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Abstract. The Twain-Hu Basin in central China is a relative “cold spot” for heat-ozone compound extremes, despite being surrounded by compound hotspots and experiencing both extreme summer heat and severe ozone pollution. This paradox arises because synoptic-scale regional transport, rather than local thermal forcing, governs severe ozone episodes, as diagnosed by PCA typing, FLEXPART-WRF, and WRF-Chem source tagging. Non-local sources contribute ~66% of basin-mean ozone. Two transport regimes (P1: 52.7%; P3: 12.9%) together explain 65.6% of the MDA8 O₃ variance. P1 (deep advective subsidence) features an East China Sea cyclone driving deep northerlies from North China, with western-flank subsidence injecting O₃ and precursors into the boundary layer. P3 (boundary-layer convergence trapping) involves low-level easterly advection from East China driven by the continental high, trapping pollutants via convergence over the basin. This transport dominance sustains



37 elevated ozone throughout the diurnal cycle with bimodal peaks (late-morning and
38 nighttime) reaching ~30% above climatology. Correspondingly, the September peak
39 of ozone exceedance lags the summer temperature maximum, decoupling the most
40 polluted month from the hottest months. These findings explain how a receptor basin
41 escapes surrounding heat-ozone compound hotspots and suggest that this
42 transport-dominated pattern may be a common feature of receptor basins surrounded
43 by multiple source regions.

44 **Keywords:** ozone pollution; regional transport; heat-ozone compound; receptor
45 region; synoptic regimes; WRF-Chem source tagging

46

47 1. Introduction

48 Heatwaves and severe ozone (O_3) pollution have become pressing
49 climate-environmental challenges in China, with compound heat-ozone extremes
50 increasingly frequent during the warm season (Ban et al., 2022; Cui et al., 2025; Gao
51 et al., 2025; Su et al., 2025). During heatwaves, national MDA8 O_3 rises from 106.9
52 to 131.8 $\mu g\ m^{-3}$, while the proportion of sites with O_3 exceedances more than doubles
53 from 11.5% to 26.6% (Zhou et al., 2025). These compound extremes are particularly
54 pronounced in the North China Plain, the Yangtze River Delta, the Pearl River Delta,
55 and the Sichuan Basin (Pan et al., 2026; Su et al., 2025; Sun et al., 2026; Wang et al.,
56 2022; Zhou et al., 2025), where ozone and heat co-occur for more than 15 days yr^{-1}
57 (Li et al., 2024). Notably, the Twain-Hu Basin in Central China, situated amid these
58 four hotspots, stands out as both a high-frequency region for ozone exceedance and
59 extreme heat (Fig. S1a, S1b), yet shows markedly limited compound frequency and
60 weaker O_3 enhancement during heatwaves (Fig. S1c, S1d; see also Zhou et al., 2025;
61 Li et al., 2024), appearing as a relative “cold spot” only when heat and ozone are
62 considered together. Yet this same basin, home to the “furnace cities” of Wuhan,
63 Changsha, and Nanchang, maintains warm-season MDA8 O_3 of 128 $\mu g\ m^{-3}$
64 (2015–2022; Fu et al., 2024), a level comparable to the most polluted regions (Shen et
65 al., 2023), but its O_3 peak occurs in September, lagging the summer heat maximum



66 (Fig. 1a, 1b). This paradox points to a mechanism distinct from local thermal forcing,
67 which we hypothesize involves synoptic-scale regional transport.

68 Comparative studies reveal a regional divide in ozone drivers: local
69 accumulation under hot, dry, stagnant conditions drives severe ozone over the North
70 China Plain and Yangtze River Delta (Gao et al., 2021; Gong and Liao, 2019; Kou et
71 al., 2025), whereas regional transport dominates in the Sichuan Basin and Pearl River
72 Delta (Yang et al., 2024). Synoptic systems influence the transport and chemical
73 transformation of ozone and its precursors (Han et al., 2020; Li et al., 2022; Li et al.,
74 2023; Zhou et al., 2026). Lying at the core of central-eastern China and surrounded by
75 the four major polluted regions, the Twain–Hu Basin is a natural receptor for regional
76 transport; air masses from multiple directions converge here, making it an ideal
77 setting for studying multi-source transport superposition (Bai et al., 2022, 2026; Shen
78 et al., 2022, 2023; Yao et al., 2025). Its north–south funnel topography further
79 channels polluted air masses from the north and east, amplifying the impact of
80 cross-regional transport on local pollution (Hu et al., 2023, 2026; Zheng et al., 2025).
81 Understanding how such multi-source receptor basins respond to pollutant transport
82 from different directions is essential for regional air quality management, yet the
83 quantitative source contributions, governing synoptic regimes, and vertical pathways
84 remain poorly constrained. The Twain–Hu Basin offers a testbed to address this gap.

85 To address this, we identified September as the peak O₃ month using 2016–2024
86 observations. We then combined PCA typing, FLEXPART-WRF, and WRF-Chem
87 tagging to quantify source contributions and to identify the weather regimes and
88 vertical pathways governing transport. This framework provides the first quantitative
89 attribution of how regional transport operates in a receptor basin, at both interannual
90 and synoptic scales. In doing so, it tests whether transport, rather than heat, drives the
91 basin’s ozone accumulation, and thus explains why a receptor basin escapes
92 surrounding heat-ozone compound hotspots.

93 **2. Data and Methods**

94 **2.1 Data and preprocessing**



95 Meteorological fields, including 10-m wind components (U10, V10), wind speed
96 (WS10), 2-m temperature (T2m), relative humidity (RH2m), downward surface solar
97 radiation (SSRD), boundary layer height (BLH), total column ozone, and
98 three-dimensional winds (u , v , ω) at multiple pressure levels, were obtained from
99 ERA5 reanalysis at 0.25° resolution for 2016–2024. O_3 and HCHO mixing ratios and
100 three-dimensional winds for vertical cross-section analysis were taken from the
101 ECMWF Atmospheric Composition Reanalysis 4 (EAC4) at 0.75° resolution. Surface
102 MDA8 O_3 was sourced from the high-resolution China High Air Pollutants (CHAP)
103 dataset (1 km, 2016–2023), which has been validated against ground measurements
104 with high accuracy (Yang et al., 2025; Wei et al., 2022). Comparison with station
105 observations averaged over the Twain-Hu Basin shows that CHAP MDA8 O_3 ($R^2 =$
106 0.99) and EAC4 daytime near-surface O_3 ($R^2 = 0.79$; Fig. S2) are both highly
107 consistent with the observed data, confirming their suitability for this study.

108 Hourly O_3 and temperature observations from monitoring stations across China
109 (2016–2024) were provided by the China National Environmental Monitoring Centre
110 and the China Meteorological Administration. From these data, we calculated MDA8
111 O_3 and daily maximum temperature ($T_{\max}$) at each station. Based on daily station
112 observations, we identified ozone exceedance (MDA8 $O_3 > 160 \mu\text{g m}^{-3}$), extreme heat
113 ($T_{\max} \geq 35^\circ\text{C}$), and compound heat-ozone events (same-day co-occurrence). To
114 quantify the coupling strength between heat and ozone across China, we further
115 calculated the probability of O_3 exceedance during hot days (P) for each station as the
116 ratio of annual compound event days to annual hot days. This conditional probability
117 reflects the likelihood of O_3 exceedance when high temperature occurs, thereby
118 characterizing the climatological heat- O_3 coupling strength (Gong et al., 2022; Sun et
119 al., 2026). A lower P indicates weaker thermal control over O_3 exceedance.

120 **2.2 Extracting O_3 -related synoptic modes via PCA**

121 To identify the dominant synoptic patterns coupling circulation and ozone
122 pollution, we applied Principal Component Analysis (PCA; Langford et al., 2009) to a
123 20-variable matrix (240 days $\times$ 20 variables) for September 2016–2023. The variables
124 included basin-averaged MDA8 O_3 , U10, V10, WS10, T2m, RH2m, SSRD, BLH,



125 and u , v , ω at 925, 850, 700, and 500 hPa (Fig. S3). The first three principal
126 components, explaining a cumulative variance of 76.4% (PC1: 35.2%, PC2: 27.4%,
127 PC3: 13.8%), are all significantly correlated with O_3 variability (Fig. S4).

128 PCA loadings (Fig. S3) measure the correlation between each variable and a PC.
129 For instance, PC1 shows strong positive loadings for O_3 , WS10, BLH, with deep
130 northeasterly winds aloft, which is a clear transport signature. In contrast, PC2
131 exhibits positive O_3 but negative WS10 loadings, reflecting local accumulation. To
132 further validate these interpretations, we composited days with standardized PC > 1
133 (44, 37, and 39 days for PC1–PC3, respectively) to obtain the three synoptic regimes
134 (Section 3.2).

135 **2.3 Semi-quantitative transport potential for O_3 from FLEXPART–WRF**

136 We performed 72-h FLEXPART–WRF backward simulations for September
137 2016–2023, releasing daily particle clusters from a representative receptor point
138 within the basin. The model calculates residence times within 0–200 m above ground
139 for each source-region grid cell. This residence time, also termed the emission
140 sensitivity response function, quantifies the potential contribution per unit emission
141 from that cell to the receptor (Eckhardt et al., 2017). Multiplying by VOC emissions
142 provides an approximate relative source influence for O_3 . The transport potential is
143 then the ratio of outside-basin to total cumulative contributions (Hu et al., 2022; Yu et
144 al., 2020), representing the fractional influence of non-local emissions on O_3
145 pollution (Section 3.1).

146 This simplified approach assumes fixed-yield conversion of all transported
147 VOCs to O_3 , necessarily neglecting the photochemical environment and NO_x
148 availability as the model omits chemical conversion for this secondary pollutant.
149 Therefore, this transport potential should be interpreted as a semi-quantitative
150 indicator of regional transport contributions rather than absolute source
151 apportionment.

152 **2.4 Ozone source apportionment with WRF–Chem**

153 WRF–Chem v3.9.1 simulations for September 2022 used two nested domains
154 (36 km and 12 km; Fig. S5) over East Asia and the Twain-Hu Basin. Meteorological



155 and chemical conditions were from FNL reanalysis and CAM-Chem global model
156 (6-hourly), respectively. CBMZ gas-phase chemistry, MEIC anthropogenic emissions
157 and MEGAN biogenic emissions were used (Table S1). Model evaluation against
158 measurements (Fig. S6) demonstrates good performance, confirming the simulation's
159 ability to capture the spatiotemporal variations of ozone in the basin.

160 To quantify contributions from different source regions to ozone over the
161 basin, we employed a mass-balance-based ozone source tagging technique in
162 WRF–Chem, following Gao et al. (2016, 2017, 2020). This method tracks emissions
163 of O₃ precursors (NO_x and VOCs) from each tagged region within a single simulation,
164 inherently preserves nonlinear photochemistry across NO_x- and VOC-limited regimes,
165 and yields source-resolved ozone concentration fields. Tagged regions include the
166 Twain-Hu Basin (receptor), North China, East China, and the remaining d01 domain
167 (Fig. S5). CAM–Chem chemical boundary conditions are treated as an independent
168 boundary source, representing large-scale extra-domain background contributions (Du
169 et al., 2026). This approach avoids the computational cost and nonlinearity-induced
170 errors of multiple sensitivity simulations.

171 **3. Results**

172 **3.1. Regional transport governs the basin's evasion from heat-ozone** 173 **coupling**

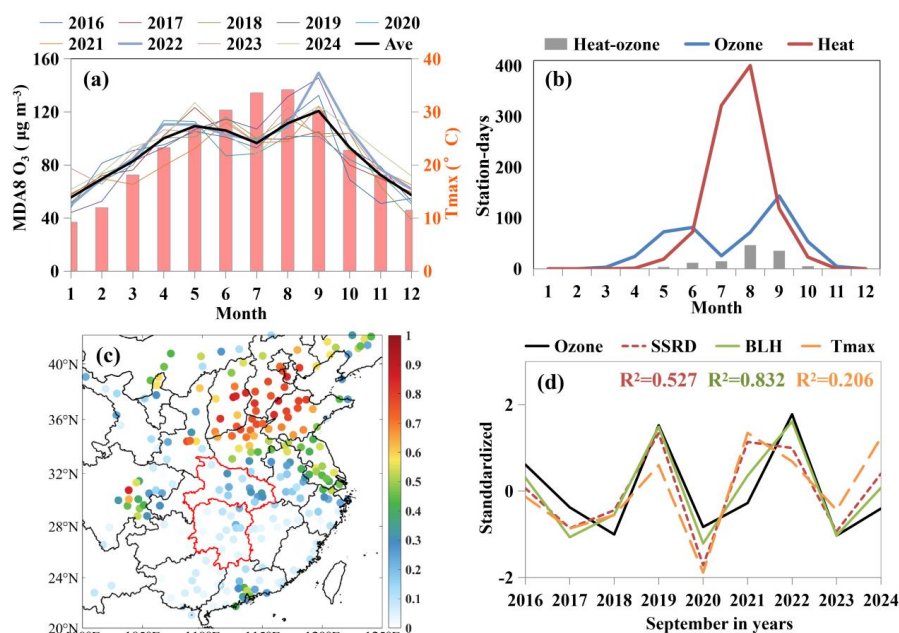
174 The Twain-Hu Basin exhibits a bimodal warm-season ozone cycle, with peaks
175 in May–June and August–September separated by a July trough during the Meiyu
176 period (Fig. 1a, 1b). September is the most polluted month, recording the highest
177 exceedance frequency, and it lags the summer heat maximum (July–August; Fig. 1a,
178 1b). Compound events peak primarily in August, with a secondary peak in September
179 (Fig. 1b). In August, extreme heat, ozone exceedance, and compound-event
180 station-days occur in a ratio of 8.9:1.6:1, indicating that most heatwave days lack
181 concurrent ozone exceedance; by September, this shifts to 3.5:4.1:1 as ozone
182 exceedance surges while heatwave days decline (Fig. 1b), clearly decoupling severe
183 ozone pollution from local temperature. This temporal decoupling is mirrored in
184 space: the Twain-Hu Basin has lower hot-day O₃ exceedance probabilities (Fig. 1c),



185 lower compound event frequencies (Fig. S1c), and weaker O₃ enhancement during
186 heatwaves (Fig. S1d) than the surrounding hotspots (the North China Plain, Yangtze
187 River Delta, Pearl River Delta, and Sichuan Basin), marking it as a relative regional
188 “cold spot” distinct from the heat-ozone coupling dominant in neighboring areas.
189 Together, these temporal and spatial patterns define the basin’s climatological evasion
190 from heat-ozone coupling.

191 The circulation during the peak month reveals how this evasion is achieved. As
192 the summer monsoon and subtropical high withdraw in early autumn, continental cold
193 highs advance, driving a low-level anticyclone over northern China in September (Fig.
194 2a). This circulation shift places the Twain-Hu Basin under northeasterly transport
195 rather than stagnant accumulation, producing contrasting ozone regimes: stagnant
196 photochemical accumulation over North China versus regional transport of upwind
197 ozone into the basin via northeasterly winds (Fig. 2a).

198



199

200 Figure 1. (a) Monthly MDA8 O₃ (lines; individual years and multi-year mean, $\mu\text{g m}^{-3}$)
201 and multi-year monthly mean daily T_{max} (bars, °C) over the Twain-Hu Basin,
202 2016–2024. (b) Multi-year monthly mean MDA8 O₃ exceedance (>160 $\mu\text{g m}^{-3}$),

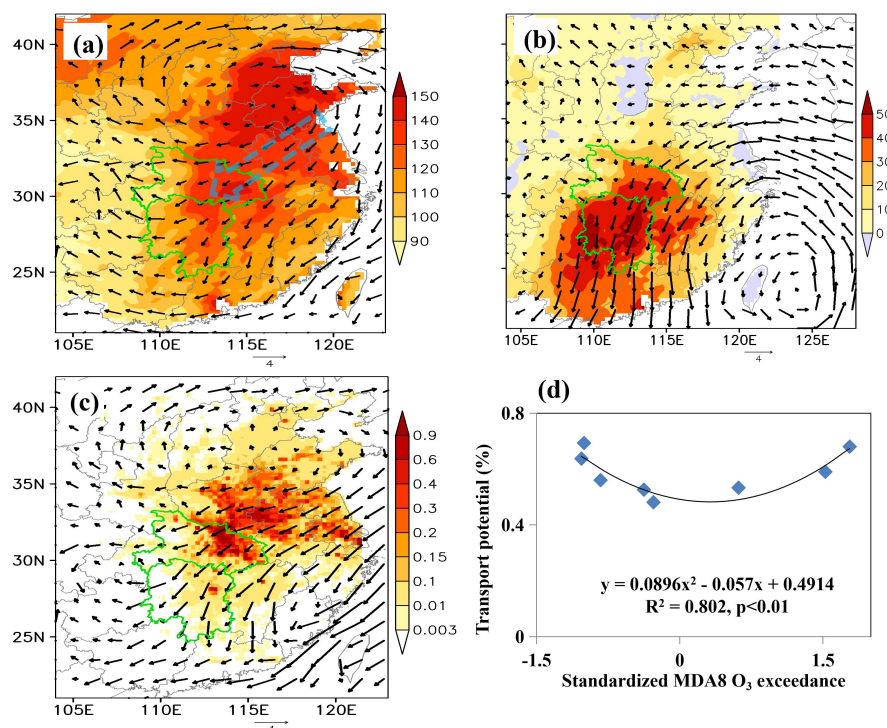


203 extreme heat ($T_{\max} \geq 35^{\circ}\text{C}$) and compound heat-ozone events, all in station-days. (c)
204 Spatial distribution of the probability of O_3 exceedance during hot days across China,
205 2016–2024; the Twain-Hu Basin is outlined in red. (d) Standardized MDA8 O_3
206 exceedance, SSRD, $T_{\max}$, and BLH in September (relative to 2016–2024 September
207 mean).

208

209 Interannually, ozone exceedance during the peak month varies markedly (high:
210 2016, 2019, 2022; low: 2018, 2020, 2023) (Fig. 1d). Boundary layer height explains
211 83.2% of this variance, far exceeding downward shortwave radiation (52.7%),
212 implicating vertical mixing and regional transport rather than local photochemistry.
213 Critically, maximum temperature explains only 20.6% of the variance, indicating that
214 interannual ozone variability is largely decoupled from thermal forcing.
215 High-minus-low ozone composites further reveal a closed cyclonic anomaly over the
216 East China Sea as the key driver (Fig. 2b). The basin lies on its western flank, where
217 anomalous northeasterlies coincide with positive ozone anomalies and outflow. This
218 configuration rules out local accumulation and confirms advective transport as the
219 dominant process. The East China Sea cyclone thus governs interannual ozone
220 variability in the basin during this peak month, providing advective supply rather than
221 local thermal forcing, which helps explain the basin's limited compound frequency.

222 This transport-dominated pattern is further reflected in the nonlinear relationship
223 between non-local transport potential and ozone exceedance. FLEXPART–WRF
224 simulations identify the upwind North China Plain and East China as dominant
225 potential source regions (Fig. 2c). The relationship is nonlinear (Fig. 2d):
226 above-average exceedance periods coincide with enhanced upwind contributions,
227 whereas below-average periods reflect dominant local accumulation under stagnant
228 conditions. This transport-accumulation dichotomy mirrors aerosol pollution patterns
229 in receptor regions (Bai et al., 2026), where mild pollution associates with local
230 accumulation and severe episodes with ventilation-enhanced transport. Regional
231 transport thus fundamentally determines severe ozone pollution in the Twain-Hu
232 Basin; this is the key to its evasion from heat-ozone coupling.



233

234 Figure 2. (a) September MDA8 O₃ (shading, $\mu\text{g m}^{-3}$) and 850 hPa winds (vectors, m
235 s^{-1}) during 2016–2023; thick arrows denote transport direction. (b) Composite
236 differences (high minus low O₃ years) in September MDA8 O₃ (shading, $\mu\text{g m}^{-3}$) and
237 850 hPa winds (vectors, m s^{-1}) during 2016–2023. (c) Potential source contributions
238 (shading, $10^{-2}\%$) derived from FLEXPART–WRF and 925 hPa winds (vectors, m s^{-1})
239 during September 2016–2023. (d) Non-local transport potential (%) versus
240 standardized September O₃ exceedance during 2016–2023. The green contour outlines
241 the basin in (a)–(c).

242

243 3.2 Synoptic Regimes and Transport Pathways

244 Regional transport dominates severe ozone pollution in the basin on
245 climatological and interannual scales. To identify the underlying synoptic processes,
246 we performed PCA on daily data from September 2016–2023. The first three principal
247 components explain 79.5% of the total MDA8 O₃ variance (Fig. S4), with PC1 alone
248 accounting for 52.7% (PC2: 13.9%, PC3: 12.9%), indicating that transport-dominant



249 regimes are the primary drivers. These components correspond to three recurring
250 synoptic regimes (Fig. 3, Fig. S7): northerly-transport (P1), local-accumulation (P2),
251 and easterly-transport (P3).

252 P1 (northerly-transport type) features an East China Sea cyclone coupled with a
253 continental high (Fig. 3a). This pattern drives strong northerlies from North China
254 into the basin, advecting ozone-rich air and producing the most widespread and
255 intense O₃ anomaly among the three regimes, extending from North China to the
256 southern basin and downwind areas (Fig. 3a, 3c, 3e). The deep trough at 500 hPa
257 drives western-flank subsidence (Fig. S8a), which combined with cyclone-induced
258 subsidence connects the free troposphere to the deepened boundary layer (Fig. S9g).
259 This produces positive total column ozone anomalies (Fig. S8b), while also
260 intensifying radiation, drying the air (Fig. S9a, S9e), and enhancing precursor
261 transport and photochemical conversion, thus sustaining severe regional surface ozone
262 anomalies. Notably, P1 occurs with the weakest positive temperature anomalies
263 among the three regimes (Fig. S9c, S9d, S7d), yet produces the strongest O₃
264 anomalies, confirming that the most severe pollution is driven by advective supply
265 rather than local heat. P1 thus represents the dominant circulation type for severe
266 ozone pollution, the synoptic-scale signature of the East China Sea cyclone that
267 governs interannual variability.

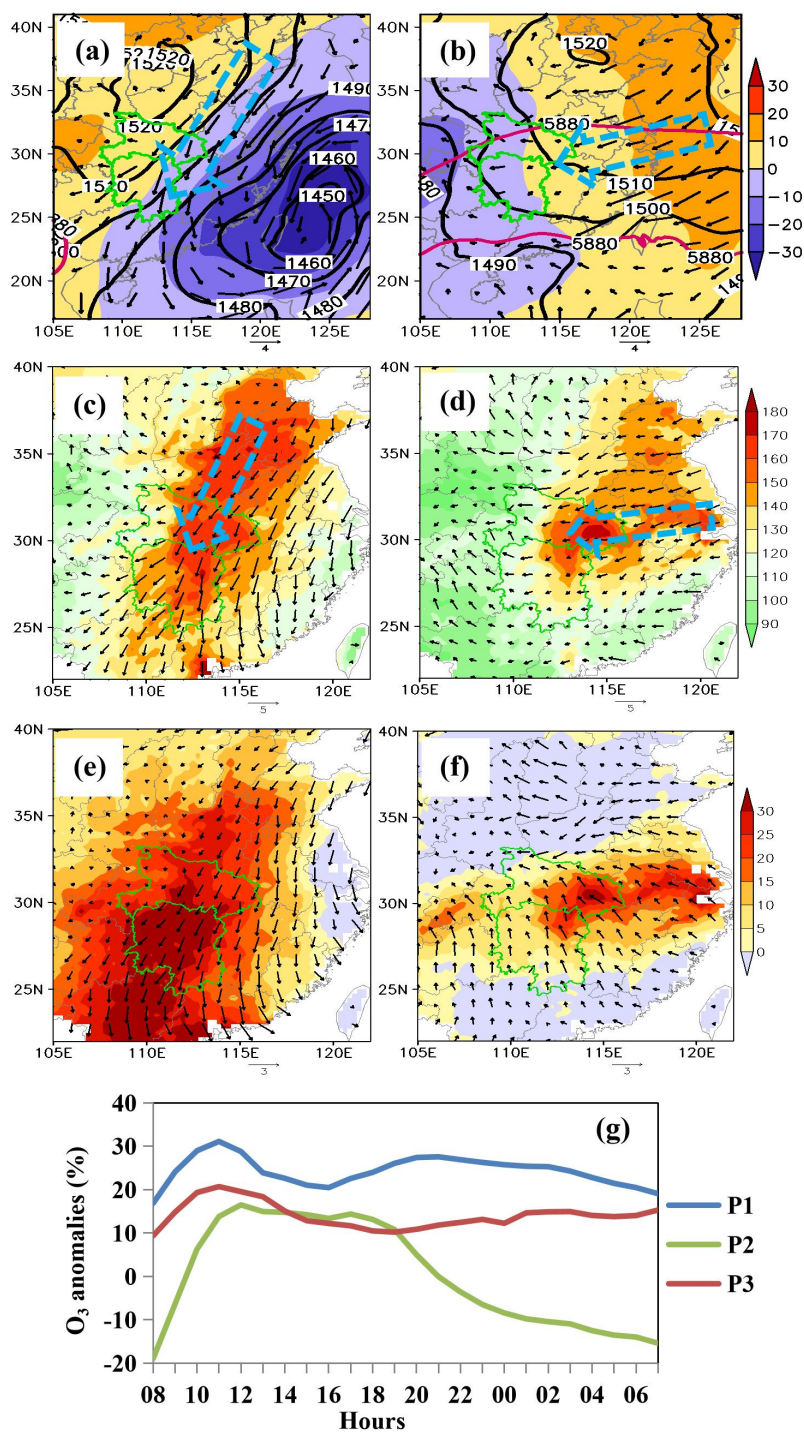
268 In contrast, P3 (easterly-transport type) is primarily driven by the continental
269 high, which generates low-level easterlies that advect ozone-rich air from East China
270 into the basin, where the terrain enhances their convergence with weak basin winds
271 and anomalous southerlies (Fig. 3b, 3d, 3f). A subtropical high dominates the Yangtze
272 River Valley (Fig. 3b) and provides a subsidence background that traps pollutants
273 within the boundary layer, along with high temperatures and strong radiation (Fig.
274 S9b, S9d), promoting photochemical production from transported and local precursors.
275 The resulting positive ozone anomaly forms a band over central-eastern China (Fig.
276 3f), underscoring the distinct imprint of convergence-driven versus pure advective
277 regimes. By contrast, P2 (local-accumulation type, Fig. S7) is characterized by
278 stagnant weak winds, anomalous southerlies, positive temperature anomalies, and



279 subsidence anomalies (Fig. S10c). On the periphery of the subtropical high, these
280 conditions enhance local photochemical production and pollution accumulation.

281 Diurnal evolution further distinguishes these regimes (Fig. 3g). Both
282 transport-dominant types (P1, P3) exhibit persistent positive ozone anomalies
283 throughout the diurnal cycle, with bimodal peaks in the late morning and at night, in
284 contrast to P2's broad daytime plateau. Under P1, regional transport elevates ozone by
285 31% at 11:00 LST, with daytime and nighttime anomalies of 24% each, suggesting
286 continuous advective supply. P3 shows similar persistence: +21% at 11:00 LST, with
287 daytime and nighttime anomalies of 15% and 14%. By contrast, P2 reaches +16%
288 during the day and drops to -19% at night. The bimodal pattern of P1/P3 coincides
289 with elevated wind speed and boundary layer height throughout the diurnal cycle (Fig.
290 S11). The nighttime peak is consistent with low-level-jet (LLJ)-enhanced turbulent
291 mixing that mixes O₃-rich residual-layer air downward (Xing et al., 2026; Wang et al.,
292 2026), while the late-morning peak arises from boundary-layer entrainment of
293 advected residual ozone (Hu et al., 2018). P2's daytime plateau reflects photochemical
294 production under stagnant conditions, while its nighttime depletion indicates NO_x
295 titration in a stable boundary layer (Pan et al., 2018). Regional transport thus reshapes
296 the diurnal ozone cycle: instead of a midday photochemical peak and nighttime loss, it
297 sustains elevated ozone throughout the day and night, raising concentrations by
298 approximately one-third above climatology. This sustained diurnal pattern contrasts
299 with the thermal-coupled cycle under the stagnant regime (P2), reinforcing the basin's
300 escape from compound extremes at the diurnal scale.

301



302

303



304 Figure 3. (a,b) Composite 850-hPa geopotential height (contours; gpm) and anomalies
305 (shading) with 1000-hPa winds (vectors; m s^{-1}) for (a) P1 (northerly-transport type)
306 and (b) P3 (easterly-transport type); thick arrows denote transport pathways. (c,d)
307 MDA8 O_3 (shading; $\mu\text{g m}^{-3}$) with 10-m winds (vectors; m s^{-1}) for (c) P1 and (d) P3.
308 (e,f) Same as (c,d) but for anomalies. (g) Basin- averaged diurnal ozone anomalies (%)
309 for P1, P2 (local-accumulation type), and P3. All anomalies are relative to the
310 2016–2023 September mean.

311

312 Vertical cross sections reveal a meridional-zonal coupled transport pathway
313 under P1 (Fig. S12a, S12b). Deep northerlies throughout the troposphere, driven by
314 the East China Sea cyclone and western-flank subsidence, transport high O_3 from
315 North China into the basin (Fig. 4a, Fig. S12b), with enhanced low-level winds
316 amplifying the advective influx (Fig. S12b). Upward transport over East China (Fig.
317 4c), westward advection by anomalous northeasterlies aloft, and downward injection
318 through the boundary layer top enrich the mixed layer while suppress vertical dilution
319 (Fig. 4c, 4a). Positive O_3 anomalies throughout the tropospheric column (Fig. S13a,
320 Fig. S8b) support this deep advection-subsidence mechanism. Correlation profiles
321 confirm strong low-level winds, deep subsidence, and pervasive dryness (Fig. S10). In
322 contrast, HCHO shows cross-boundary-layer downward transport toward the surface
323 but lacks the deep tropospheric component seen in O_3 , with anomalies peaking near
324 the boundary-layer top and turning negative below (Fig. 4b, 4d, S13b). This indicates
325 that transported precursors fuel boundary-layer O_3 production, distinct from direct O_3
326 injection from aloft. Severe O_3 pollution under P1 thus involves both direct
327 tropospheric advection and local photochemical production from transported
328 precursors.

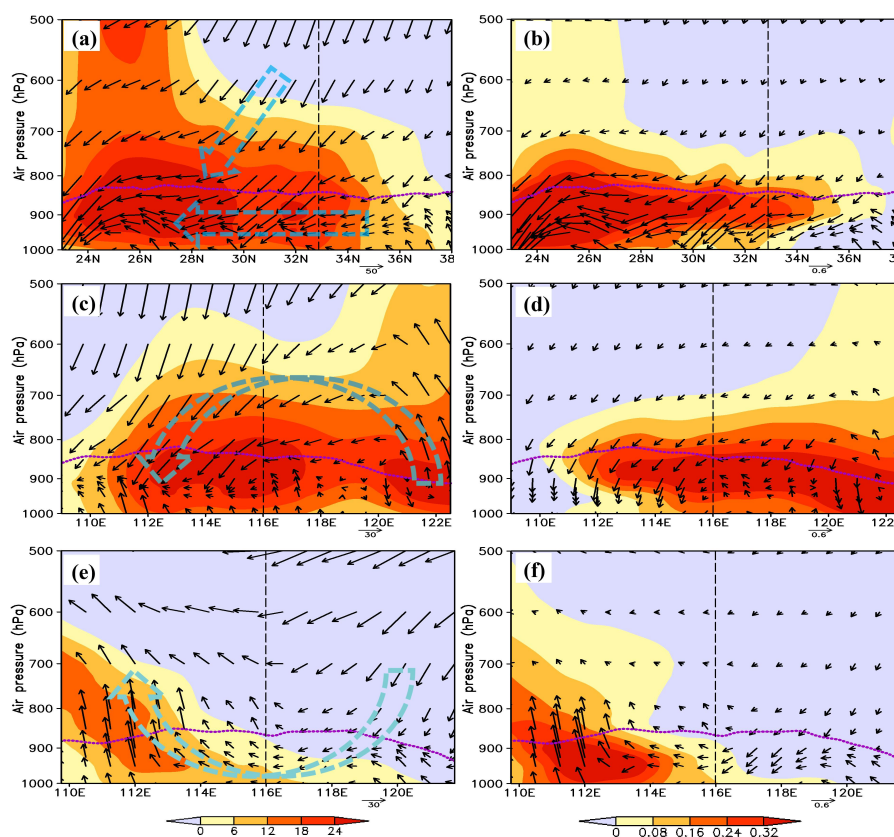
329 P3 features strong easterly advection within the boundary layer and weak
330 meridional winds that favor convergence and local accumulation (Fig. S12c, S12d),
331 characterizing it as a transport-convergence regime. Subtropical high subsidence traps
332 O_3 and HCHO flux anomalies within the boundary layer over East China, while
333 low-level easterlies driven by the continental high advect them westward into the



334 basin (Fig. 4e, 4f). Unlike P1's deep injection, basin-interior convergence
335 favors upward cross-boundary-layer transport, trapping pollutants and enhancing local
336 photochemical production. Correlation profiles (Fig. S10) confirm boundary-layer
337 convergence, upward motion, and well-mixed temperature over the basin.

338 These distinct vertical processes confirm that P1 and P3 represent two
339 fundamentally different transport-dominant pathways: P1 events require monitoring
340 of anomalous deep northerlies and cyclone-induced subsidence, whereas P3 events
341 demand attention to low-level easterly surges and boundary-layer convergence.

342



343

344 Figure 4. Vertical cross-sections of O_3 (a, c, e) and $HCHO$ (b, d, f) transport flux
345 anomalies (shading; $10^9 \text{ kg m}^{-1} \text{ s}^{-1}$) with anomalous transport flux vectors (vertical
346 flux $\times 100$), averaged over the Twain-Hu Basin ($110\text{--}116^\circ\text{E}$, $24\text{--}33^\circ\text{N}$) for P1 (a–d)
347 and P3 (e–f) regimes. All anomalies are relative to the 2016–2023 September mean.



348 Purple dashed line: convective boundary layer top. Thick arrows denote transport
349 pathways.

350

351 **3.3 Source apportionment of the basin ozone**

352 September 2022 was the most severe ozone episode in the Twain-Hu Basin
353 (Fig. 1c), driven by anomalous northerlies that concentrated positive O₃ anomalies
354 over the southern basin, primarily from upwind North China and East China
355 (Fig. S14). WRF–Chem source tagging quantifies the contributions (Fig. 5), directly
356 validating the transport-dominant synoptic regimes identified in Section 3.2. Spatially,
357 North China sources dominate the northern basin, East China sources the eastern rim,
358 and local emissions accumulate in the southern basin due to terrain trapping under
359 northerly flow (Fig. 5a–5c).

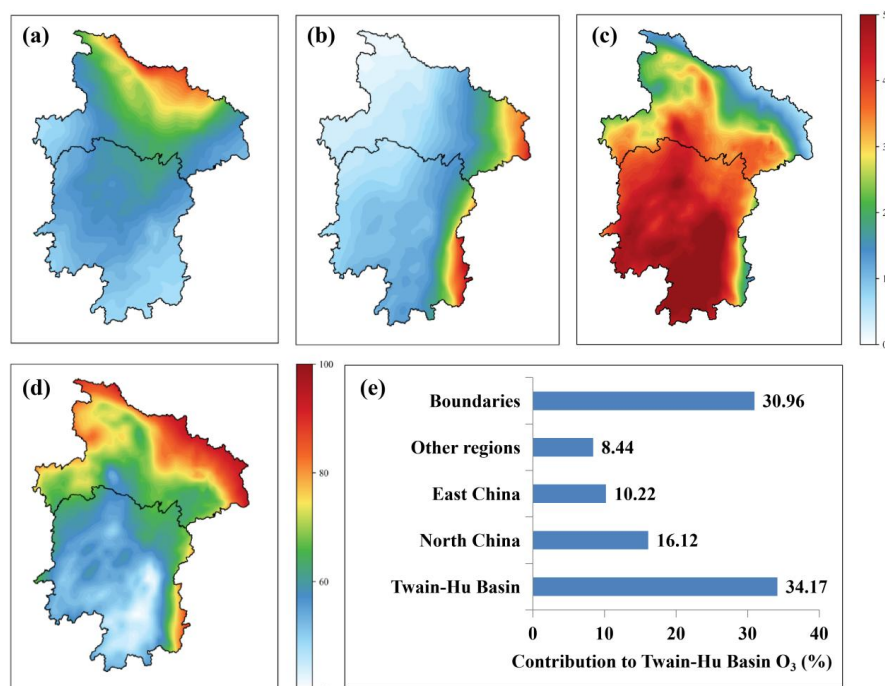
360 Local emission controls face diminishing returns during transport-dominant
361 episodes. On average, local emissions account for only ~34% of basin-mean O₃,
362 whereas non-local transport contributes ~66% (exceeding 80% near basin boundaries;
363 Fig. 5d). Within the non-local portion, extra-domain background (~31%) and
364 regional sources (North China ~16%, East China ~10%, others ~8%) together
365 dominate the ozone budget. The near-equal split among local (~34%), regional
366 (~35%), and background (~31%) contributions demonstrates that non-local transport
367 is the primary driver of severe ozone pollution. The background contribution rivals
368 regional sources, pointing to extra-domain and possibly intercontinental transport, a
369 role consistent with the East China Sea cyclone (Fig. 2b), which efficiently imports
370 both regional pollution and background ozone.

371 The overwhelming non-local contribution (~66%) explains why the basin,
372 despite being a heatwave hub, exhibits only limited compound frequency: the ozone
373 supply is governed by synoptic-scale advection, not by local temperature.
374 Consequently, mitigating severe ozone pollution in the Twain-Hu Basin requires
375 multi-scale collaborative control, including local precursor reductions, regional
376 transport management, and attention to extra-domain sources.

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378



379

380 Figure 5. WRF-Chem source tagging for September 2022. (a–d) Spatial distribution
381 of relative O₃ contributions (%) from (a) North China, (b) East China, (c) local
382 (Twain-Hu Basin), and (d) non-local (transport) sources. (e) Basin-averaged
383 source-apportioned contributions to surface O₃ from different source regions.

384

385 4. Conclusions and Discussions

386 This study finds that the Twain-Hu Basin escapes the surrounding heat-ozone
387 compound hotspots because synoptic-scale regional transport, rather than local heat,
388 drives its severe ozone pollution. Non-local sources contribute ~66% of basin-mean
389 ozone, and the PCA-derived transport regimes explain 65.6% of the MDA8 O₃
390 variance. The September ozone peak also lags the summer temperature maximum, as
391 subtropical-high-controlled heatwaves give way to continental cold high-driven
392 transport. This temporal offset from the peak heat period limits compound extreme
393 frequency, and is reinforced by spatial evidence: the basin exhibits weaker O₃
394 enhancement and lower probabilities of O₃ exceedance during hot days than the



395 surrounding hotspots. Even though the basin is both a heatwave hub and an ozone
396 pollution center, these temporal and spatial decouplings collectively point to a
397 mechanism distinct from the thermal-photochemical coupling that dominates
398 surrounding hotspots (Zhou et al., 2025; Li et al., 2024).

399 Our results place the Twain-Hu Basin at the upper end of the 40–80%
400 cross-regional transport range reported for China (Qu et al., 2024). Two distinct
401 transport regimes—P1 (deep advective subsidence) and P3 (low-level convergence
402 trapping)—govern severe episodes through contrasting vertical pathways, providing
403 process-based insight into regional transport. P1’s deep subsidence, occurring behind
404 an upper-level trough and coupled with the East China Sea cyclone, resembles
405 typhoon-induced ozone enhancement (Qi et al., 2024; Meng et al., 2022) but differs in
406 its extratropical transition origin, with more widespread and sustained influx. Notably,
407 P1 exhibits the weakest temperature forcing among all regimes yet produces the most
408 severe ozone pollution, indicating that advective supply rather than
409 temperature-accelerated local production dominates the heaviest episodes. P3, by
410 contrast, involves boundary-layer easterly convergence over the basin, driven by the
411 continental high, trapping pollutants. Together, these pathways replace local
412 emission-driven, temperature-enhanced production with advective mass supply,
413 explaining why the basin escapes the heat-ozone compound extremes prevalent in
414 surrounding regions.

415 Decoupling from heat-driven local photochemistry does not preclude the
416 photochemical conversion of transported precursors. Both O₃ and HCHO exhibit
417 boundary-layer exchange, but only O₃ receives additional supply from the free
418 troposphere via deep subsidence. HCHO anomalies are positive near the
419 boundary-layer top and negative near the surface, consistent with precursor transport
420 from upwind regions into the boundary layer followed by photochemical loss under
421 conditions of strong radiation and low humidity. Thus, such episodes involve both
422 direct O₃ advection and in-situ photochemical production from transported precursors,
423 although their relative contributions, chemical pathways, and O₃ yields remain to be
424 quantified.



425 The basin shares the same boundary-layer processes observed elsewhere,
426 including morning entrainment and nocturnal LLJ-driven peaks (An et al., 2024; Zhao
427 et al., 2019). However, persistent synoptic forcing from the East China Sea cyclone
428 (P1) and the continental high (P3) sustains elevated ozone throughout the diurnal
429 cycle, yielding bimodal peaks (~30% above climatology). In contrast to the
430 thermal-coupled diurnal cycle under P2, this persistent day-night elevation represents
431 a diurnal decoupling from heat, reinforcing the basin's escape from compound
432 extremes.

433 Methodologically, the closed-loop framework of PCA synoptic classification,
434 FLEXPART–WRF transport potential, and WRF–Chem source tagging provides a
435 replicable approach for ozone source attribution. Unlike circulation-only PCA (Hu et
436 al., 2022; Yao et al., 2025), our approach extracts ozone-coupled synoptic modes;
437 unlike brute-force sensitivity simulations (Clappier et al., 2017; Thunis et al., 2019),
438 the tagging preserves chemical nonlinearity; and unlike coarse-resolution global
439 models with ozone-only tagging (Shen et al., 2022, 2023), our WRF–Chem tracks
440 precursor emissions. This framework is transferable to other receptor regions,
441 enabling process-based ozone attribution across diverse topographic and climatic
442 settings.

443
444 **Data availability.** The ground-level ozone observation data were obtained from the National
445 Air Quality Monitoring Network (<https://quotsoft.net/air/>). The 2-m air temperature data were
446 provided by the National Meteorological Information Centre of the China Meteorological
447 Administration (<http://data.cma.cn/en/>). The daily seamless 1 km ground-level O₃ data were
448 sourced from the ChinaHighO₃ dataset (Yang et al., 2025; Wei et al., 2022), available
449 at <https://doi.org/10.5281/zenodo.16883507>. The ERA5 reanalysis pressure-level data (Hersbach
450 et al., 2023a) and single-level data (Hersbach et al., 2023b) were obtained from the Copernicus
451 Climate Change Service
452 (<https://doi.org/10.24381/cds.bd0915c6> and <https://doi.org/10.24381/cds.adbb2d47>, respectively).
453 The EAC4 reanalysis datasets are available from the Copernicus Atmosphere Monitoring Service
454 (2020) at <https://doi.org/10.24381/d58bbf47>.



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457

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462

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465

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