



A foundation diagnostic framework reveals more frequent yet spatially shrinking local atmospheric circulations over plateau-basin regions

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Abstract. Local atmospheric circulations critically affect hazardous weather and environment forecasting, yet their vertical structures remain unclear. Here, a foundational physical-constrained framework for objectively identifying and quantifying the vertical structures of terrain-driven circulations is developed and applied over the Tibetan Plateau (TP)-Sichuan Basin. Three typical circulation patterns, i.e., one-cell, two-cell, and three-cell circulations are detected for the first time, enabling quantification of their intensity, spatial extent, and central height. Results indicate that free-atmosphere circulations present higher altitudes and weaker intensity than boundary-layer circulations. For two- and three-cell patterns, west circulations adjacent to the TP expand and weaken during daytime but contract and descend at nighttime. From 1980 to 2022, local atmospheric circulations become more frequent while spatial extent shrink, suggesting enhanced localization of frequent convective weather and air pollution. These findings provide a basis for vertical quantification of terrain-driven circulations, supporting operational forecasting of hazardous weather and environment over plateau-basin regions.

1 Introduction

Plateau-basin regions are global hotspots of frequent and diverse local atmospheric circulations induced by surface heterogeneity (Letcher and Minder, 2018; Zardi and Whiteman, 2013; Lobos-Roco et al., 2021). Unlike thermally dominated mountain-valley and sea-land breezes (Defant, 1949; Vergeiner and Dreiseitl, 1987; Prtenjak and Grisogono, 2007), plateau-basin circulations are jointly regulated by thermal and dynamical forcing (Lareau et al., 2024). These forcing drive not only



thermally dominated circulation in the atmospheric boundary layer but also dynamically driven circulation in the free
30 atmosphere, which combine to form vertically stacked two-cell circulations (Lu et al., 2026). By substantially modulating the
exchange of mass, energy, and momentum between the atmospheric boundary layer and free atmosphere, these circulations
accelerate convective triggering and pollutant accumulation (Bao et al., 2011; Zhao et al., 2023; Zhang et al., 2025; Wagner
et al., 2015). Consequently, convective weather and air pollution over plateau–basin regions are highly localized and often
abrupt (Lu et al., 2024; Wu et al., 2026), complicating forecasts of hazardous meteorological and environmental conditions.
35 Notably, the high population density in these regions leaves large populations particularly vulnerable to such hazards
(O’kane and Copley, 2021). In-depth investigations of plateau-basin local atmospheric circulations are therefore crucial for
improving prediction and risk mitigation of associated weather and air pollution hazards.

Currently, the horizontal distribution and impacts of local atmospheric circulations are well-documented, whereas their
40 vertical structures remain poorly understood (Wang et al., 2023; Zhang et al., 2024; Fonseca et al., 2025). Key vertical
attributes of local circulations, including central height, spatial extent, and intensity, critically modulate weather and
environmental conditions (Shu et al., 2021; Peng et al., 2023; Hu et al., 2014). For instance, circulation cores reaching or
exceeding the level of free convection, may trigger deep convection and amplify hazardous weather (Metzger et al., 2014).
Moreover, larger circulation extents coupled with abundant moisture favour earlier convective initiation and enhance
45 precipitation efficiency (Göbel et al., 2023). In contrast, weak circulations trap air pollutants elevated reservoir layers,
exacerbating nocturnal pollution by limiting ventilation (Miao et al., 2015). Over plateau-basin regions, local circulations co-
existing within the atmospheric boundary layer and free atmosphere can form vertically stacked two-cell structures,
promoting cross-layer interactions and thus complicating their modulations on convective weather and air pollution.
Nevertheless, most existing objective identification methods for local atmospheric circulations rely on near-surface or single-
50 level observations without physical constraints (McCabe and Freedman, 2023; Shen et al., 2022; Yu et al., 2021; Shen et al.,
2026; Li et al., 2020), limiting their capability to resolve vertically stacked two-cell circulation and understand
meteorological and environmental hazards. A physics-constrained framework is therefore urgently required to objectively
detect and quantify circulation vertical structures, advancing our comprehension of hazardous weather and air pollution over
plateau-basin regions.

55 Under global warming, local atmospheric circulations exhibit pronounced long-term variations, which substantially modulate
convective initiation and pollutant dispersion (You et al., 2019; Li et al., 2016). For instance, the frequency of mid-latitude
sea-land breeze generally declines (Xiao et al., 2026; Xiao et al., 2023; Ventura et al., 2026), weakening moisture transport
and convergence lifting, thereby reducing the probability of convective precipitation (Ventura et al., 2026). Similarly, the
60 sea-land breeze over the Pearl River Delta exhibits a decreasing trend in both intensity and duration (Liu et al., 2026b; Liu et
al., 2026a), thereby reducing turbulent mixing and increasing the risk of pollutant accumulation (Liu et al., 2026a).
Collectively, these evidences demonstrate that the long-term changes in the frequency, intensity, and duration of local



atmospheric circulations exert profound impacts on regional weather and environment. Despite these quantitative understanding, the long-term changes in the central height and spatial extent of local circulations remain poorly quantified, especially for the vertically stacked circulations co-existing within the atmospheric boundary layer and free atmosphere over plateau–basin regions. To elucidate how vertical structural variations of local atmospheric circulations modulate convective weather activity and air pollution, systematic quantitative evaluation of the long-term changes in the frequency, intensity, central height, and spatial extent of local circulations is therefore essential.

Taking the Tibetan Plateau–Sichuan Basin (TP–SCB) as a representative plateau–basin region with complex terrain, this study aims to develop a novel physics-constrained framework to objectively identify and quantitatively characterize the vertical structures of diverse local atmospheric circulations within the atmospheric boundary layer and free atmosphere. The framework is constrained by a vertical stream function, diagnosed from the observed zonal (radial) and vertical wind fields, which enables a physically consistent diagnosis of vertically circulating flow. Applying the framework, we extract multi-dimensional features of the vertical structure of local atmospheric circulations, including the frequency, central height, intensity, and spatial extent, and finally quantify their long-term changes. Our findings are expected to provide a paradigm for quantitatively profiling local atmospheric circulations over plateau–basin regions and advance a comprehensive understanding of how terrain-induced circulations modulate weather and environment variability.

2 Data and Methodology

2.1 Data

Hourly ERA5 reanalysis dataset is employed to examine the vertical structure of local atmospheric circulations over the TP–SCB of China during April to September from 1980 to 2022 (Hersbach et al., 2020). In detail, the u - w wind fields at 14:00 and 02:00 Beijing Time (BJT) on each day are selected to objectively identify and quantitatively characterize daytime and nighttime local atmospheric circulations, respectively.

2.2 Vertical Stream Function

According to the circulation theorem and vorticity equation in atmospheric dynamics, the horizontal atmospheric velocity field can be decomposed into non-divergent and irrotational components, where vorticity quantifies rotational motion and divergence characterizes dilatational motion (Holton and Hakim, 2013). For horizontal non-divergent flow, horizontal stream function ψ can be introduced to represent the horizontal purely rotational motion by the following equation (Holton and Hakim, 2013; Bijlsma et al., 1986).

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \nabla^2 \psi \quad (1)$$



where ζ is the vorticity, u represents the zonal component of wind, v represents radial component of wind, and ψ is the horizontal stream function.

95 Local atmospheric circulations are vortical circulations induced by heterogeneous underlying surfaces, which can be analogous to non-divergent flow. Based on the concept of the horizontal stream function that quantitatively describes horizontal atmospheric vortical motions, we construct a vertical stream function ψ' that fully characterizes the zonal-vertical vortical structure composed of the zonal component of wind and vertical velocity. The vertical stream function ψ' is obtained by solving the Poisson equation (Chen and Kuo, 1992).

$$100 \quad \xi = \frac{\partial w}{\partial x} - \frac{\partial u}{\partial z} = \nabla^2 \psi' \quad (2)$$

where ξ is the vorticity of zonal-vertical circulation, w represents the vertical velocity, u represents the zonal component of wind, and ψ' is the vertical stream function.

3 Result

3.1 Overview of the novel identification and characterization framework

105 A framework is developed to objectively identify and quantitatively characterize the vertical structure of local atmospheric circulations. As illustrated in **Fig. 1**, the identification algorithm comprises four steps. First, we calculated the vertical stream function ψ' using hourly ERA5 data. Second, we simultaneously detected the closed centers of ψ' isoline and whether the corresponding wind field satisfies the clockwise or counterclockwise closed-circulation criteria over the TP-SCB. When a ψ' isoline closed centre is detected and the corresponding wind field satisfies the closed-circulation criteria, enclosed centre of ψ' isolines is classified as a valid closed centre. If no ψ' isoline closed centre is identified but the wind field satisfies the closed-circulation criteria, the enclosed centre of u - w wind field is also classified as a valid closed centre. By contrast, no circulation is identified when neither a ψ' isoline closed centre is detected nor the wind field satisfies the closed-circulation criteria. Third, we classified the local atmospheric circulations according to the number of valid closed centres over the TP-SCB. One, two, or three valid closed centres corresponds to one-cell, two-cell, or three-cell local circulations, respectively.

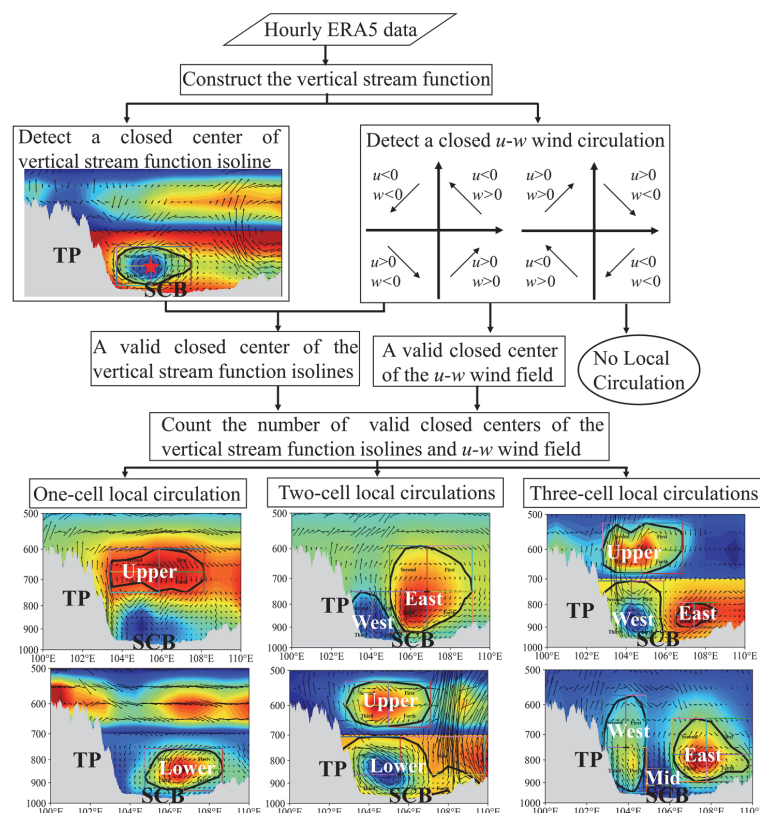


Figure 1. Flowchart of the framework objectively identifying and quantitatively characterizing the local atmospheric circulations. Shaded contours depict the vertical stream function, red pentagrams indicate the circulation centres, and grey shading represents the topography.

Notably, the vertical structures of local atmospheric circulations vary substantially with the locations of their circulation centres. In the fourth step, we further classify these circulations according to their centres' positions. Specifically, one-cell circulations are divided into lower-level and upper-level types, two-cell circulations are categorized into east-west and upper-lower types, and three-cell circulations were classified into upper-east-west and west-mid-east types (Fig. 1). Upper circulations are defined by centres heights ≥ 750 hPa and reside within the free atmosphere, whereas the other circulations with centres heights < 750 hPa are mainly confined within the atmospheric boundary layer. Compared with exiting studies, this objective identification algorithm can comprehensively extract and characterize the spatial structures of one-cell, two-cell, and three-cell local atmospheric circulations. In particular, it enables the simultaneous detection of local circulations in



both the atmospheric boundary layer and free atmosphere, thereby improving our understanding of the complex structures of diverse terrain-induced local circulations.

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To quantitatively characterize diverse local atmospheric circulations, we developed a suit of metrics to describe their vertical structures, including frequency, intensity, spatial extent, and central height (**Table 1**). Specifically, the intensity was measured by the normalized vertical stream function at the centre of a valid closed ψ' isoline or valid closed $u-w$ wind field, the spatial extent was defined by the spatial area of the outermost closed ψ' isoline or outermost $u-w$ wind field boundary, and the central height corresponded to the altitude of these valid closed centres. Overall, the developed framework not only effectively identifies and quantitatively characterizes the diverse vertical structures of one-cell, two-cell, and three-cell local atmospheric circulations, but also offers a new perspective for unravelling how these circulations modulate the initiation, development, and evolution of hazardous weather and air pollution events.

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Table 1

140 Summary of the metrics to characterize local atmospheric circulations

Metric	Unit	Description
Intensity	dimensionless	The vertical stream function corresponding to the valid closed centre of the vertical stream function isoline or $u-w$ wind field after normalization
Spatial extent	km ²	The total impacted area of the outermost closed ψ' isoline or the outermost closed $u-w$ wind field boundary
Central height	m	The altitude of valid closed ψ' isolines centre or valid closed $u-w$ wind field centre

3.2 Vertical structure of local circulations

The vertical structure of local atmospheric circulations, including the intensity, spatial extent, and central height of one-cell, two-cell, and three-cell circulations during both daytime and nighttime are systematically investigated. For the one-cell circulation, it has been categorized into lower-level and upper-level types according to the circulation centre's position (**Fig. 1**). In terms of spatial extent, the upper-level type's one-cell circulation exhibits a pronounced larger average area than the lower-level type during both daytime and nighttime, with neither type showing obvious diurnal variations (**Fig. 2a and Fig. S1a**). Similarly, the upper-level type also exhibits a much higher average central height than the lower-level type during both daytime and nighttime. The upper-level type displays no significant diurnal variation, with average central height of 3034.78 m (daytime) and 2987.68 m (nighttime). Both values exceed the atmospheric boundary layer height, confirming these

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150 circulations reside within the free atmosphere (Ning et al., 2019) (**Fig. 2d and Fig. S1d**). By contrast, the lower-level type shows distinct diurnal differences, with central height decreasing sharply from 1937.9 m at daytime to 1540.95 m at nighttime (**Fig. 2d and Fig. S1d**). Regarding intensity, the lower-level type is consistently stronger than the upper-level type during both daytime and nighttime, and both types exhibit greater intensity in the daytime than at night (**Fig. 2g and Fig. S1g**). These results indicate that the upper-level type's one-cell circulation in the free atmosphere has a larger spatial extent and higher central height than the lower-level type, whereas the lower-level type is more intense and exerts dominant effects within the atmospheric boundary layer, thereby playing a stronger modulation on variations in near-surface weather and air pollution.

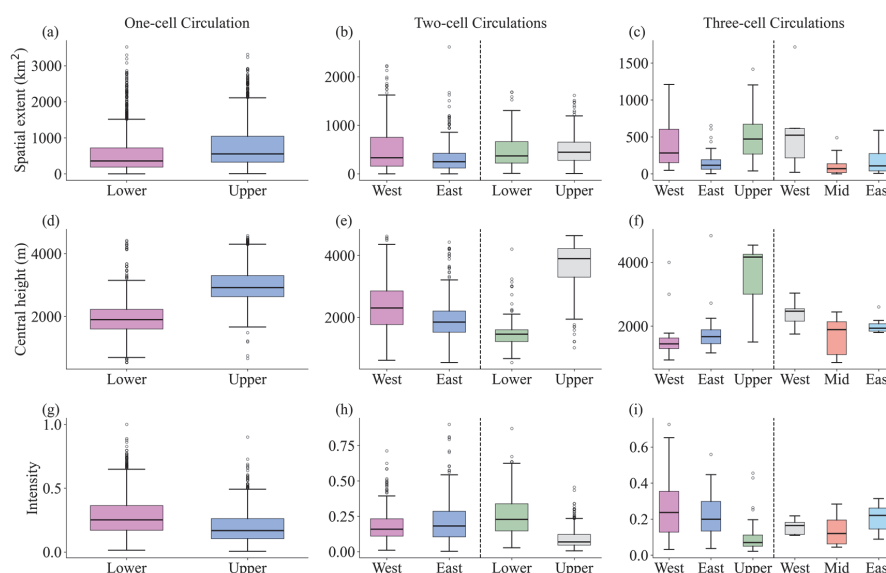


Figure 2. Box plots of the spatial extent, central height, and intensity associated with each circulation among the three types of local atmospheric circulations during the daytime. The boxes and bars represent percentiles (25th (bottom of the box), 50th (median), 75th (top of the box), maximum value (the upper bar), and minimum value (the lower bar)) of the metrics.

Similarly, two-cell circulations are divided into two types, i.e., upper-lower and west-east (**Fig. 1**). In terms of upper-lower type's two-cell circulations, the upper-level circulation has a larger average spatial area than the lower-level circulation during the daytime, while the lower-level circulation occupies a larger average spatial area at nighttime (**Fig. 2b and Fig. S1b**). Specifically, the spatial scale of upper-level circulation declines from 502.78 km² (daytime) to 483.79 km² (nighttime), and the lower-level circulation increases from 470.04 km² to 530.82 km² accordingly (**Fig. 2b and Fig. S1b**). Moreover, the upper circulation shows a much higher average central height, with daytime and nighttime average values of 3721.94 m and



3622.69 m, respectively, compared to 1470.18 m and 1387.21 m for the lower circulation (**Fig. 2e and Fig. S1e**). Both
170 upper-level and lower-level circulations show a slight decrease in central height from daytime to nighttime (**Fig. 2e and Fig. S1e**). Regarding intensity, the upper-level circulation is weaker than the lower-level circulation, and both circulations weaken slightly at night (**Fig. 2h and Fig. S1h**).

In terms of west-east type's two-cell circulations, the average spatial extent of the west circulation is pronouncedly larger
175 than that of east circulation during both daytime and nighttime. The average area of the west circulation decreases substantially from daytime 508.86 km² to nighttime 376.88 km², while that of the east circulation exhibits negligible diurnal changes (**Fig. 2b and Fig. S1b**). Vertically, the west circulation exhibits a higher central height than the east circulation during the daytime, whereas the east circulation is higher than the west circulation at nighttime. In details, the average central height of the west circulation decreases markedly from 2346.37 m during daytime to 1369.39 m at nighttime, while
180 the east circulation remains about 1800 m during both daytime and nighttime (**Fig. 2e and Fig. S1e**). Regarding intensity, the east circulation is stronger than the west circulation during daytime and nighttime. After sunset, the east circulation's intensity rises distinctly, whereas the west circulation weakens (**Fig. 2h and Fig. S1h**). These results highlight that, relative to the lower-level circulation mainly confined within the atmospheric boundary layer, the upper-level circulation residing in the free atmosphere exhibits larger spatial extent during the daytime with persistently higher central height and weaker
185 intensity. For the west-east two-cell circulations, relative to the east cell, the west cell adjacent to the Tibetan Plateau maintains broader spatial extent with weaker intensity and presents higher central height at the daytime.

The three-cell circulations are also divided into two types, i.e., upper-east-west and west-mid-east. In terms of the upper-east-west type's three-cell circulations, the east circulation exhibits the smallest spatial extent, while the upper circulation has
190 the largest area during both daytime and nighttime. At nighttime, the east circulation expands in spatial extent, while the upper circulation contracts, thus reducing their discrepancy in spatial extent (**Fig. 2c and Fig. S1c**). The average central height of the upper circulation exceeds 3600 m during both daytime and nighttime, markedly higher than those of the east and west circulations, and all three circulations show weak diurnal variations in central height (**Fig. 2f and Fig. S1f**). In contrast, the upper circulation exhibits the weakest intensity persisting day and night, while the west and east circulations are
195 the strongest during daytime and nighttime, respectively (**Fig. 2g and Fig. S1g**). In details, the intensity of the west circulation weakens at nighttime, while that of the east circulation remains negligible diurnal changes (**Fig. 2g and Fig. S1g**).

In terms of the west-mid-east type's three-cell circulation, the west circulation has the largest spatial extent and the mid circulation is the smallest during both daytime and nighttime. In details, the average area of the west circulation decreases
200 sharply from 513.93 km² during daytime to 299.05 km² at nighttime, but remains the largest spatial extent (**Fig. 2c and Fig. S1c**). The average central heights of all three circulations are below 2500 m persisting day and night. In details, the west circulations' central heights decrease markedly from daytime to nighttime (**Fig. 2f and Fig. S1f**), while the mid and the east



circulation's central height exhibits negligible diurnal changes. Regarding intensity, all three circulations exhibit obvious diurnal changes, i.e., the daytime intensity are stronger than at nighttime, and the mid (east) circulation is the weakest (strongest) persisting day and night (**Fig. 2g and Fig. S1g**). Overall, all three circulations exhibit distinct diurnal variations in spatial extent, central height, and intensity, and these diurnal variations also differ among circulation cells, highlighting the diversity and complexity of the local atmospheric circulations over the plateau-deep basin region.

3.3 Long-term changes of local circulations vertical structures

We now proceed to investigate the long-term changes associated with multiple metrics of local atmospheric circulations, including the frequency, spatial extent, central height, and intensity. As shown in **Fig. 3**, the long-term changes in the occurrence frequencies of no-circulation, one-cell, two-cells, and three-cells local atmospheric circulations during 1980–2022 exhibit pronounced disparities. In details, the annual total occurrences of no local atmospheric circulation significant decreased at a rate of 3.39 and 4.55 events per decade during daytime and nighttime, respectively (**Fig. 3a and 3e**). On the contrary, the annual total occurrences of two-cell circulations increased significantly during both daytime and nighttime, with trends of 1.55 and 2.65 events per decade, respectively (**Fig. 3c and 3g**). One-cell circulation showed a significant increasing trend only during daytime, increasing by 1.86 events per decade (**Fig. 3b and 3f**). By comparison, no significant trend was detected for three-cell circulations during either daytime and nighttime (**Fig. 3d and 3h**). These results collectively indicate that local atmospheric circulations over the TP-SCB have become more frequent, underscoring their growing role in modulating local weather and environmental conditions.

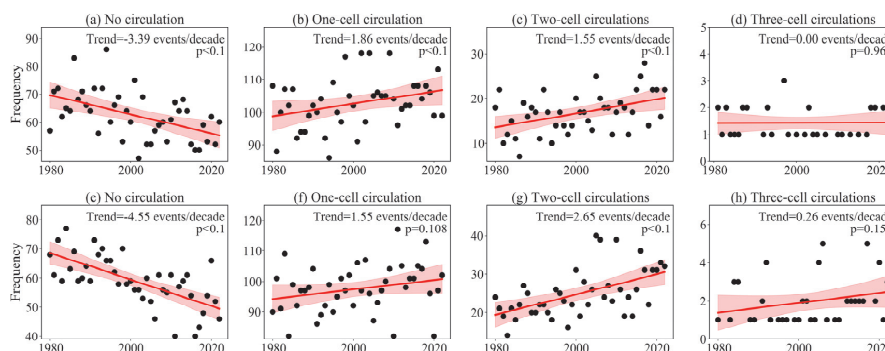


Figure 3. Long-term changes in the frequency of no circulation, one-cell circulation, two-cell circulations, and three-cell circulations. The straight line indicates the corresponding linear trend. The red shading indicates the 95% confidence interval of the fitted line. The estimates of the slope and P values for the trend analysis are given in the upper right corner of each figure. The top row represents daytime local atmospheric circulations, and the bottom row represents nighttime local atmospheric circulations.



Based on the objective identification method, one-cell circulations are classified into upper-level and lower-level types as well as two-cell (three-cell) circulations are divided into upper-lower (upper-east-west) and east-west (west-mid-east) types, including a total of 12 circulation cells in total (**Fig. 1**). We further analysed the long-term changes of all 12 circulation cells in terms of spatial extent, central height, and intensity. For spatial extent, during the daytime, the lower- and upper-level type's one-cell circulation, the east circulation of the east-west type's two-cell circulations, the lower- and upper-lower type's two-cell circulations, and the west circulation of both the upper-east-west and west-mid-east types' three-cell circulations all show significant decreasing trends (**Fig. 4a-g**). At nighttime, notable contraction in spatial extent is also detected in the lower- and upper-level type's one-cell circulation, the east circulation of the east-west type's two-cell circulation, and the lower- and upper-lower type's two-cell circulation (**Fig. S3a-e**).

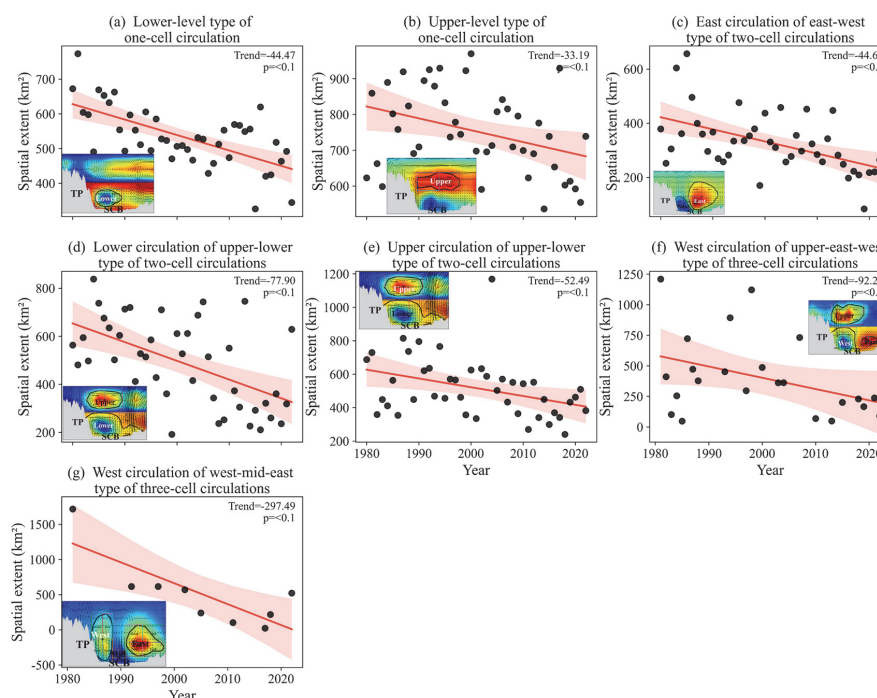


Figure 4. Long-term changes in the spatial extent of each cell of the three types of local atmospheric circulations during the daytime. The straight line indicates the corresponding linear trend. The red shading indicates the 95% confidence interval of the fitted line. The estimates of the slope and P values for the trend analysis are given in the upper right corner of each figure.

In terms of central height, during the daytime, the lower-level types' one-cell circulation and the mid circulation of the west-mid-east type's three-cell circulations exhibit significant increasing trends, while the central height of the upper circulation of



the upper-lower type's two-cell local circulations and the west circulation of the west-mid-east type's three-cell circulations decreases significantly (**Fig. S2a-d**). At nighttime, the central height of the east circulation of the east-west type's two-cell circulations decreases significantly at a rate of -87.96 m per decade (**Fig. S3f**). In terms of intensity, the east circulation of the east-west type's two-cell circulation exhibits pronounced weakening trends during the daytime, whereas the upper-level of the upper-lower type's two-cell circulations and the east circulation of the upper-east-west type's three circulation show obvious increasing trends (**Fig. S2e-g**). In addition, no significant trends are detected in circulation intensity at nighttime. These results suggest that the local atmospheric circulations over the TP-SCB occur more frequently and present smaller areas. Notably, these novel changing features extracted by our developed objective identification and quantitative characterization framework underscore the challenges in refined meteorological and environmental forecasting skills, which, whereas, have not been proposed in previous studies.

4 Conclusions and Discussion

In this study, we develop a novel physics-constrained framework to objectively identify and quantitatively characterize the vertical structures of local atmospheric circulations. Applying over the TP-SCB, the framework newly identifies three typical patterns of local atmospheric circulation, i.e., one-cell, two-cell, and three-cell circulations and further enables vertically resolved profiling of their key structural attributes including intensity, spatial extent, and central height. Particularly for two- and three-cell circulations, local circulations co-existing within the atmospheric boundary layer and free atmosphere form a vertically stacked two-cell structure. Quantitative assessment of long-term changes in both the occurrence frequency and structural attributes of the three typical circulations indicates that local atmospheric circulations over the TP-SCB are becoming more frequent, while their spatial extent contracts. These findings fill a methodological gap in quantifying the vertical structure of local atmospheric circulations. They yield provide new insight into how terrain-forced boundary-layer and free-atmosphere circulations jointly modulate regional hazardous weather and air pollution, while delivering a practical diagnostic tool with strong potential for operational forecasting over plateau-basin regions.

Most existing studies have emphasized the horizontal characteristics of local atmospheric circulations (Xiao et al., 2023), whereas objective identifications of their vertical structures remain limited. The key limitation is that existing objective identification methods primarily rely on near-surface observations or single-level meteorological data and lack physical constraints, which makes fail to capture vertical structures and distinguish circulations co-existing within the atmospheric boundary layer and free atmosphere (McCabe and Freedman, 2023; Bedoya-Valestt et al., 2023; Prtenjak and Grisogono, 2007; Azorin-Molina and Lopez-Bustins, 2008; Cao et al., 2025; Vergeiner and Dreiseitl, 1987; Zhang et al., 2023). In contrast, we develop a novel framework that constructs vertical stream function ψ' based on atmospheric dynamical constraints, and identify circulation cell numbers and spatial positions by detecting closed centres of ψ' and $u-w$ wind fields. This improved framework can robustly discriminate circulation mainly within the atmospheric boundary layer and



275 circulation residing in the free atmosphere, thereby providing a physically consistent basis for diagnosing vertically stacked
two-cell structures and yielding new insights for interactions between the atmospheric boundary layer and free atmosphere.

Notably, the vertical height and spatial extent of local atmospheric circulations have been demonstrated to exert substantial
impacts on deep-convection initiation and air pollutant dispersion, thereby modulating the severity of hazardous weather and
280 air pollution (Ning et al., 2019; Göbel et al., 2023). Nevertheless, existing findings are mostly restricted to valley-mountain
and sea-land breeze circulations within the atmospheric boundary layer. In contrast, our study reveals that the local
atmospheric circulations occur not only within the atmospheric boundary layer but also in the free atmosphere over plateau-
basin regions, and can co-exist to form vertically stacked two-cell or three-cell circulations. These results demonstrate the
inherent complexity of vertical structures for plateau-basin local circulations, underscoring the necessity of further
285 investigating their hazardous weather and environment impacts from the perspective of boundary-layer-free-atmosphere
interactions. Furthermore, quantitative assessments of the vertical structures and related impacts remain scarce. To address
this gap, we quantitatively profile the vertical structures of local circulations including spatial extent, central height, and
intensity. By precisely evaluating the horizontal locations of the local circulation's ascending and descending branches and
quantifying their vertical influence range, our findings provide a practical quantitative basis for further diagnosing the
290 capabilities of convective triggering and air-pollutant dispersion, thereby improving forecast skills for hazardous weather
and air pollution over complex terrain.

Additionally, long-term changes in the characteristics of local atmospheric circulations substantially modulate variations in
convective initiation and air pollutant dispersion (Fan et al., 2020; Kim et al., 2021). Existing studies indicate that the
295 frequency and intensity of sea-land breeze have declined, contributing to more frequent air pollution and reduced convective
precipitation (Xiao et al., 2023; Ventura et al., 2026). However, long-term changes in the spatial extent and central height of
local atmospheric circulation remain poorly quantified. Our findings further reveal that local atmospheric circulations within
the atmospheric boundary layer and free atmosphere are becoming more frequent, while their spatial extent contract. This
implies that both convective triggering and air pollutant accumulation become increasingly localized, complicating accurate
300 forecasting of convective weather and air pollution. These long-term changes also likely reflect climate-driven modifications
to the underlying thermal forcing and atmospheric stability in the lower troposphere, which alter the spatial scale and vertical
placement of associated local circulations. Importantly, our findings provide transferable guidance for improving hazardous
weather and environment forecasts in other plateau-basin regions with frequent local atmospheric circulations, including the
Rocky Mountains (Adler et al., 2025), Tarim Basin (Wang et al., 2019), and Salt Lake City Basin (Blaylock et al., 2017).

305 **Data availability**

The ERA5 reanalysis data are available at <https://cds.climate.copernicus.eu/datasets>.



Author contributions

GCN conceived the study, conducted the majority of the data analyses, developed the foundational framework, and wrote and revised the manuscript. XDX conceived and supervised the study. JYX participated in the development of framework and statistical analyses. TLZ, SGW, and YJY assisted in supervising and revising the manuscript.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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