

Seasonal effects of the Tibetan plateau on the cyclonic transient eddies: a system-centered view

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1 **Seasonal Effects of the Tibetan Plateau on Cyclonic Transient**

2 **Eddies: A System- centered View**

3
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24 ABSTRACT

25 Using an objective feature tracking algorithm and ECMWF fifth-generation
26 hourly reanalysis data (ERA5), the seasonal behaviors of cyclonic transient eddies
27 (cyclones) at different levels around the Tibetan Plateau (TP) were examined to
28 understand the effects of the TP on cyclones. Results show that the TP tends to change
29 the moving directions of the remote cyclones when they are close to the TP, with only
30 2 percent of the 250-hPa eastward-moving cyclones directly passing over the TP. The
31 sudden reductions of their moving speeds and relative vorticity intensities around the
32 TP suggest a suppression effect of the plateau. Over 70 percent of these cyclones
33 perish over the TP regardless of the altitude. This percentage decreases to around 65
34 percent during summertime, exhibiting a weaker summer suppression effect. On the
35 other hand, the TP has a stimulation effect on local cyclones through its dynamic
36 forcing in winter, thermodynamic forcing in summer, and both forcings in the
37 transitional seasons. The numbers of locally-generated cyclones, especially at 500
38 hPa, just above the TP, are significantly larger than those of the remote cyclones
39 during all seasons. Although about half of the local cyclones dissipate over the TP, the
40 cyclones moving off the plateau significantly outnumber the moving-in cyclones, with
41 the differences ranging from 0 to 6 cyclones per month. Only the 250-hPa wintertime
42 moving-off cyclones are fewer than the cyclones entering the TP, which may be
43 caused by the weaker stimulation effect and stronger suppression effect of the TP on
44 the wintertime upper-level cyclones.

45
46 SIGNIFICANCE STATEMENT

47 Cyclonic transient eddies (cyclones), steered by westerly jet streams, can
48 influence climate and induce extreme weather processes under certain conditions.
49 Tibetan Plateau (TP), the highest and largest obstacle embedded in the westerly jet
50 streams, suppresses the remote cyclones entering the TP region, destroying over 70
51 percent of these cyclones. However, due to the excitation effect of the TP on local
52 cyclones, the numbers of cyclones moving off the TP are still larger than or equal to

53 those of the moving-in cyclones, except at the upper levels in winter. This feature
54 suggests that the TP cannot significantly decrease the total cyclone numbers in most
55 cases, but it indeed weakens the mean intensity and moving speed of the cyclones.
56

57 **1. Introduction**

58 Transient eddies (TEs), an important part of the atmospheric circulation, are
59 cyclonic or anti-cyclonic disturbances that move with the background flow, including
60 extratropical cyclones, westerly troughs, shear lines, and other types of weather systems.
61 They can influence the global climate through the transport of energy and matter
62 (Peixoto and Oort 1992; Lorenz and Hartmann 2003; Ren et al. 2022) and are also an
63 important factor affecting local weather processes (Liu et al. 2018; Zhao et al. 2020).
64 The occurrence and development of TEs are affected by various factors such as the
65 westerly jet streams, diabatic heating, and topography (Chang et al. 2002; Kang and
66 Son 2021). In particular, topography as a long-standing fixed external forcing can
67 significantly affect TEs in a variety of ways, including topographic drag (Ólafsson and
68 Bougeault 1997), mechanical obstruction (Son et al. 2009), altered temperature field
69 (Davis 1997), and orographically forced stationary waves (Yu and Hartmann 1995; Park
70 et al. 2013). Topographic effects substantially depend on the mountain size, shape, and
71 height as well as the background flow (Qian and Jiao 1995; Yu and Hartmann 1995;
72 Son et al. 2009). Thus, the interaction between topography and TEs has always been a
73 key issue in global meteorological research.

74 As a zonally-extending terrain with the highest average elevation and largest area
75 in the world, the Tibetan Plateau (TP) is linked to the Hengduan Cordillera to the east,
76 the Iranian Plateau to the west, the Mongolian Plateau to the north, and the Indian Ocean
77 with abundant water vapor to the south. Thus, the topography around the plateau is
78 remarkably complex. Numerous studies have shown the vital roles played by the TP in
79 global climate through thermal forcing in summer and mechanical forcing in winter
80 (Molnar et al. 2010; Wu et al. 2007, 2012, 2015). In addition, the meridional location
81 of the TP is the key latitude for the seasonal evolution of the westerly jet stream. From
82 winter to summer, the jet stream moves from the south to the north of the TP, and it
83 moves oppositely from summer to winter (Schiemann et al. 2009), indicating the
84 varying background flow around the plateau. As the westerly jet stream is an important
85 waveguide and a region that tends to generate TEs, it is necessary to investigate the

86 seasonal effects of the TP on TEs.

87 Based on numerical experiments with and without the TP in a dry global general
88 circulation model (GCM), Chang (2009) noted that the existence of this large terrain
89 could significantly suppress the activity of TEs in winter. Park et al. (2010) and Lee et
90 al. (2013) obtained a similar result through changing the height of the TP respectively
91 in an atmospheric GCM and in a coupled atmosphere-ocean GCM, and further found
92 that the suppression effect became weaker in other seasons. They argued that the
93 weakened eddy seeding-feeding process (Zurita-Gotor and Chang 2005; Penny et al.
94 2010) induced by the suppression effect of the TP played a role in the midwinter
95 suppression of the North Pacific storm track, which is a striking phenomenon that TE
96 activities over the North Pacific are weaker in winter than in fall and spring even
97 though the low-level baroclinicity peaks in winter (Park et al. 2010; Lee et al. 2013).
98 Ren et al. (2021) used a nudging method to modify the suppression effect of the TP on
99 TEs in the NCAR Community Earth System Model and discovered that the suppression
100 effect could significantly influence East Asian rainfall in early summer through
101 weakening the westerly jet stream.

102 Nevertheless, several issues in these insightful studies need further explanations.
103 First, most of their conclusions were obtained based on numerical simulations, which
104 are sensitive to the models applied (Chang and Lin 2011). Secondly, their results were
105 mainly based on the Eulerian method of TE diagnosis, using the bandpass-filtered
106 variance field. This method can easily provide a general measure of TEs, and can be
107 used in atmospheric heat and momentum budget analyses. However, it cannot show the
108 features of the frequency, intensity, moving speed, generation, and dissipation situations
109 of each individual eddy, which can be obtained from system-centered methods (Hoskins
110 and Hodges 2002; Penny et al. 2010). Thirdly, these studies have mainly focused on the
111 TEs in the upper troposphere, neglecting the effects of the TP on the mid- and lower-
112 level TEs while the TP is a large topography soaring into the middle troposphere. Thus,
113 a study using observed data and system-centered methods to explore the effects of the
114 TP on the TEs at different altitudes is still needed, which is the motivation of this study.

115 Existing studies from a system-centered perspective often have been focused on

116 the particular types of observed TEs around the TP. For example, based on one-year
117 500-hPa geopotential height data over 50-60°N, Yeh (1952) noted that most wintertime
118 low-pressure troughs cannot move across the plateau from the west to the east, which
119 may be related to the semi-permanent high-pressure ridge induced by the deflection of
120 the westerly jet stream impinging upon the TP. In summer, the high-pressure ridge to
121 the north of the TP disappears with the northward movement of the jet stream, and more
122 low-pressure troughs can move across the plateau. Jiao and Qian (1994) utilized the
123 500-hPa daily historical synoptic maps around the TP for 5 winters to count the
124 activities of eastward-moving troughs, whose meridional length is larger than 10
125 degrees. They found that these troughs often slow down, weaken, and even disappear,
126 when they approach the western side of the TP, also suggesting the suppression effect
127 of the TP. Some studies have been focused on the behaviors of westerly disturbances
128 that account for over 50% of the total annual precipitation in western Himalaya and
129 Karakoram (Cannon et al. 2016; Hunt et al. 2018; Javed et al. 2022), and the Central
130 Asian vortexes that can have severe impacts such as rainstorms, snowstorms, and low
131 temperatures to the northwest of the TP (Zhang et al. 2012; Zhuang et al. 2017). Since
132 these studies employ a range of different methods and terminologies, a coherent
133 analysis for all kinds of TEs around the TP region is called for.

134 Moreover, the above studies have mainly concentrated on the eastward moving
135 eddies influenced by the TP; however, there are many TEs generated around the TP due
136 to the widely accepted lee cyclogenesis theory and the cyclonic shear induced by the
137 topographic drag, such as the TP shear lines and the southwest vortexes (Wang 1954;
138 Guan et al. 2018; Li and Zhang 2019). Other studies also argued that the diabatic heating
139 forced by high topography in summer was necessary for the generation of TP vortexes
140 (Zhang et al. 2021; Ma et al. 2022), which can induce heavy rainfall locally and
141 downstream (Wang 1987; Li et al. 2014; Curio et al. 2019). Previous studies also prove
142 that the north-south dipole precipitation trend over the TP is closely linked to the
143 activities of TP vortexes (Li et al. 2021; Li and Zhang 2023). These studies hint the
144 stimulation effect of the TP on local generation of TEs, which may be different from
145 the effects of the TP on the remote eddies propagating from outside. Thus, several

146 questions arise naturally. 1) How do the effects of the TP on the remote and local TEs
147 change with altitudes and seasons? 2) What are the differences between these effects?

148 To answer the above questions, an objective feature tracking algorithm is applied
149 to a high-resolution reanalysis dataset to analyze and quantify the seasonal behaviors
150 of the remote and locally-generated TEs around the TP at three commonly used pressure
151 levels (850, 500, and 250 hPa) focusing on their generation, dissipation, moving path,
152 and intensity variation. This analysis can reveal the detailed manifestations of the
153 effects of the TP on TEs. Examining the seasonal cycle is also helpful for understanding
154 how the effects of the TP on TEs are related to the winter-dominated dynamic and
155 summer-dominated thermal effects of the TP and the north-south movement of the jet
156 stream over the TP. According to Hoskins and Hodges (2002), cyclonic eddies are
157 stronger than anti-cyclonic eddies, and can almost reflect the characteristics of TEs
158 highlighted by the Eulerian method. Combined with the fact that many impactful TEs
159 around the TP are cyclonic eddies, this paper is focused on the cyclonic eddies, which
160 are referred to as cyclones below for the sake of convenience. The used data and feature
161 tracking method are introduced in section 2. Seasonal effects of the TP on the remote
162 and locally-generated cyclones are described and compared in section 3. Results are
163 summarized and discussed in section 4.

164

165 **2. Data and methodology**

166 The data used in this study comes from the fifth-generation European Centre for
167 Medium-range Weather Forecast (ECMWF) atmospheric reanalysis (ERA5), which
168 provides a much higher temporal and spatial resolution than the previous reanalysis
169 datasets. It is the latest global climate and weather reanalysis based on the Integrated
170 Forecasting System Cy41r2 that exhibits large improvements in model physics, core
171 dynamics, and data assimilation over earlier versions. Vast amounts of historical
172 observations have been combined into the ERA5 via 4D-Var data assimilation with a
173 12-h window and variational bias correction. Hourly atmospheric products with a
174 horizontal resolution of 31 km and 137 levels spanning from land surface to 0.01 hPa

175 are available from the ERA5, which can capture much finer details of atmospheric
176 phenomena (Hersbach et al. 2020).

177 To identify and track cyclones, the objective feature tracking algorithm developed
178 by Hodges (1994, 1995, 1999) is used, which can be flexibly adapted to track different
179 systems based on different fields and constraints, and has been used in previous studies
180 of midlatitude cyclones (Hoskins and Hodges 2002, 2005), tropical cyclones (Hodges
181 et al. 2017; Studholme et al. 2022), TP vortices (Curio et al. 2018, 2019). Any suitable
182 field can be used with the algorithm but usually the sea level pressure, 500-hPa
183 geopotential height, or relative vorticity is used. The relative vorticity is usually used
184 as it is less influenced by the large-scale background flow. Moreover, it can focus on
185 more smaller scales to allow systems to be identified much earlier in their life cycles
186 (Hoskins and Hodges 2002). As there may be many small-scale cyclones induced by
187 the TP, hourly ERA5 relative vorticity fields from 1979 to 2021 at 850, 500 and 250
188 hPa have been chosen to identify the cyclones around the TP. The 500 hPa level is just
189 above the surface of the TP, while the 850 and 250 hPa levels are typical representatives
190 of the lower and upper atmosphere.

191 Since the relative vorticity at high resolution is a very noisy field, it is first
192 spectrally filtered to T63 to remove small-scale noise. The large-scale background with
193 total wavenumbers $n \leq 5$ is also removed to focus on synoptic-scale cyclones. Then,
194 the objective feature tracking algorithm identifies cyclone centers as the off-grid
195 maxima above a threshold of $1.0 \times 10^{-5} \text{ s}^{-1}$ for all three levels using the B-spline
196 interpolation and a steepest ascent/descent optimization (Hodges 1995). Next, the
197 tracking is performed by first initializing as set of tracks by linking the identified
198 cyclone centers together in a time order using a nearest-neighbor approach. These tracks
199 are then refined through the minimization of a cost function for track smoothness based
200 on direction and speed, using adaptive constraints for displacement distance and track
201 smoothness (Hodges 1994, 1999). In general, the higher the temporal resolution, at a
202 fixed spatial resolution, the more reliable the cyclone tracking might be expected to be
203 (Curio et al. 2018). Although this paper is focused on the cyclones around the TP, the
204 cyclones throughout the whole northern hemisphere have been tracked to ensure the

205 integrity of the cyclones through their life history, especially those with long lifetimes
206 and long travel distances. Besides, the cyclones that persist for at least one day and
207 travel more than 500 km have been chosen to focus on the mobile cyclones.

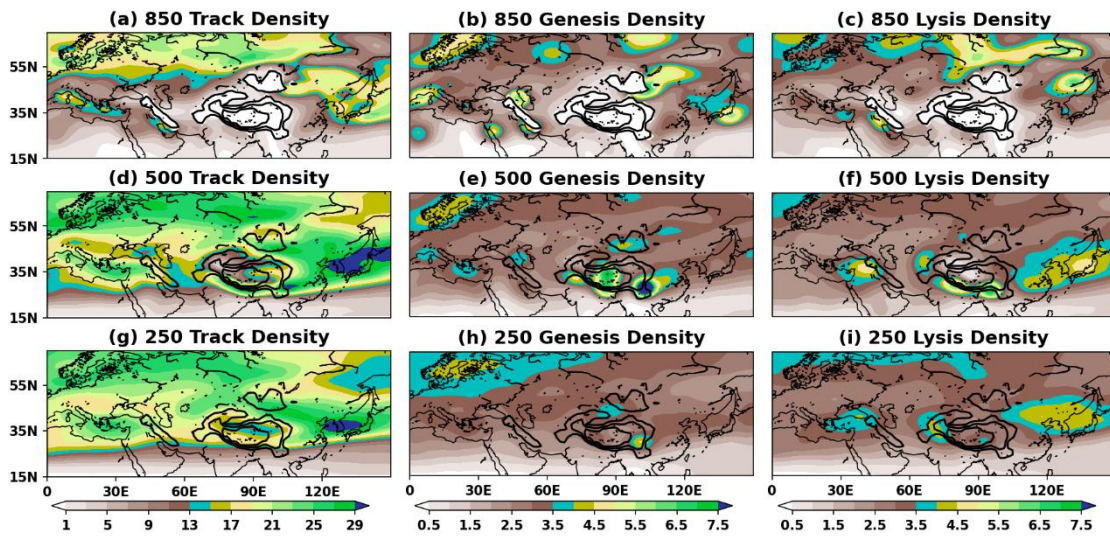
208 Then, cyclones interacting with the TP have been selected by choosing those
209 whose shortest distance from the TP is less than the cyclone size. Among these selected
210 cyclones, if the shortest distances between the cyclone genesis points and the TP are
211 less than their cyclone sizes, these cyclones are further defined as local cyclones
212 generated over the TP, while the others are the remote cyclones that are created at other
213 places but can pass over the TP. Similarly, a cyclone with the shortest distance between
214 its cyclolysis point and the TP less than the cyclone size is regarded as a cyclone dying
215 over the TP, while the others are the cyclones that can move out of the TP. Here the TP
216 is defined as the region bounded by 23~45°N/60~110°E, and where the altitude is
217 higher than 1500 m, excluding the Mongolian Plateau. The cyclone size varies with the
218 type, development stage, and geographic location of the cyclone (Hawcroft et al. 2012;
219 Zappa et al. 2015; Curio et al. 2019). There are various methods to define the cyclone
220 size, but none can accurately measure it (Rudeva and Gulev 2007; Dai and Nie 2022).
221 Considering that the cyclones analyzed in this study involve both the small-scale TP
222 vortices and the mesoscale extratropical cyclones, the cyclone size is roughly set at 6°
223 to define the remote cyclones that move into the TP, locally-generated cyclones over
224 the TP, and the cyclones that dissipate over the TP, Besides, the cyclone size of 3° has
225 also been used to select the above cyclones and similar results have been obtained (not
226 shown).

227 Similar to previous studies, the climatological spatial statistics are calculated from
228 the cyclone tracks to produce track, genesis, and lysis densities using the spherical
229 kernel approach (Hodges 1996). The genesis (lysis) density is calculated from the
230 starting (ending) point of a cyclone lifetime excluding any cyclones that start (end) at
231 the first (last) time step, while the track density refers to the number of cyclones per
232 unit area passing through a region. The units of these densities are the number per month
233 per unit area that is equivalent to a 5° radius spherical cap, an area of about 10⁶ km².
234 Note, that regions of high density just mean the preferred regions for cyclones to occur,

235 and individual cyclones can also appear in other regions. Mean attributes of cyclones
 236 over particular regions have also been calculated, including intensity, moving speed,
 237 growth rates, and lifetime. Since attributes calculated from a small sample are less
 238 reliable, results where the track densities are lower than one cyclone per month per unit
 239 area are not shown in the following figures.

240

241 3. Results



242

243 **FIG. 1.** Annual average (left) track, (center) genesis, and (right) lysis densities
 244 (shading; the number of cyclones per month per unit area) of all (upper) 850-hPa,
 245 (middle) 500-hPa, and (bottom) 250-hPa cyclones. Thick black contours indicate the
 246 elevation of 1500, 3000, and 4500 m.

247

248 Before focusing on the cyclones passing through the plateau, the annual average
 249 distribution of all cyclones in an extended region are shown in Fig. 1 to help us
 250 understand the roles played by the TP in the cyclones. It can be seen that the track
 251 densities at all altitudes are large over northern Europe, western Russia, East Asia, and
 252 the Mediterranean, consistent with previous studies (Hoskins and Hodges 2002). These
 253 track densities fall away rapidly to the south due to the weak baroclinicity at low
 254 latitudes. Close to the TP, the 850-hPa track densities suddenly decrease to a value less
 255 than 3 cyclones per month per unit area (Fig. 1a). Variations in the 500-hPa track
 256 densities are more dramatic when the tracks encounter the TP, decreasing from 15 to 3

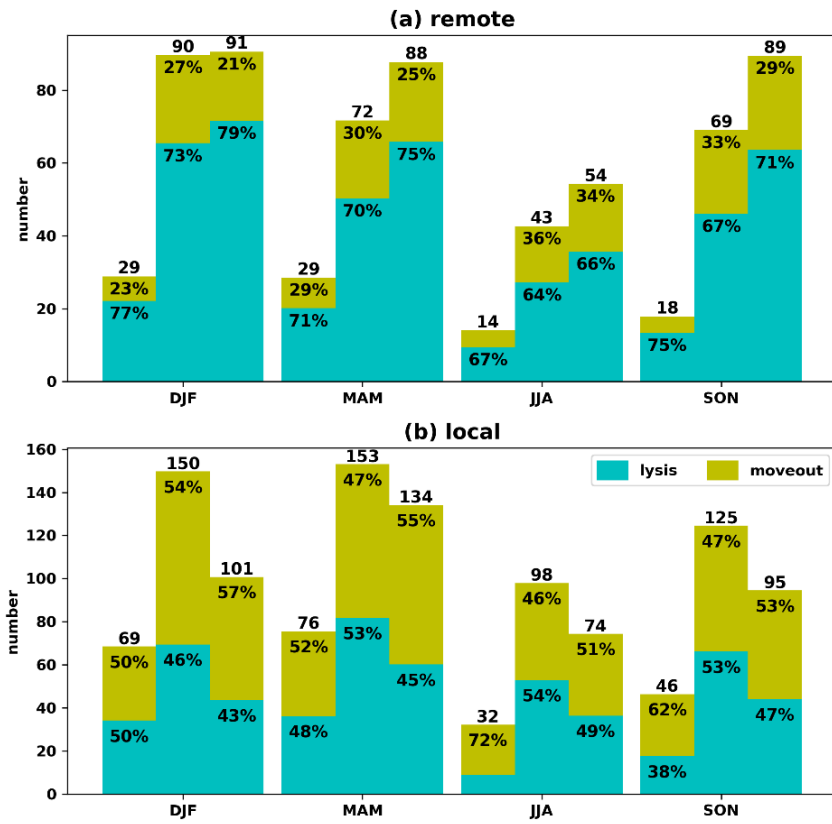
257 over a small distance. However, the lowest 500-hPa track density is mainly confined to
258 the western TP while it starts to increase over the eastern TP (Fig. 1d). The 250-hPa
259 track densities over the TP have the lowest value around 11 over a small area of the
260 northern TP, but are larger than those at 500 hPa (Fig. 1g), hinting that there may be
261 more cyclones passing through the TP at the upper levels.

262 Due to the complex topography near the surface, several high 850-hPa genesis
263 density regions can be seen around the Scandinavian Peninsula, the Alps, the Ural
264 Mountains, the Caspian Sea, the southwestern Iranian Plateau, the central Siberian
265 Plateau, the Mongolian Plateau, and southern Japanese Island, all of which decrease
266 with altitude (middle column in Fig. 1). However, there are two high 500-hPa genesis
267 densities over the southeastern and central TP, much stronger than the others, signifying
268 the stimulation effect of the TP on local cyclogenesis. High genesis density region over
269 the southeastern TP can extend to the upper level while that over the central TP
270 disappears at 250 hPa (Figs. 1e and h), implying that the local cyclones generated over
271 the central TP may be mostly shallow systems. Besides, it is apparent that the western
272 and southern borders of the TP are the main cyclolysis regions (except for East Asia
273 and the Iranian Plateau), where 500- and 250-hPa cyclolysis occurs frequently (Figs. 1f
274 and i), further suggesting the suppression effect of the TP on the remote cyclones
275 entering the TP region. The fact that the 850-hPa lysis densities around the TP are lower
276 than those over Russia may be related to the small track densities around the TP at this
277 level (Fig. 1c).

278 In general, Fig. 1 shows that the TP exerts a suppression effect on remote cyclones
279 and a stimulation effect on local cyclones. To evaluate and compare these two effects,
280 Fig. 2 shows the numbers of the remote and local cyclones per season as well as the
281 percentages of those cyclones dying over the TP. Clearly over 73% of the wintertime
282 remote cyclones die out over the TP regardless of the altitude, and the percentage
283 gradually drops to around 64% in summer, exhibiting a weak summertime suppression
284 effect (Fig. 2a). The numbers of local cyclones are always larger than those of remote
285 cyclones. While the numbers of remote cyclones increase with altitude for all seasons,
286 consistent with the track densities shown in Fig. 1, the numbers of local cyclones are

287 always largest at 500 hPa, consistent with Fig. 1e, suggesting a strong stimulation effect
 288 just above the surface of the TP. The numbers of local cyclones at all three levels are
 289 maximized in spring and minimized in summer, while the numbers of remote cyclones
 290 peak in winter, highlighting a particular seasonal variation of the stimulation effect (Fig.
 291 2). To further understand the detailed manifestations of these two effects and their
 292 seasonal variations, the seasonal behaviors of the remote and local cyclones are further
 293 examined below.

294

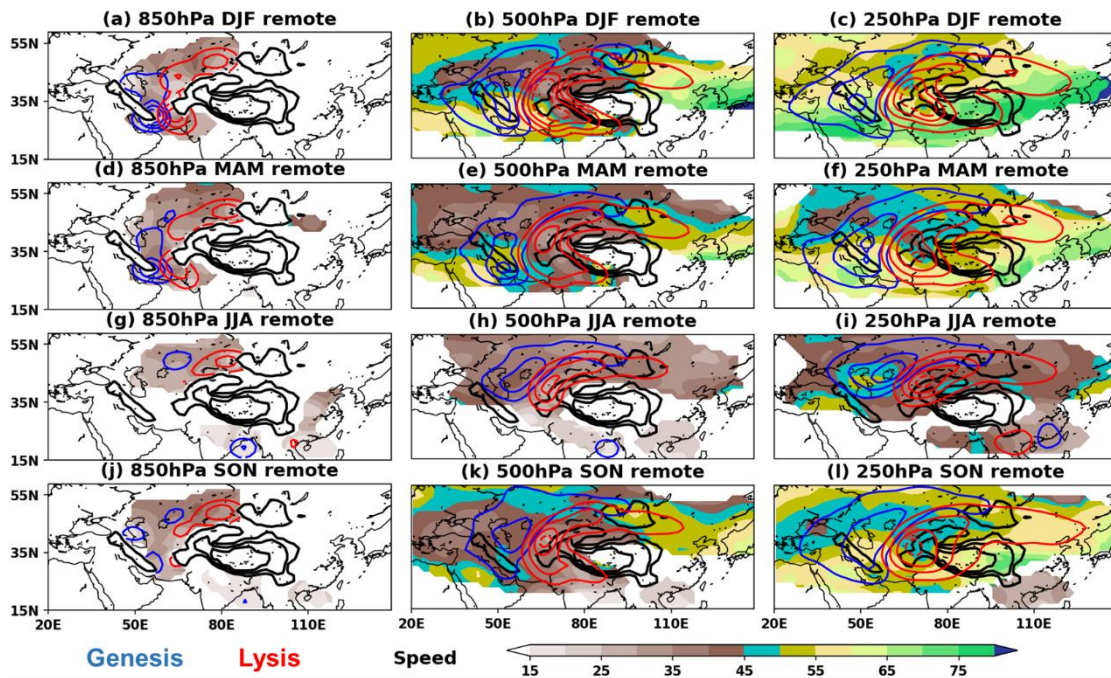


295

296 **FIG. 2.** Numbers of (a) remote cyclones moving eastward into the TP and (b) local
 297 cyclones generated around the TP per season, averaged over 41 years, with the three
 298 bars in each season representing the 850-, 500-, and 250-hPa cyclones, respectively.
 299 Cyan parts represent the cyclones that dissipate over the TP while yellow parts signify
 300 the cyclones that move out of the TP. Their percentages relative to the total numbers
 301 of cyclones at each level for each season, which are denoted on the top of each bar,
 302 are marked in each part if the percentages are large enough.

303

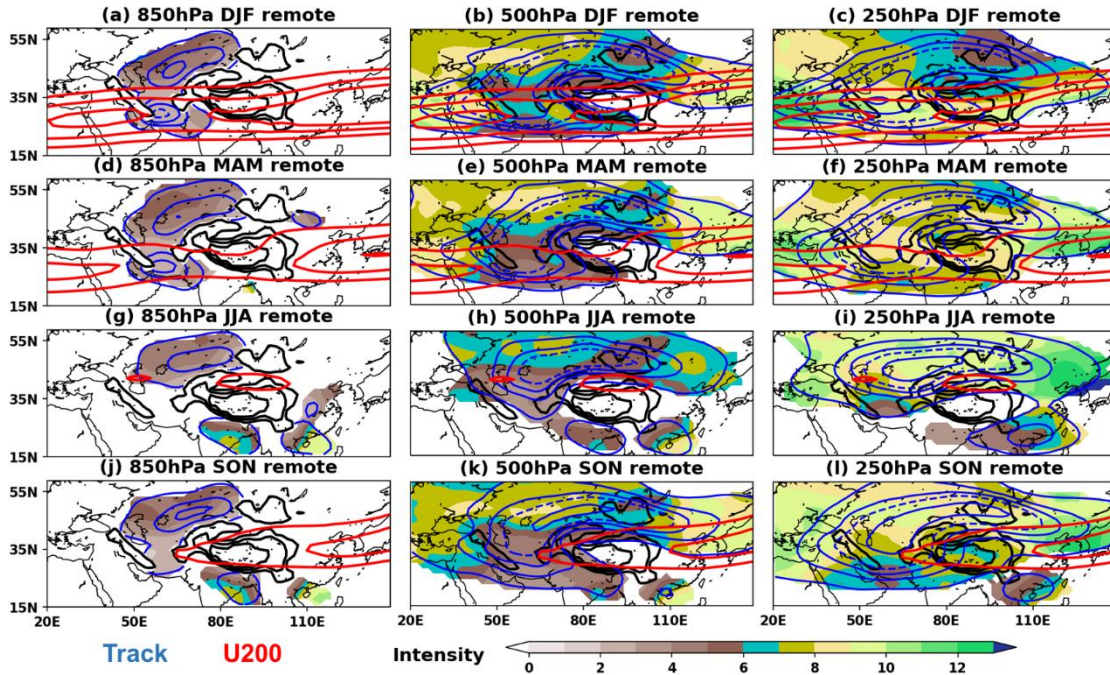
304 a. *TP effects on remote cyclones*



305

306 **FIG. 3.** Climatological genesis densities (blue contours), lysis densities (red contours)
307 and mean phase speeds (shading; $m s^{-1}$) of (left) 850-hPa, (center) 500-hPa, and
308 (right) 250-hPa remote cyclones for each season: (first row) winter, (second row)
309 spring, (third row) summer, and (fourth row) autumn. Contour values are 1, 2, 3, 4
310 (dashed), 7, 10, and 13 cyclones per month per unit area for both blue and red
311 contours. Mean phase speed is not shown for track densities below 1. Thick black
312 contours indicate the elevation of 1500, 3000, and 4500 m.

313



314

315 **FIG. 4.** Climatological track densities (blue contours) and mean intensities (shading;
 316 10^{-5} s^{-1}) of (left) 850-hPa, (center) 500-hPa, and (right) 250-hPa remote cyclones
 317 for each season: (first row) winter, (second row) spring, (third row) summer, and
 318 (fourth row) autumn. Track density contours are 1, 3.5, 6, 8.5 (dashed), 13.5, and 18.5
 319 cyclones per month per unit area. Mean intensity is not shown for track densities
 320 below 1. The 200-hPa westerly jet stream is indicated using the 30, 40, and 50 m/s red
 321 contours of 200-hPa zonal wind. Thick black contours indicate the elevation of 1500,
 322 3000, and 4500 m.

323

324 Previous studies have shown that the westerly jet stream, together with strong
 325 atmospheric baroclinicity, is closely related with cyclone intensities and can influence
 326 the trajectories and moving speeds of cyclones (Chang et al. 2002; Holton 2004). Thus,
 327 the seasonal characteristics of the remote cyclones and the 200-hPa westerly jet stream
 328 are displayed in Figs. 3 and 4. As shown in Fig. 3a, the preferred genesis region for
 329 wintertime 850-hPa remote cyclones is the leeside of the Iranian Plateau (see blue
 330 contours), with a maximum genesis density to the southeast of the Iranian Plateau,
 331 consistent with the lee cyclogenesis theory. These cyclones mainly die out to the west
 332 of the TP, along the 1500-m isohypse, with high lysis densities over the southwestern

333 and northwestern corners of the TP and the upstream region of the Mongolian Plateau
334 (Fig. 3a). This configuration suggests that the low-level cyclones tend to turn north or
335 south when they encounter the TP, exhibiting as two bands of high track densities
336 relatively located to the north and south of the TP (blue contours in Fig. 4a). This feature
337 reflects the diversion effect of the TP on remote cyclones. Due to the blockage of the
338 TP, the activities of low-level cyclones are mainly confined to the west of 90°E.

339 At the middle and higher levels, the spatial distributions of remote cyclones are
340 similar to those of the low-level cyclones, but covering a larger area. Specially, the
341 preferred genesis regions extend further westward to the Mediterranean and
342 northeastward to the Mongolian Plateau. The preferred lysis regions spread to 117°E
343 for the northern branch and 92°E for the southern branch, with the highest lysis densities
344 to the west of the TP. This feature of distribution appears like a letter “C”, but with a
345 longer upper branch (Figs. 3b and c). The northern and southern branches thus have
346 higher track densities and longer moving distances than those of the low-level cyclones.
347 Some northern cyclones can move into East Asia (Figs. 4b and c). It is worth noting
348 that there are also no values over the central TP at the 500hPa, suggesting that no
349 cyclone can move across the TP in this level while some 250-hPa cyclones can do this.
350 However, more cyclones die over the TP at 250 hPa (79%) than at 500 hPa (73%),
351 which is also observed in the other seasons (Fig. 2a). It suggests that the diversion effect
352 of the TP decreases with altitude, leading to more 250-hPa cyclones directly moving
353 into the TP and dying over the plateau. Only about 2 percent of the upper-level cyclones
354 that can move eastward to East Asia across the TP.

355 Consistent with the seasonal variation of the background flow (Fleming et al. 1987),
356 the distributions of remote cyclones in spring are similar to those in winter but with
357 slightly weaker maximum densities (first two rows in Figs. 3 and 4). In summer, due to
358 the northward shift of atmospheric baroclinicity, reflected in the westerly jet stream, the
359 preferred activity regions for the remote cyclones entering the TP shrink to the north,
360 and the southern branch disappears. Thus, the diversion effect of the TP becomes weak
361 in summer. The weakened gradients of the track densities to the west of the TP in
362 summer also suggest a weak suppression effect of the TP, which is also reflected in Fig.

363 2a. The decreased distances traveled by the remote cyclones may be related to their
364 weak intensities and small moving speeds, which result from the weak baroclinicity and
365 slow background flow in summer. Besides, some tropical cyclones are generated over
366 the Bay of Bengal and the South China Sea, and they move eastward to interact with
367 the TP under the control of the tropical easterly jet stream (third row in Figs. 3 and 4).
368 The behaviors of the remote cyclones in autumn are comparable to the conditions in
369 spring, but with fewer southern cyclones (fourth row in Figs. 3 and 4). Furthermore, it
370 can be seen that the spatial and temporal distributions of remote cyclones are consistent
371 in all three levels (Figs. 3 and 4), implying the high probability for deep cyclones to
372 occur in the remote cyclones.

373 In addition to the decrease in cyclone densities over the TP, the effects of the TP on
374 the remote cyclones are also reflected in their sudden decrease in moving speeds and
375 relative vorticity intensities around the TP, shown as the shadings in Figs. 3 and 4. The
376 decrease in moving speeds mainly occurs upstream of the TP and the Mongolian Plateau,
377 overlapping the increase in their lysis densities at all three levels and during all seasons,
378 further reflecting the blocking effect of the topography (Fig. 3). Since the moving
379 speeds depend on the background flow, northern cyclones accelerate when they move
380 into the westerly jet stream after bypassing the TP from the north (Figs. 3b, c, e, f, k,
381 and l). This feature also explains that the summertime upper-level remote cyclones
382 accelerate to the north of the TP (Fig. 3i) and that the southern branch, co-located with
383 the westerly jet stream, has a larger moving speed than the northern branch in the middle
384 and high levels during winter and spring (Figs. 3b, c, e, and f).

385 Decreases in the relative vorticity intensities appear to the west of the TP at the low
386 and middle levels, co-located with the westerly jet stream where the atmospheric
387 baroclinicity is strong (Fig. 4), signifying a strong suppression effect of the TP. This
388 phenomenon is noticeable during all seasons except summer when the southern branch
389 disappears and the traveled distances of remote cyclones are short due to the weak
390 westerly jet stream (third row in Fig. 4). Besides, another weakening feature appears
391 over the Mongolian Plateau at 500 hPa during all seasons (middle column in Fig. 4),
392 possibly by the Mongolian Plateau or TP induced northern high-pressure ridge, as

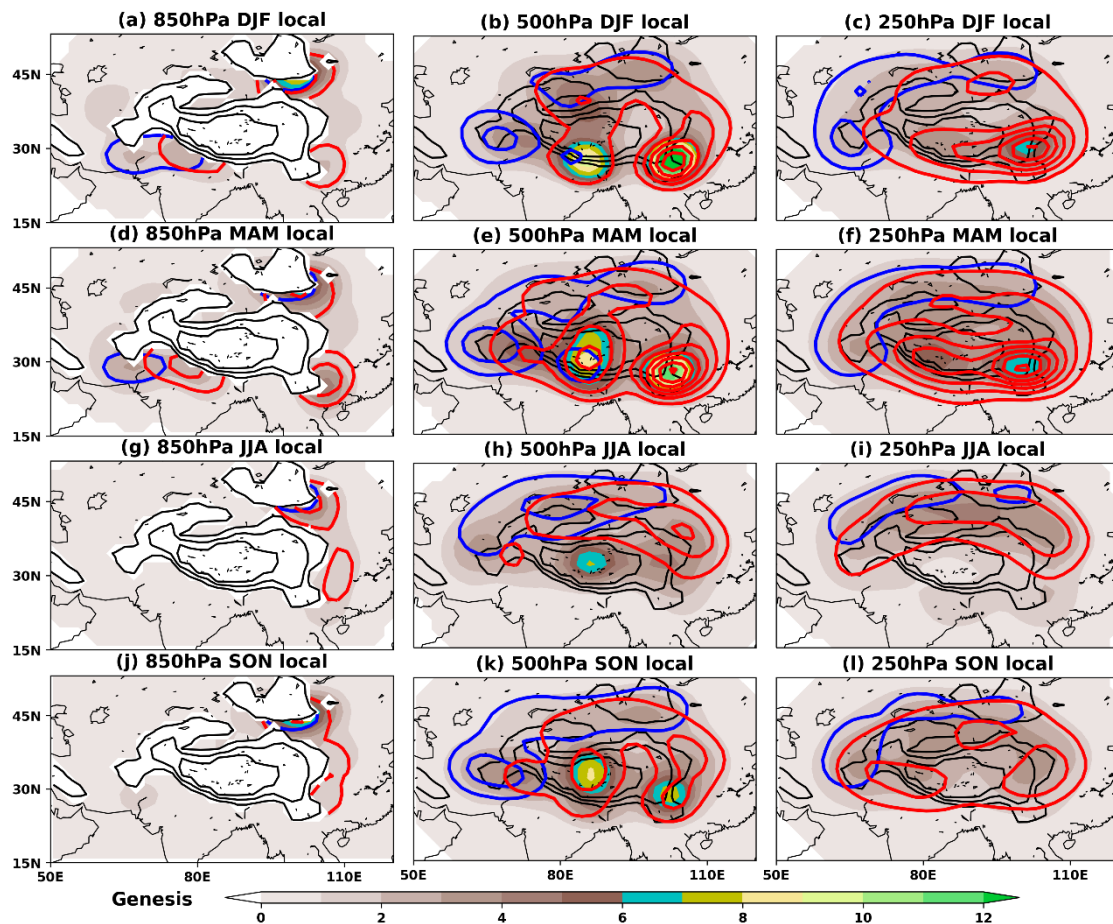
393 suggested by Yeh (1952). This weakening is also marked at 250h Pa during winter and
394 spring (Figs. 4c and f), when the TP induced northern high-pressure ridge is strong due
395 to the powerful westerly jet stream. Consistent with the variation of the moving speeds,
396 there is an increase in the cyclone intensities over northern East Asia. In addition, the
397 intensities of winter and spring southern cyclones undergo a re-intensification to the
398 southwest of the TP in all levels especially at 500 hPa (Figs. 4b and e). This feature may
399 be induced by latent heat feedback, since the southern cyclones in winter and spring
400 can carry ample water vapor from the Mediterranean, the Red Sea, Persian, and the
401 Arabian Seas, which is blocked by the TP to produce heavy precipitation to the
402 southwest of the TP (Cannon et al. 2016).

403

404 *b. TP effects on local cyclones*

405 The seasonal average genesis densities of the local cyclones generated over the TP
406 are shown in Fig. 5. There are two areas of high genesis densities over the southeastern
407 corner and the southernmost border of the TP during winter, which exists in all three
408 levels but with a maximum at 500 hPa (first row in Fig. 5), consistent with Fig. 2b.
409 According to previous studies, the former preferred genesis region may be related to
410 the enhancement of potential vorticity caused by the stretched air column downstream
411 of the plateau (Holton 2004; Wang and Tan 2014), while the latter may be produced by
412 the friction and topographic drag induced cyclonic shear under the background of
413 strong westerly winds (Wang 1954; Luo and Wei 1985). One may argue about the role
414 of atmospheric baroclinicity in the cyclogenesis, but the spatial distribution of genesis
415 densities around TP is inconsistent with the meridional gradient of potential
416 temperature (not shown), hinting that the above two high genesis densities are both
417 dynamically induced. These two mechanisms can also be applied to explain the above-
418 mentioned re-intensification of the southern remote cyclones in the small open area
419 behind the southwestern corner of the TP (Figs. 4b and e). Besides, another 850-hPa
420 cyclogenesis preferred area is located downstream of the Mongolian Plateau (Fig. 5a),
421 which can be viewed as the lee cyclogenesis of the Mongolian plateau.

422



423

424 **FIG. 5.** Climatological (left) 850-hPa, (center) 500-hPa, and (right) 250-hPa genesis

425 densities of locally-generated cyclones (shading) for each season: (first row) winter,

426 (second row) spring, (third row) summer, and (fourth row) autumn. Blue (red)

427 contours represent the genesis densities of secondary locally-generated cyclones that

428 may be induced by the pre-existing remote (local) cyclones at the closest altitudes,

429 which are (left) 500, (center) 250, and (right) 500 hPa. These specific vertical levels

430 are determined from Fig. 6. Contour values are 0.5, 1, 1.5, 2, and 2.5 cyclones per

431 month per unit area for both blue and red contours. Thick black contours indicate the

432 elevation of 1500, 3000, and 4500 m.

433

434 In spring, as the westerly jet stream weakens, the two high genesis densities seen

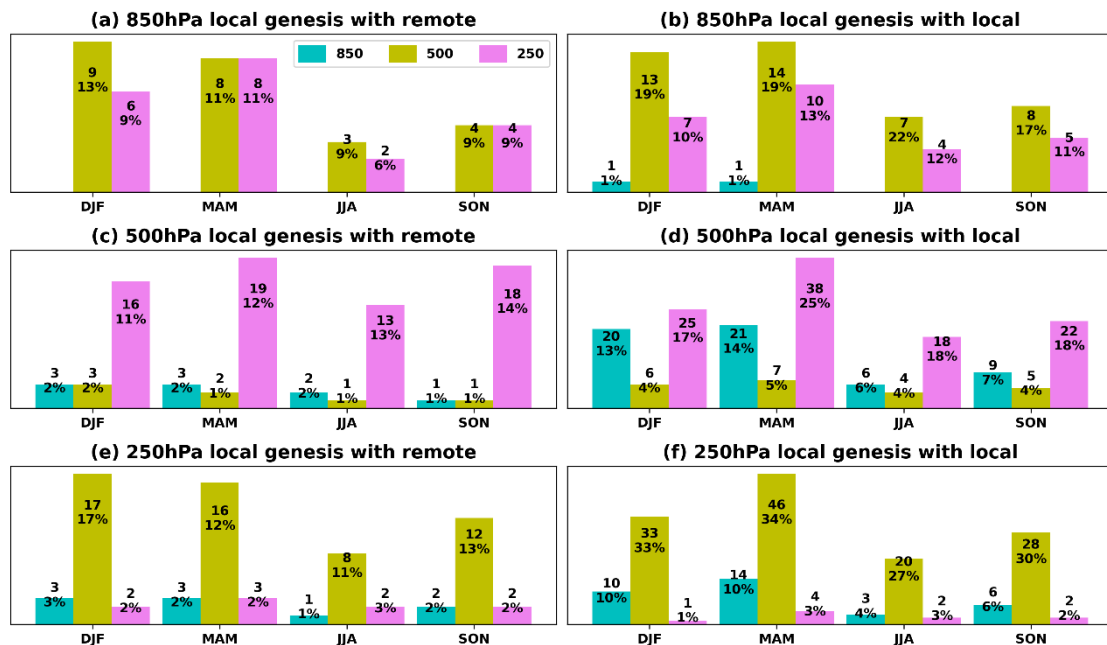
435 in DJF decrease somewhat at 500 hPa but slightly increase at 250 hPa (Figs. 5e and f).

436 The increase in 850-hPa southeast genesis densities may be caused by the gradual

437 increase in water vapor over this region during spring, which can supply latent heating

438 to enhance the low-level relative vorticity (Fig. 6d). Another high genesis densities

439 induced by the gradually increasing TP diabatic heating appear over the central TP (Fig.
 440 5e), but only exist at 500 hPa, signifying the high probability of these local cyclones
 441 with shallow structures, consistent with the result from other studies focusing on TP
 442 vortices (Li et al. 2014; Curio et al. 2019). All of these phenomena lead to the springtime
 443 maximized numbers of local cyclones at all three levels (Fig. 2b), indicating the
 444 strongest stimulation effect in spring. During summer, although the TP diabatic heating
 445 is maximized, the high genesis densities over the central TP are weaker than those in
 446 spring, which may be related to the weaker and more northerly located westerly jet stream
 447 (Fig. 5h) (Curio et al. 2019). The preferred genesis regions at 250 hPa move with the
 448 westerly jet stream to the north of the TP (Fig. 5i). High genesis densities at all three
 449 levels disappear over the southeastern TP (third row in Fig. 5), further suggesting that
 450 their appearance is associated with the interaction between the westerly jet stream and
 451 the southeastern TP. The cyclone formation in autumn is similar to that in spring but
 452 with a weaker magnitude (fourth row in Fig. 5), consistent with the seasonal variations
 453 of the westerly jet stream.
 454



455
 456 **FIG. 6.** Seasonal numbers of (upper) 850-hPa, (middle) 500-hPa, and (bottom) 250-
 457 hPa local cyclogenesis accompanied with the pre-existing (left) remote and (right)
 458 local cyclones at 850 hPa (cyan bars), 500 hPa (yellow bars), and 250 hPa (purple

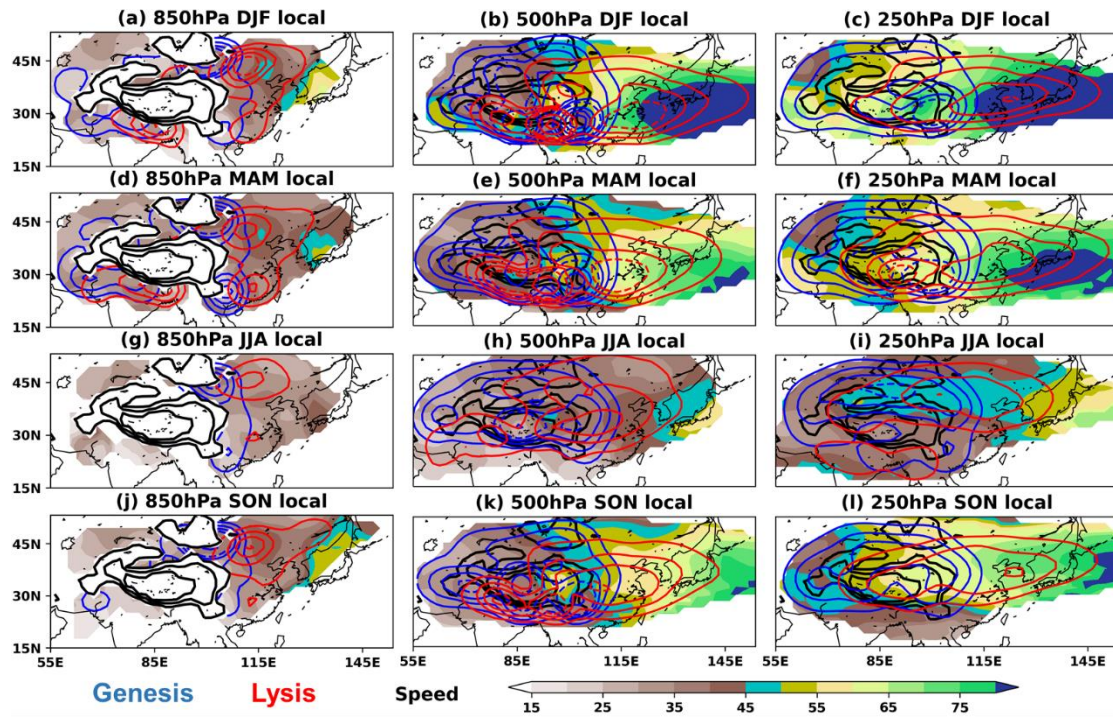
459 bars). The numbers and their percentages relative to the total locally-generated
460 cyclones at each level for each season are marked on each bar.

461

462 As is well-known, pre-existing cyclones can also trigger cyclogenesis at the same
463 or other altitudes. For example, TP vortices are favorable for the cyclogenesis over the
464 southwestern China through anomalous cyclonic circulations, convergence, ascending
465 motion, and moisture transport (Li et al. 2017, 2020b). A shallow cyclone can develop
466 into a deep cyclone under certain conditions and thus induce cyclogenesis at other
467 altitudes. Westerly trough moving from the upstream can split into small-scale westerly
468 troughs to the north and south of TP (Qian and Jiao 1995). To estimate the contributions
469 of pre-existing remote and local cyclones to the cyclogenesis over the TP, an
470 accompanied local cyclone is defined if other cyclones pass within 6 degrees of its
471 starting point at the moment of its formation. Contours shown in Fig. 5 refer to the 850,
472 500, and 250-hPa genesis densities of these cyclones that may be induced by the pre-
473 existing cyclones at 500, 250, and 500 hPa, respectively. For example, blue contours in
474 Fig. 5a suggest that some 850-hPa local cyclogenesis to the southwestern TP may be
475 induced by 500-hPa remote cyclones. Contributions of the pre-existing cyclones at
476 other levels are estimated in Fig. 6, which are lower than those shown in Fig. 5,
477 suggesting that local cyclogenesis is more likely to be induced by the pre-existing
478 cyclones at the closest altitudes.

479 Left column in Fig. 6 shows that no matter at which levels and which seasons, only
480 around 10% of local cyclogenesis may be contributed by remote cyclones, which are
481 located over the western and northern parts of the TP (blue contours in Fig. 5). The
482 contributions of pre-existing local cyclones to local cyclogenesis are around 20%, even
483 up to 30% at 250 hPa (right column in Fig. 6), higher than those of remote cyclones,
484 implying that some local cyclones may be indirectly caused by the TP. The preferred
485 regions of these secondary local cyclogenesis are over the southeastern and central TP
486 during all seasons except summer (red contours in Fig. 5). Local cyclogenesis
487 accompanied by pre-existing local cyclones occurs more frequently in spring than in
488 winter, which may be related to the slightly weaker westerly jet stream allowing

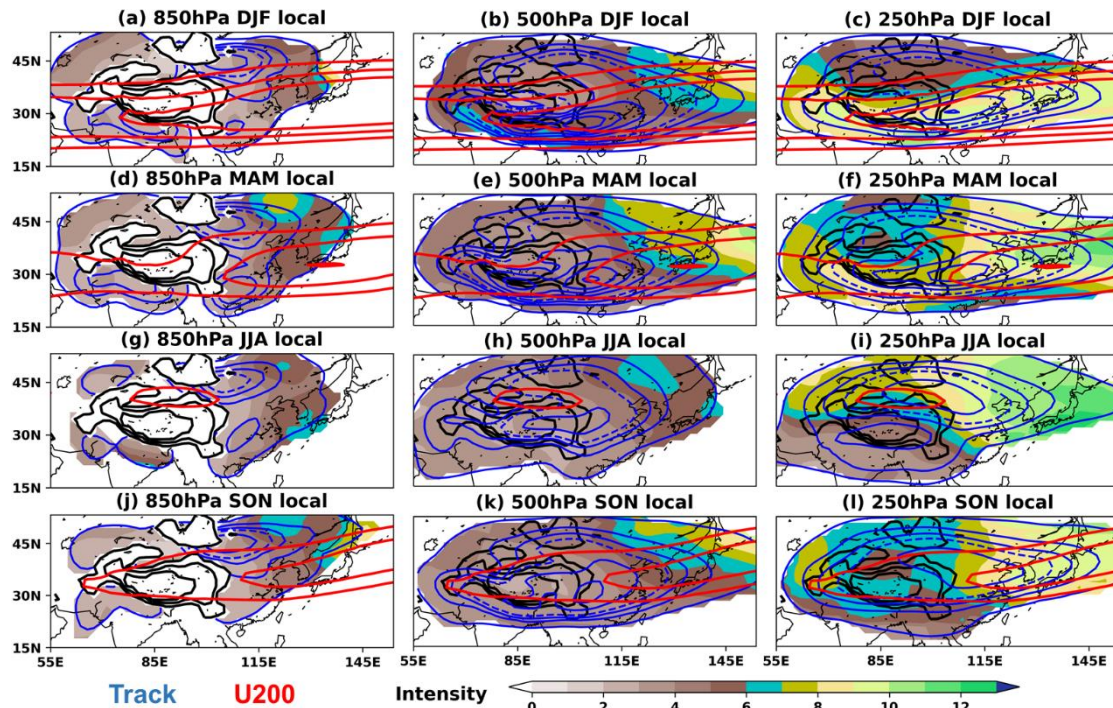
489 cyclones more time to develop into other altitudes. This may be used to justify the slight
 490 increase in the 250-hPa genesis densities over the southeastern TP in spring (Fig. 5f).
 491 If the accompanied local cyclone is defined by the distance of 3 degrees between the
 492 pre-existing cyclones and the cyclogenesis over the TP, the contributions of pre-existing
 493 cyclones to local cyclogenesis decrease, but their relative magnitude distribution and
 494 seasonal variations (not shown) are similar to those shown in Figs. 5 and 6.
 495



496

497 **FIG. 7.** As in Fig. 3, but for locally-generated cyclones around the TP.

498



499

500 **FIG. 8.** As in Fig. 4, but for locally-generated cyclones.

501

502 The basic characteristics of local cyclones have also been examined in Figs. 7 and
 503 8. High lysis densities to the south of the TP nearly overlap with the high genesis
 504 densities, showing the short lifetime and short moving distance of these cyclones
 505 generated by the frictional cyclonic shear (Figs. 7a-f). These cyclones can still
 506 contribute a large part to the 500-hPa high track densities to the south of the TP (Figs.
 507 8b and e). Cyclones forming over the leeside of the TP and the Mongolian plateau are
 508 more likely to move northeastward and southeastward, forming two bands of high track
 509 density to the north and south of East Asia. These two bands converge near the Yellow
 510 Sea at the middle and high levels during winter and spring, implying the long traveling
 511 distances of these cyclones (Figs. 8b, c, e, and f). Consistent with the seasonal variations
 512 of the genesis densities, the 500-hPa southern band of high track density moves to the
 513 central TP during summer, different from that at other levels, again signifying that these
 514 local cyclones possess predominantly shallow vertical structures, as is known for TP
 515 vortices. Due to the slow background flow in summer, the distances traveled by the
 516 local cyclones are significantly shorter than those in other seasons (third rows in Figs.
 517 7 and 8).

518 Similar to the behaviors of remote cyclones, the mean moving speeds of local
519 cyclones are also influenced by the background flow, which increase with altitude and
520 maximize in winter (shading in Fig. 7). The mean intensities of the southern branch,
521 co-located with the westerly jet stream, are stronger than those of the northern branch
522 at the middle and high levels during winter and spring. However, the northern branch
523 at all levels can undergo a significant intensification downstream during all seasons,
524 similar to the northern remote cyclones. During summer and autumn, the northern
525 branch is stronger than the southern branch due to the poleward shift of atmospheric
526 baroclinicity (shading in Fig. 8). Clearly, the intensities of the local cyclones over the
527 TP are weaker than those of the remote cyclones over the TP or upstream (Figs. 4 and
528 8).

529

530 **4. Summary and discussion**

531 While previous studies were mainly focused on the effects of the TP on the westerly
532 trough or TP vortices, in this study the effects of the plateau on all kinds of remote and
533 local cyclones during all four seasons are comprehensively presented and compared
534 using an objective feature tracking algorithm. Similar to the diversion effect of the TP
535 on the wintertime circulation (Wu et al. 2007), the TP also tends to change the moving
536 directions of remote cyclones when they approach the TP, leading to the northern and
537 southern bands of high track densities. Only some northern cyclones move into East
538 Asia. This diversion effect decreases with altitude, and thus some 250-hPa cyclones can
539 directly pass over the TP from the west to the east. The TP also exhibits a suppression
540 effect on remote cyclones, reflected in the decrease in track densities over the plateau
541 and the suddenly-weakened moving speeds and intensities of remote cyclones upstream
542 of the TP. Over 70% of these remote cyclones dissipate over the TP regardless of the
543 altitude, which slightly decreases to around 65% during summer, implying a weak
544 summertime suppression effect. This weak suppression effect is also manifested by the
545 small decreases in the moving speeds and intensities of summertime remote cyclones
546 when they encounter the TP. The diversion effect also becomes weakened in summer

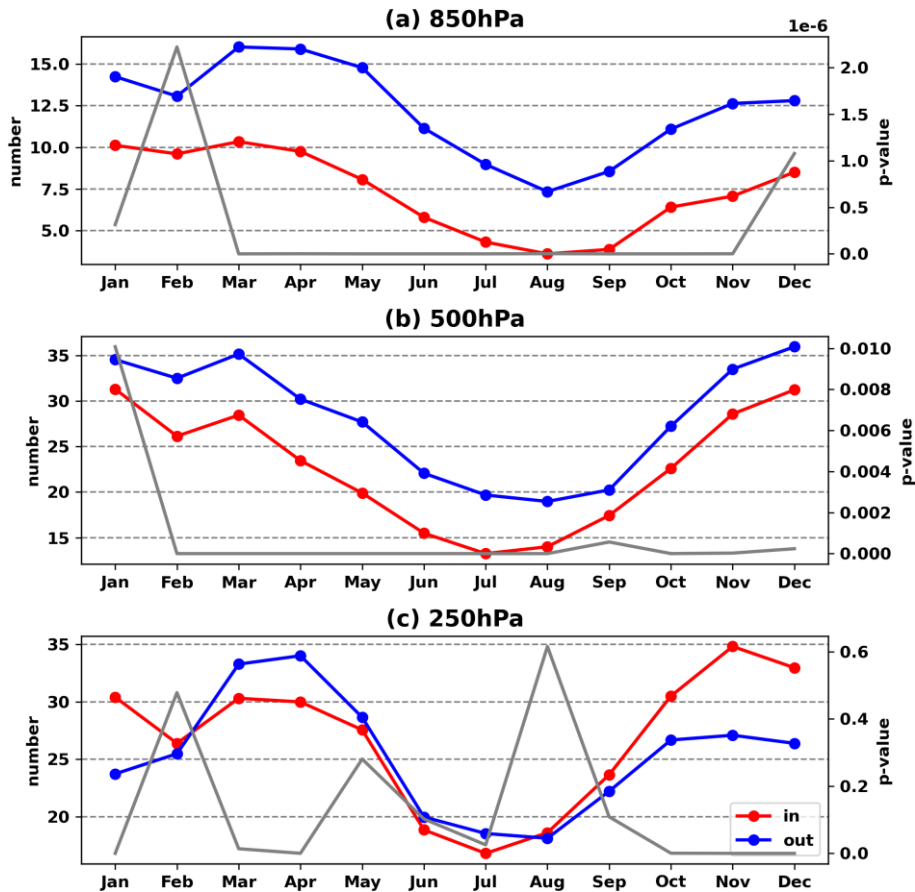
547 since the main trajectories of remote cyclones move with the westerly jet stream to the
548 north of the TP.

549 On the other hand, the TP also plays a strong stimulation effect on local
550 cyclogenesis mainly through its dynamic forcing in winter, thermodynamic forcing in
551 summer, and both forcings in the transitional seasons. Dynamic forcing, associated with
552 the westerly jet stream, tends to induce cyclones over the southeastern corner and the
553 southernmost border of the TP, while thermodynamic forcing favors the formation of
554 cyclones over the central TP. Due to the relatively strong westerly jet stream and the
555 gradually-enhanced TP thermodynamic forcing in spring, the stimulation effect of the
556 TP in spring is stronger than that in winter. This effect is minimized in summer when
557 the dynamic forcing of the TP weakens. The genesis densities of local cyclones are
558 maximized just above the TP during all seasons. Their track densities also vary with
559 altitude, reflecting the fact that most of these local cyclones are shallow, consistent with
560 the vertical configuration of TP vortices. Moreover, around 10% of local cyclogenesis
561 may be induced by the remote cyclones at the closest altitudes, and about 20% by the
562 vertically closest pre-existing local cyclones, both of which may not be directly induced
563 by the TP.

564 There are many more local cyclones than remote cyclones during all seasons (Fig.
565 2). Although about half of these local cyclones dissipate over the TP, the total number
566 of cyclones that move off the TP, including both remote and local cyclones, are
567 significantly more than the cyclones that enter the plateau, especially at the low and
568 middle levels (Fig. 9). The differences range from 0 to 6 cyclones per month. According
569 to the downstream development theory (Zurita-Gotor and Chang 2005), these moving-
570 off cyclones can develop into strong cyclones that play an important role in the
571 downstream weather and climate. This situation is reversed only at upper level in winter,
572 with the differences of about 7 cyclones per month (Fig. 9c), which may be caused by
573 the slightly weaker stimulation effect on the 250-hPa local cyclogenesis and the
574 stronger suppression effect on the remote cyclones in winter. This phenomenon is
575 similar to the result shown in the Fig. 6 of Penny et al. (2010), hinting a possible role
576 of the TP in the midwinter suppression of the North Pacific storm track that mainly

577 occurs at the upper level (Hoskins and Hodges 2019). In a word, the TP does not
 578 significantly decrease the total cyclone numbers in most cases. However, since local
 579 cyclones are weaker than remote cyclones, the TP still exerts a suppression effect on
 580 the intensities of total cyclones around the plateau, which becomes weaker in summer
 581 (Fig. 10).

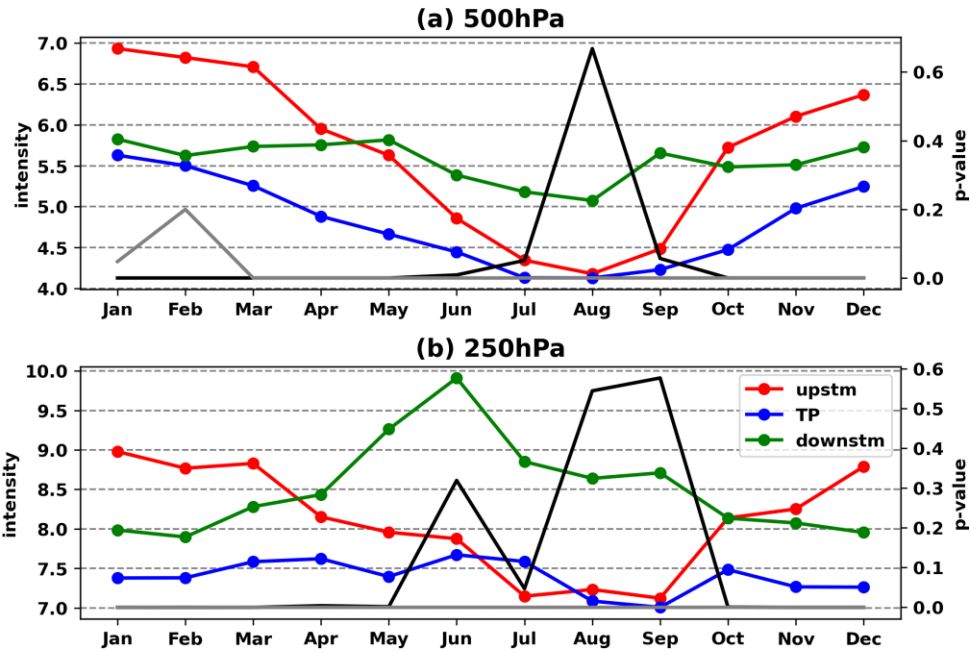
582



583

584 **FIG. 9.** Averaged monthly numbers (left y-axis) of (a) 850-hPa, (b) 500-hPa, and (c)
 585 250-hPa cyclones moving eastward into (red) and out of (blue) the TP region. Gray
 586 lines show the probability values (right y-axis). When the probability is less than 0.01,
 587 number difference between moving-in and -off cyclones significantly exceeds the
 588 99% confidence level of Student's two-sided t test.

589



590

591 **FIG. 10.** Mean intensity (left y-axis, unit: $10^{-5} s^{-1}$) of (a) 500-hPa, and (c) 250-hPa
 592 cyclones appearing over the TP (20~55°N/65~105°E, blue line), upstream of the TP
 593 (20~55°N/40~65°E, red line), and downstream of the TP (20~55°N/105~130°E, green
 594 line). Gray (black) lines show the probability values (right y-axis) of getting a result
 595 that the mean intensity of cyclones over the TP is similar to that over the downstream
 596 (upstream).

597

598 Considering that cyclones are the main systems that induce extreme weather
 599 processes such as rainstorms, windstorms, and cold-air outbreak, this study can provide
 600 a coherent reference for studying the roles played by the TP in the surrounding extreme
 601 weather processes and is conducive to the predictability of extreme weather around the
 602 plateau. It is well-known that cyclones are three-dimensional systems, whose vertical
 603 structure may display multiple configurations during their lifetimes. They may
 604 vertically extend from 850 hPa to 500 hPa at the initial stage, from 850 hPa to 200 hPa
 605 at the mature stage, and finally only exist at 200 hPa, or reversed (Schwierz and Davies
 606 2003; Li et al. 2020a). Nevertheless, the above analysis is a simple study of the
 607 behaviors of cyclones at different pressure levels, neglecting the variations of vertical
 608 structure when these cyclones move into or off the TP, which needs more investigations
 609 in the future.

610

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621

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623 [https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview)
624 [levels?tab=overview](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview).

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REFERENCES

- 627
- 628 Cannon, F., L. M. V. Carvalho, C. Jones, and J. Norris, 2016: Winter westerly
 629 disturbance dynamics and precipitation in the western Himalaya and Karakoram:
 630 a wave-tracking approach. *Theor. Appl. Climatol.*, **125**,
 631 <https://doi.org/10.1007/s00704-015-1489-8>.
- 632 Chang, E. K. M., 2009: Diabetic and orographic forcing of northern winter stationary
 633 waves and storm tracks. *J. Clim.*, **22**, 670–688,
 634 <https://doi.org/10.1175/2008JCLI2403.1>.
- 635 ———, and W. Lin, 2011: Comments on “the role of the central Asian mountains on the
 636 midwinter suppression of North Pacific storminess.” *J. Atmos. Sci.*, **68**, 2800–
 637 2803, <https://doi.org/10.1175/JAS-D-11-021.1>.
- 638 ———, S. Lee, and K. L. Swanson, 2002: Storm track dynamics. *J. Clim.*,
 639 [https://doi.org/10.1175/1520-0442\(2002\)015<02163:STD>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<02163:STD>2.0.CO;2).
- 640 Curio, J., Y. Chen, R. Schiemann, A. G. Turner, K. C. Wong, K. Hodges, and Y. Li,
 641 2018: Comparison of a Manual and an Automated Tracking Method for Tibetan
 642 Plateau Vortices. *Adv. Atmos. Sci.*, **35**, 965–980, [https://doi.org/10.1007/s00376-](https://doi.org/10.1007/s00376-018-7278-4)
 643 [018-7278-4](https://doi.org/10.1007/s00376-018-7278-4).
- 644 ———, R. Schiemann, K. I. Hodges, and A. G. Turner, 2019: Climatology of Tibetan
 645 Plateau vortices in reanalysis data and a high-resolution global climate model. *J.*
 646 *Clim.*, **32**, 1933–1950, <https://doi.org/10.1175/JCLI-D-18-0021.1>.
- 647 Dai, P., and J. Nie, 2022: Robust Expansion of Extreme Midlatitude Storms Under
 648 Global Warming. *Geophys. Res. Lett.*, <https://doi.org/10.1029/2022GL099007>.
- 649 Davis, C. A., 1997: The modification of baroclinic waves by the rocky mountains. *J.*
 650 *Atmos. Sci.*, **54**, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1997)054<0848:TMOBWB>2.0.CO;2)
 651 [0469\(1997\)054<0848:TMOBWB>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<0848:TMOBWB>2.0.CO;2).
- 652 Fleming, E. L., G.-H. Lim, and J. M. Wallace, 1987: Differences between the spring
 653 and autumn circulation of the Northern Hemisphere. *J. Atmos. Sci.*,
 654 [https://doi.org/10.1175/1520-0469\(1987\)044<1266:dbtsaa>2.0.co;2](https://doi.org/10.1175/1520-0469(1987)044<1266:dbtsaa>2.0.co;2).
- 655 Guan, Q., X. Yao, Q. Li, Y. Ma, and H. Zhang, 2018: Study of a horizontal shear line
 656 over the Qinghai–Tibetan Plateau and the impact of diabatic heating on its

657 evolution. *J. Meteorol. Res.*, <https://doi.org/10.1007/s13351-018-7186-7>.

658 Hawcroft, M. K., L. C. Shaffrey, K. I. Hodges, and H. F. Dacre, 2012: How much
659 Northern Hemisphere precipitation is associated with extratropical cyclones?
660 *Geophys. Res. Lett.*, **39**, <https://doi.org/10.1029/2012GL053866>.

661 Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Q. J. R. Meteorol.*
662 *Soc.*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.

663 Hodges, K., A. Cobb, and P. L. Vidale, 2017: How well are tropical cyclones
664 represented in reanalysis datasets? *J. Clim.*, **30**, [https://doi.org/10.1175/JCLI-D-](https://doi.org/10.1175/JCLI-D-16-0557.1)
665 16-0557.1.

666 Hodges, K. I., 1994: A general method for tracking analysis and its application to
667 meteorological data. *Mon. Weather Rev.*, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0493(1994)122<2573:AGMFTA>2.0.CO;2)
668 0493(1994)122<2573:AGMFTA>2.0.CO;2.

669 ———, 1995: Feature tracking on the unit sphere. *Mon. Weather Rev.*,
670 [https://doi.org/10.1175/1520-0493\(1995\)123<3458:ftotus>2.0.co;2](https://doi.org/10.1175/1520-0493(1995)123<3458:ftotus>2.0.co;2).

671 ———, 1996: Spherical nonparametric estimators applied to the UGAMP model
672 integration for AMIP. *Mon. Weather Rev.*, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0493(1996)124<2914:SNEATT>2.0.CO;2)
673 0493(1996)124<2914:SNEATT>2.0.CO;2.

674 ———, 1999: Adaptive constraints for feature tracking. *Mon. Weather Rev.*,
675 [https://doi.org/10.1175/1520-0493\(1999\)127<1362:acfft>2.0.co;2](https://doi.org/10.1175/1520-0493(1999)127<1362:acfft>2.0.co;2).

676 Holton, J. R., 2004: *An Introduction to Dynamic Meteorology: Fourth edition*.
677 Academic Press, 535 pp.

678 Hoskins, B. J., and K. I. Hodges, 2002: New perspectives on the Northern
679 Hemisphere winter storm tracks. *J. Atmos. Sci.*, **59**, 1041–1061,
680 [https://doi.org/10.1175/1520-0469\(2002\)059<1041:NPOTNH>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<1041:NPOTNH>2.0.CO;2).

681 Hoskins, B. J., and K. I. Hodges, 2005: A new perspective on Southern Hemisphere
682 storm tracks. *J. Clim.*, **18**, <https://doi.org/10.1175/JCLI3570.1>.

683 ———, and K. I. Hodges, 2019: The annual cycle of Northern Hemisphere storm tracks.
684 Part I: Seasons. *J. Clim.*, **32**, 1743–1760, [https://doi.org/10.1175/JCLI-D-17-](https://doi.org/10.1175/JCLI-D-17-0870.1)
685 0870.1.

686 Hunt, K. M. R., A. G. Turner, and L. C. Shaffrey, 2018: The evolution, seasonality

687 and impacts of western disturbances. *Q. J. R. Meteorol. Soc.*, **144**,
688 <https://doi.org/10.1002/qj.3200>.

689 Javed, A., P. Kumar, K. I. Hodges, D. V. Sein, A. K. Dubey, and G. Tiwari, 2022:
690 Does the Recent Revival of Western Disturbances Govern the Karakoram
691 Anomaly? *J. Clim.*, **35**, 4383–4402, <https://doi.org/10.1175/JCLI-D-21-0129.1>.

692 Jiao, Y., and Z. Qian, 1994: Studies of dynamic influence of Qinghai-Xizang Plateau
693 on the eastward moving trough in winter. Part I: Some aspects of statistical facts.
694 *Plateau Meteorol. (in Chinese)*, **13**, 153–161.

695 Kang, J. M., and S. W. Son, 2021: Development processes of the explosive cyclones
696 over the northwest pacific: Potential vorticity tendency inversion. *J. Atmos. Sci.*,
697 **76**, <https://doi.org/10.1175/JAS-D-20-0151.1>.

698 Lee, S. S., J. Y. Lee, K. J. Ha, B. Wang, A. Kitoh, Y. Kajikawa, and M. Abe, 2013:
699 Role of the Tibetan Plateau on the annual variation of mean atmospheric
700 circulation and storm-track activity. *J. Clim.*, [https://doi.org/10.1175/JCLI-D-12-](https://doi.org/10.1175/JCLI-D-12-00213.1)
701 [00213.1](https://doi.org/10.1175/JCLI-D-12-00213.1).

702 Li, G., and W. Zhang, 2019: Recent advances in the research of heavy rain associated
703 with vortices and shear lines come from the Tibetan Plateau. *Torrential Rain*
704 *Disasters (in Chinese)*, **38**, 464–471, [https://doi.org/10.3969/j.issn.1004-](https://doi.org/10.3969/j.issn.1004-9045.2019.05.008)
705 [9045.2019.05.008](https://doi.org/10.3969/j.issn.1004-9045.2019.05.008).

706 Li, L., and R. Zhang, 2023: Interdecadal Shift in Dipole Pattern Precipitation Trends
707 Over the Tibetan Plateau: Roles of Local Vortices. *Geophys. Res. Lett.*,
708 <https://doi.org/10.1029/2022gl1101445>.

709 ———, ———, M. Wen, and L. Liu, 2014: Effect of the atmospheric heat source on the
710 development and eastward movement of the Tibetan Plateau vortices. *Tellus A*
711 *Dyn. Meteorol. Oceanogr.*, **66**, 24451, <https://doi.org/10.3402/tellusa.v66.24451>.

712 ———, ———, and ———, 2017: Genesis of southwest vortices and its relation to Tibetan
713 Plateau vortices. *Q. J. R. Meteorol. Soc.*, **143**, <https://doi.org/10.1002/qj.3106>.

714 ———, ———, and ———, 2020a: Structure characteristics of the vortices moving off the
715 Tibetan Plateau. *Meteorol. Atmos. Phys.*, [https://doi.org/10.1007/s00703-019-](https://doi.org/10.1007/s00703-019-00670-z)
716 [00670-z](https://doi.org/10.1007/s00703-019-00670-z).

717 ———, ———, P. Wu, M. Wen, and J. Duan, 2020b: Roles of Tibetan Plateau vortices in
718 the heavy rainfall over southwestern China in early July 2018. *Atmos. Res.*, **245**,
719 <https://doi.org/10.1016/j.atmosres.2020.105059>.

720 ———, ———, M. Wen, and J. Lv, 2021: Regionally Different Precipitation Trends Over
721 the Tibetan Plateau in the Warming Context: A Perspective of the Tibetan
722 Plateau Vortices. *Geophys. Res. Lett.*, <https://doi.org/10.1029/2020GL091680>.

723 Liu, X., E. Ma, Z. Cao, and S. Jin, 2018: Numerical study of a southwest vortex
724 rainstorm process influenced by the eastward movement of Tibetan Plateau
725 vortex. *Adv. Meteorol.*, **2018**, <https://doi.org/10.1155/2018/9081910>.

726 Lorenz, D. J., and D. L. Hartmann, 2003: Eddy-zonal flow feedback in the Northern
727 Hemisphere winter. *J. Clim.*, **16**, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0442(2003)16<1212:EFFITN>2.0.CO;2)
728 [0442\(2003\)16<1212:EFFITN>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)16<1212:EFFITN>2.0.CO;2).

729 Luo, S., and L. Wei, 1985: The dynamical and synoptical analysis of the effect of the
730 Tibetan Plateau on a cut-off processes of the trough in May, 1979. *Plateau*
731 *Meteorol. (in Chinese)*, **4**, 14–22.

732 Ma, T., G. Wu, Y. Liu, and J. Mao, 2022: Abnormal warm sea-surface temperature in
733 the Indian Ocean, active potential vorticity over the Tibetan Plateau, and severe
734 flooding along the Yangtze River in summer 2020. *Q. J. R. Meteorol. Soc.*,
735 <https://doi.org/10.1002/qj.4243>.

736 Molnar, P., W. R. Boos, and D. S. Battisti, 2010: Orographic controls on climate and
737 paleoclimate of Asia: Thermal and mechanical roles for the Tibetan Plateau.
738 *Annu. Rev. Earth Planet. Sci.*, **38**, 77–102, [https://doi.org/10.1146/annurev-earth-](https://doi.org/10.1146/annurev-earth-040809-152456)
739 [040809-152456](https://doi.org/10.1146/annurev-earth-040809-152456).

740 Ólafsson, H., and P. Bougeault, 1997: The effect of rotation and surface friction on
741 orographic drag. *J. Atmos. Sci.*, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1997)054<0193:TEORAS>2.0.CO;2)
742 [0469\(1997\)054<0193:TEORAS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<0193:TEORAS>2.0.CO;2).

743 Park, H. S., J. C. H. Chiang, and S. W. Son, 2010: The role of the central Asian
744 mountains on the midwinter suppression of North Pacific storminess. *J. Atmos.*
745 *Sci.*, <https://doi.org/10.1175/2010JAS3349.1>.

746 ———, S. P. Xie, and S. W. Son, 2013: Poleward stationary eddy heat transport by the

747 Tibetan Plateau and equatorward shift of westerlies during northern winter. *J.*
748 *Atmos. Sci.*, **70**, 3288–3301, <https://doi.org/10.1175/JAS-D-13-039.1>.

749 Peixoto, J. P., and A. H. Oort, 1992: *Physics of Climate*. American Institute of
750 Physics, 520 pp.

751 Penny, S., G. H. Roe, and D. S. Battisti, 2010: The source of the midwinter
752 suppression in storminess over the North Pacific. *J. Clim.*, **23**, 634–648,
753 <https://doi.org/10.1175/2009JCLI2904.1>.

754 Qian, Z., and Y. Jiao, 1995: Studies of dynamic influence of Qinghai-Xizang Plateau
755 on the eastward moving trough in winter. Part III: The analyses simulations
756 experiments results. *Plateau Meteorol. (in Chinese)*, **14**, 55–66.

757 Ren, Q., X. Jiang, Y. Zhang, Z. Li, and S. Yang, 2021: Effects of suppressed transient
758 eddies by the Tibetan Plateau on the East Asian summer monsoon. *J. Clim.*,
759 <https://doi.org/10.1175/jcli-d-20-0646.1>.

760 ———, W. Wei, M. Lu, and S. Yang, 2022: Dynamical analysis of the winter Middle
761 East jet stream and comparison with the East Asian and North American jet
762 streams. *J. Clim.*, **35**, 4455–4468, <https://doi.org/10.1175/JCLI-D-21-0664.1>.

763 Rudeva, I., and S. K. Gulev, 2007: Climatology of cyclone size characteristics and
764 their changes during the cyclone life cycle. *Mon. Weather Rev.*,
765 <https://doi.org/10.1175/MWR3420.1>.

766 Schiemann, R., D. Lüthi, and C. Schär, 2009: Seasonality and interannual variability
767 of the westerley jet in the Tibetan Plateau region. *J. Clim.*, **22**, 2940–2957,
768 <https://doi.org/10.1175/2008JCLI2625.1>.

769 Schwierz, C. B., and H. C. Davies, 2003: Evolution of a synoptic-scale vortex
770 advecting toward a high mountain. *Tellus, Ser. A Dyn. Meteorol. Oceanogr.*,
771 <https://doi.org/10.1034/j.1600-0870.2003.01396.x>.

772 Son, S. W., M. Ting, and L. M. Polvani, 2009: The effect of topography on storm-
773 track intensity in a relatively simple general circulation model. *J. Atmos. Sci.*, **66**,
774 393–411, <https://doi.org/10.1175/2008JAS2742.1>.

775 Studholme, J., A. V. Fedorov, S. K. Gulev, K. Emanuel, and K. Hodges, 2022:
776 Poleward expansion of tropical cyclone latitudes in warming climates. *Nat.*

777 *Geosci.*, <https://doi.org/10.1038/s41561-021-00859-1>.

778 Wang, B., 1954: The formation and development of dynamic cyclones in China under
779 the influence of the Tibetan Plateau. *J. Shandong Univ. (in Chinese)*, **4**, 94–110.

780 Wang, B., 1987: The development mechanism for Tibetan Plateau warm vortices. *J.*
781 *Atmos. Sci.*, **44**, 2978–2994, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1987)044<2978:tdmftp>2.0.co;2)
782 [0469\(1987\)044<2978:tdmftp>2.0.co;2](https://doi.org/10.1175/1520-0469(1987)044<2978:tdmftp>2.0.co;2).

783 Wang, Q. W., and Z. M. Tan, 2014: Multi-scale topographic control of southwest
784 vortex formation in Tibetan plateau region in an idealized simulation. *J.*
785 *Geophys. Res.*, <https://doi.org/10.1002/2014JD021898>.

786 Wu, G., and Coauthors, 2007: The influence of mechanical and thermal forcing by the
787 Tibetan Plateau on Asian climate. *J. Hydrometeorol.*, **8**, 770–789,
788 <https://doi.org/10.1175/JHM609.1>.

789 ———, Y. Liu, B. He, Q. Bao, A. Duan, and F.-F. Jin, 2012: Thermal controls on the
790 Asian summer monsoon. *Sci. Rep.*, **2**, <https://doi.org/10.1038/srep00404>.

791 ———, and Coauthors, 2015: Tibetan Plateau climate dynamics: Recent research
792 progress and outlook. *Natl. Sci. Rev.*, **2**, 100–116,
793 <https://doi.org/10.1093/nsr/nwu045>.

794 Yeh, T., 1952: The seasonal variation of the influence of Tibetan Plateau on the
795 general circulation. *Acta Meteorol. Sin. (in Chinese)*, **23**, 33–47.

796 Yu, J. Y., and D. L. Hartmann, 1995: Orographic influences on the distribution and
797 generation of atmospheric variability in a GCM. *J. Atmos. Sci.*,
798 [https://doi.org/10.1175/1520-0469\(1995\)052<2428:oiotda>2.0.co;2](https://doi.org/10.1175/1520-0469(1995)052<2428:oiotda>2.0.co;2).

799 Zappa, G., M. K. Hawcroft, L. Shaffrey, E. Black, and D. J. Brayshaw, 2015:
800 Extratropical cyclones and the projected decline of winter Mediterranean
801 precipitation in the CMIP5 models. *Clim. Dyn.*, [https://doi.org/10.1007/s00382-](https://doi.org/10.1007/s00382-014-2426-8)
802 [014-2426-8](https://doi.org/10.1007/s00382-014-2426-8).

803 Zhang, G., J. Mao, Y. Liu, and G. Wu, 2021: PV Perspective of Impacts on
804 Downstream Extreme Rainfall Event of a Tibetan Plateau Vortex Collaborating
805 with a Southwest China Vortex. *Adv. Atmos. Sci.*,
806 <https://doi.org/10.1007/s00376-021-1027-9>.

807 Zhang, Y., L. Yang, D. Xiaokaiti, H. Qin, Y. Li, and X. Yang, 2012: The central
808 Asian vortexes activity during 1971—2010. *J. Appl. Meteorol. Sci. (in Chinese)*,
809 **23**, 312–321, <https://doi.org/10.3969/j.issn.1001-7313.2012.03.007>.
810 Zhao, Y., L. Fu, C. F. Yang, and X. F. Chen, 2020: Case study of a heavy snowstorm
811 associated with an extratropical cyclone featuring a back-bent warm front
812 structure. *Atmosphere (Basel)*, **11**, <https://doi.org/10.3390/atmos11121272>.
813 Zhuang, X., R. Li, B. Li, J. Li, and Z. Sun, 2017: Analysis on rainstorm caused by
814 central Asian vortex in northern Xinjiang. *Meteorol. Mon. (in Chinese)*, **43**, 924–
815 935, <https://doi.org/10.7519/j.issn.1000-0526.2017.08.003>.
816 Zurita-Gotor, P., and E. K. M. Chang, 2005: The impact of zonal propagation and
817 seeding on the eddy-mean flow equilibrium of a zonally varying two-layer
818 model. *J. Atmos. Sci.*, **62**, <https://doi.org/10.1175/JAS3473.1>.
819