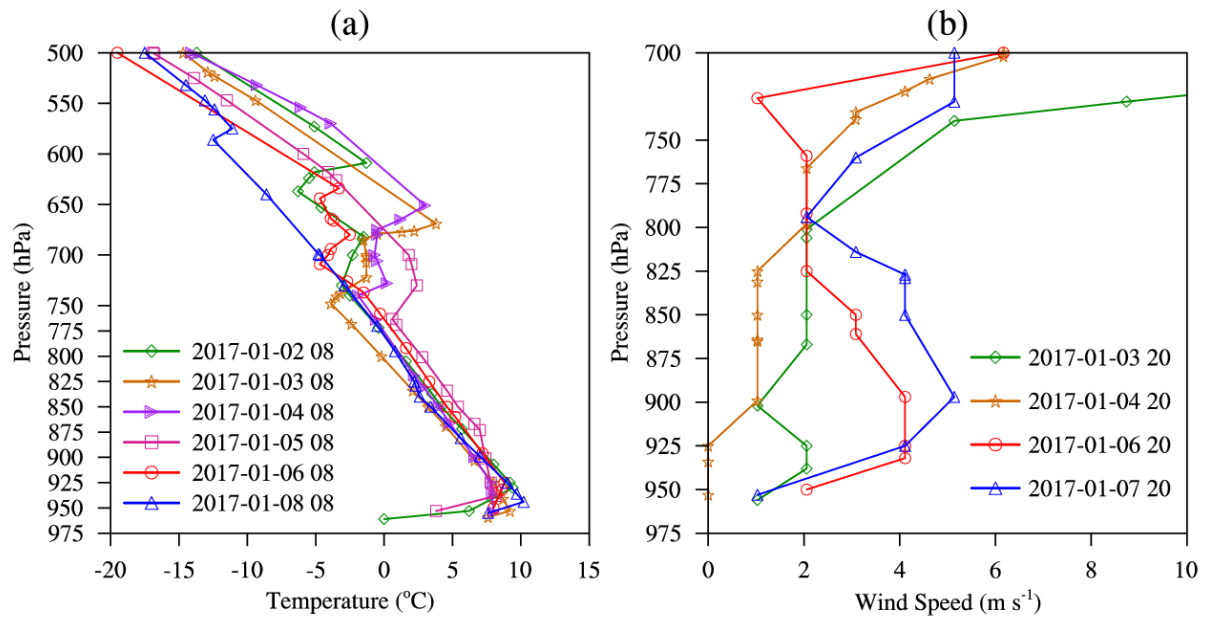
Fig. 4 Weather maps at 700 hPa for event 8 at (a) 02:00 BST on 2 January 2017, (b) 14:00 BST on 2 January 2017, (c) 08:00 BST on 4 January 2017 and (d) 02:00 BST on 5 January 2017. The blue lines are isopleths of geopotential height, the red lines are isotherms and the black arrows are wind vectors. The green dots show the location of the urban agglomeration.



652

653 **Fig. 5** West-to-east vertical cross-sections of 24-hour temperature change (shading, units: °C) and wind vectors
 654 (synthesized by u and w) through the most polluted area (30.75 °N) during event 8 at (a) 14:00 BST on 3 January
 655 2017, (b) 08:00 BST on 4 January 2017, (c) 14:00 BST on 4 January 2017 and (d) 14:00 BST on 5 January 2017
 656 during event 8. Note that the vertical velocity is multiplied by 100 when plotting the wind vectors. The most polluted
 657 area is marked by red solid dots. The gray shading represents the terrain.

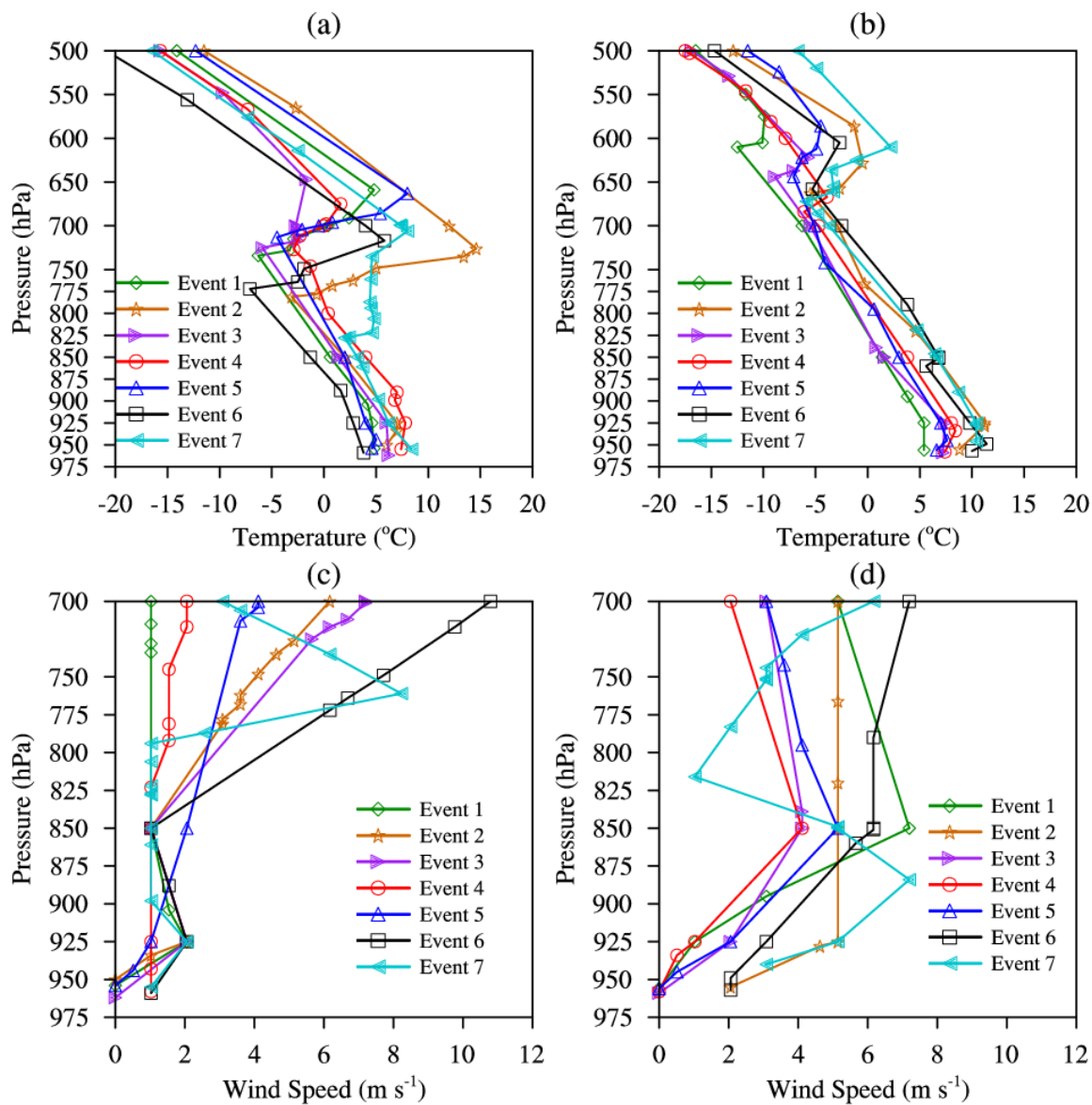
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661 **Fig. 6** Vertical profiles of (a) temperature and (b) horizontal wind speed at Wenjiang station (30.75 °N, 103.875 °E,
 662 see **Fig. 1**) measured by radiosonde during event 8.

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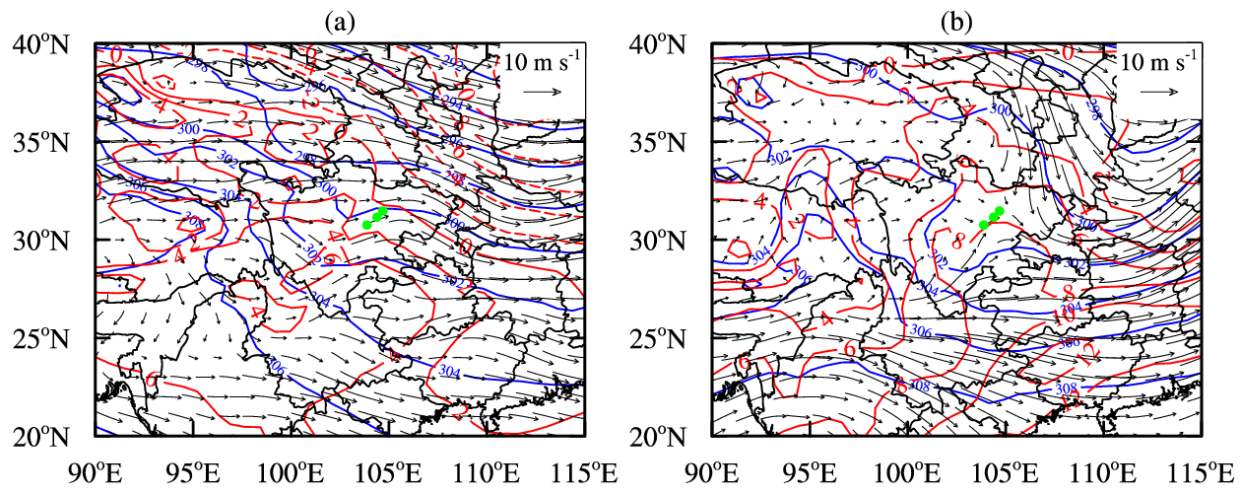
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Fig. 7 Vertical profiles of (a) temperature and (c) horizontal wind speed in the urban agglomeration during periods controlled by the low-pressure system. Vertical profiles of (b) temperature and (d) horizontal wind speed after the low-pressure system had transited across the urban agglomeration for seven heavy air pollution events (events 1–7).



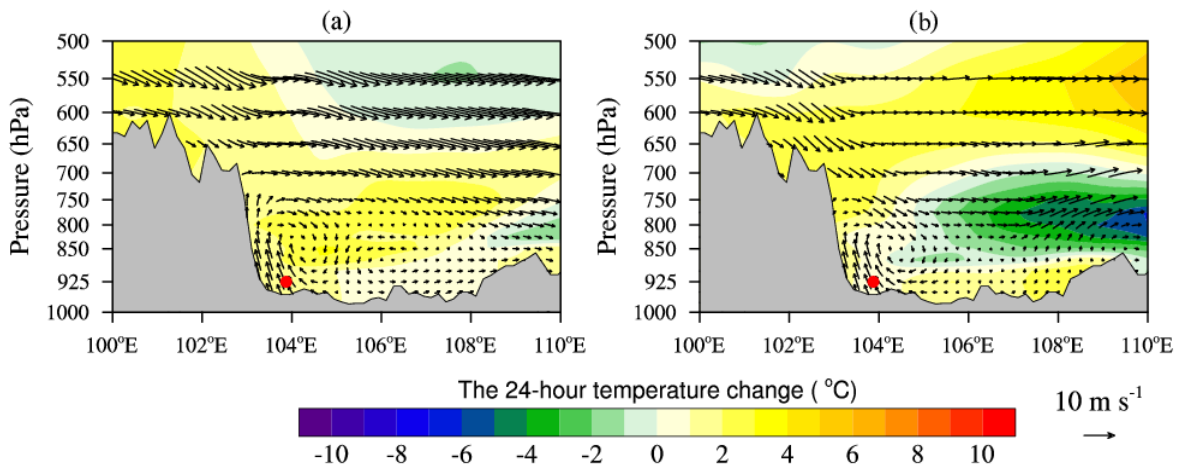
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Fig. 8 Weather maps at 700 hPa during periods of improving air quality (a) for event 6 and (b) for event 7. The blue lines are isopleths of geopotential height, the red lines are isotherms and the black arrows are wind vectors. The green dots show the location of the urban agglomeration.

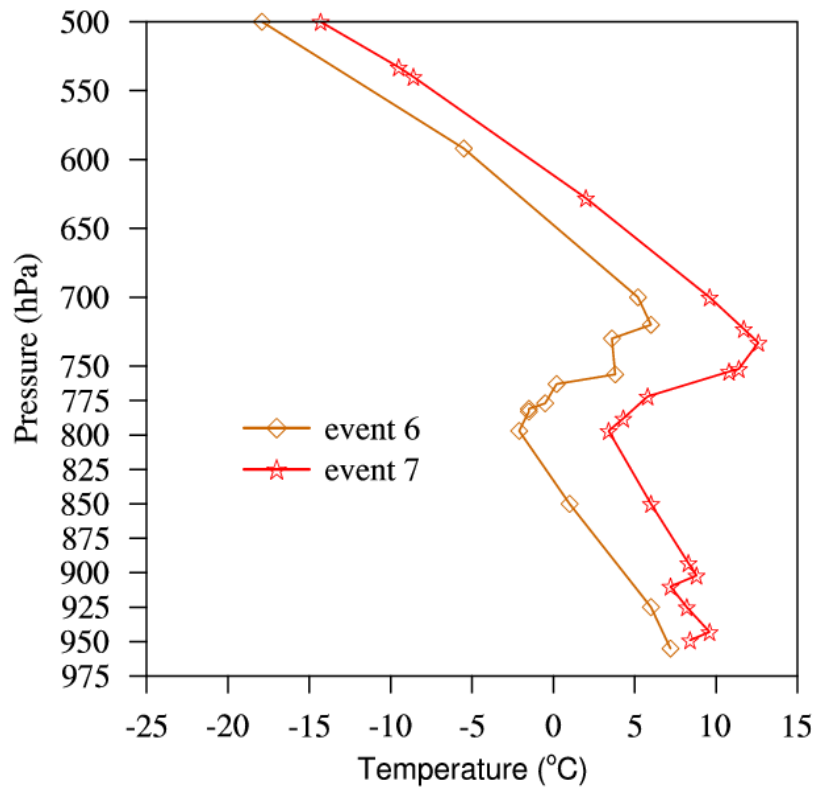


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676 **Fig. 9** West-to-east vertical cross-sections of 24-hour temperature change (shading, units: °C) and wind vectors
 677 (synthesized by u and w) through the most polluted area (30.75 °N) during the periods of improving air quality (a)
 678 for event 6 and (b) for event 7. Note that the vertical velocity is multiplied by 100 when plotting the wind vectors.
 679 The most polluted area is marked by red solid dots. The gray shading represents the terrain.

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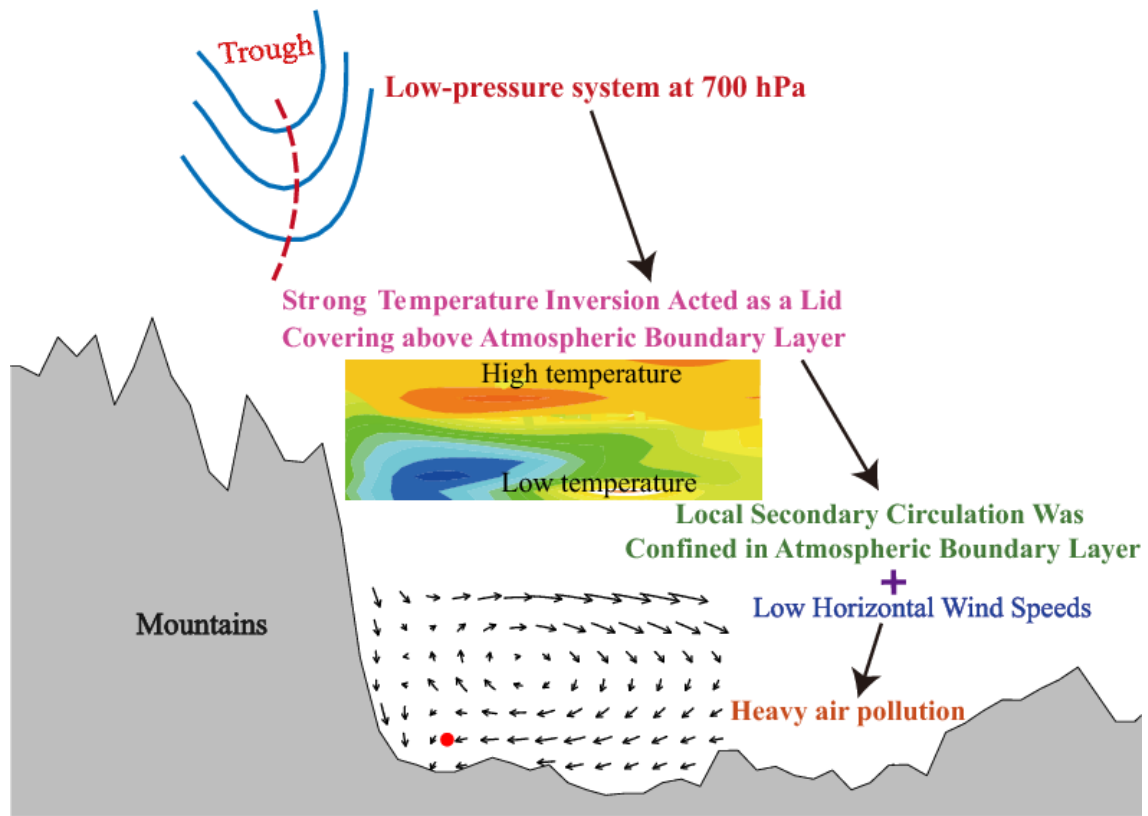


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683 **Fig. 10** Vertical profiles of temperature at Wenjiang station (30.75 °N, 103.875 °E) measured by radiosonde during
684 periods of improving air quality for event 6 and 7.

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689 **Fig. 11** Schematic diagram of the mechanism of influence of a dry low-pressure system on winter heavy air pollution
 690 events in the urban agglomeration.

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