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Key Points:

- 356-m Meteorological Tower observations reveal an anomalous time-evolving counterclockwise wind turning across the lower boundary layer
- The counterclockwise turning transitions to clockwise turning aloft, with regionally varying transition heights
- Enhanced turbulent vertical mixing associated with urbanization elevates the transition height relative to less urbanized regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Anomalous Counterclockwise Turning of the Boundary-Layer Winds Revealed by Observations From the 356-m Shenzhen Meteorological Tower

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Abstract Boundary-layer winds strongly impact heavy rainfall through low-level convergence, moisture transport, and vertical wind shear. Using high-resolution observations from the 356-m Shenzhen Meteorological Tower, together with ERA5 reanalysis and semi-idealized numerical experiments, this study investigates the vertical structure and diurnal variation of boundary-layer winds during April–June 2018–2020. Observations reveal an anomalous counterclockwise (CCW) wind turning with time throughout all tower levels, contrasting with the clockwise (CW) inertial oscillations typical of the Northern Hemisphere. ERA5 analysis further shows that this CCW turning gradually transitions to CW turning within the 975–925 hPa layer, forming a distinct vertical CCW-to-CW mode. Numerical experiments demonstrate that turbulent vertical mixing governs the vertical scale of this mode. Consequently, spatial heterogeneity in urbanization and land-use types leads to pronounced regional differences in the transition height. These findings provide new observational evidence of deep CCW wind turning in an urbanized coastal environment.

Plain Language Summary Winds in the lower atmosphere change direction and speed over the course of a day, and these variations strongly affect rainfall and storm development. Using detailed wind measurements from a 356-m-high meteorological tower in Shenzhen, China, we identify an unexpected daily behavior: instead of clockwise rotating with time as typically expected due to the Earth's rotation, winds near the ground rotate counterclockwise. Remarkably, this unusual rotation extends much higher than previously observed in other places. By combining tower observations with atmospheric reanalysis and numerical model experiments, we show that this counterclockwise rotation gradually transitions to the normal clockwise rotation at higher altitudes. The height of this transition varies regionally and is significantly higher over large urban areas. Our results indicate that urbanization strengthens turbulent air mixing near the surface, allowing surface friction to influence winds at greater heights. This study highlights how cities can modify diurnal wind patterns and improves our understanding of weather processes in coastal urban regions.

1. Introduction

The structure and evolution of boundary-layer winds play a significant role in convection and precipitation. In particular, strong boundary-layer winds, commonly referred to as boundary-layer jets, enhance low-level moisture and momentum transport, thereby providing favorable thermodynamic and dynamic conditions for strong convective development (e.g., Du & Chen, 2019a, 2019b; Du et al., 2022; Stensrud, 1996). Vertical wind shear within the boundary layer further modulates the organization and longevity of convective storms (e.g., Mulholland et al., 2024; Peters et al., 2022; Thompson et al., 2007). Beyond these primary drivers, interactions between boundary-layer winds and cold pools can regulate the maintenance and upscale growth of convective systems (e.g., Bryan et al., 2006; Fu et al., 2025; Luiz & Fiedler, 2023). In addition, local circulations such as land-sea and mountain-valley breezes interact with the background boundary-layer flow to induce low-level convergence, thereby influencing the initiation and propagation of convective cells (e.g., Eigenmann et al., 2009; Fang & Du, 2022; Miao & Yang, 2020).

The diurnal cycle of boundary-layer winds is a fundamental and widely documented atmospheric phenomenon, driven by both thermal and dynamic processes. Two classical theories have been proposed to explain this diurnal variability. One emphasizes the role of diurnally varying boundary-layer friction (Blackadar, 1957), while the

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other focuses on diurnal thermal forcing over sloping terrain (Holton, 1967). The former, known as the “Blackadar mechanism,” highlights the dynamical response of winds to the diurnal evolution of turbulent vertical mixing in the boundary layer. During daytime, enhanced turbulent mixing couples boundary-layer winds to surface friction, whereas after sunset, the rapid reduction of turbulent stress leads to an inertial oscillation of the decoupled flow within the stable boundary layer (Blackadar, 1957). The latter, the “Holton mechanism,” describes the influence of diurnally varying thermal forcing on pressure gradients and associated ageostrophic circulations. Daytime solar heating and nighttime radiative cooling over sloping surfaces induce diurnal oscillations in the horizontal pressure gradient force, producing corresponding variations in wind speed and direction (Holton, 1967). Together, these two mechanisms are widely regarded as key contributions to the formation of nocturnal low-level jets (e.g., Du & Rotunno, 2014; Parish & Oolman, 2010).

As a consequence of the diurnal variation in boundary-layer winds, wind hodographs typically exhibit a rotational evolution with time. Under idealized conditions, this rotation is commonly attributed to the Coriolis force acting on an inertially oscillating flow following the reduction of turbulent stress after sunset (Blackadar, 1957). In the Northern Hemisphere, such hodographs are therefore expected to rotate clockwise (CW) with time (e.g., Shapiro et al., 2016). However, both observations (e.g., Bluestein et al., 2018; Moisseeva & Steyn, 2014; Sakazaki & Fujiwara, 2008) and numerical studies (e.g., Rotunno et al., 2018; Steyn & Kallos, 1992) have revealed that this theoretical expectation is not universally satisfied near the surface. In many regions, counterclockwise (CCW) rotation of surface wind hodographs has been documented, indicating departures from the idealized inertial oscillation framework.

Previous studies have attributed this anomalous CCW turning of near-surface wind to the combined effects of the Blackadar and Holton mechanisms (e.g., Bluestein et al., 2018; Rotunno et al., 2018). For instance, Bluestein et al. (2018) found that wind hodographs derived from 10-m observations in the southern Great Plains of the United States exhibit CCW turning, a feature also reproduced in mesoscale numerical model forecasts. In contrast, hodographs at levels above the surface tend to show the expected CW rotation. Further diagnosis indicated the contrasting impacts of turbulent vertical mixing on winds at different heights during the diurnal cycle are central to this behavior. During daytime, strong turbulent mixing transfers momentum downward, decelerating winds aloft while accelerating near-surface flow. After sunset, the rapid collapse of turbulent mixing weakens downward momentum transport, allowing winds aloft to accelerate as the drag from below weakens, whereas near-surface winds decelerate under persistent surface drag. This asymmetric response leads to opposite turning tendencies. Although the Blackadar mechanism primarily governs the meridional oscillation of wind perturbations under a predominant southerly background flow, meridional oscillations alone are insufficient to produce a sustained rotation. In contrast, the zonal wind component exhibits a strong dependence on terrain slope, highlighting the role of the Holton mechanism. Diurnally varying thermal forcing over sloping terrain induces oscillations in the horizontal pressure-gradient force, generating zonal wind response whose amplitudes increase with slope. These processes explain the observed CCW turning of near-surface winds as the superposition of frictionally driven meridional oscillations and thermally driven zonal oscillations. Notably, the CCW turning near the surface is not driven by the CW rotation aloft. Instead, different vertical layers respond to the same diurnal evolution of boundary-layer mixing and surface friction, resulting in height-dependent phase structures of wind oscillations.

Despite increasing evidence for anomalous CCW turning of near-surface wind hodographs, the vertical structure of this phenomenon remains poorly documented. Most previous studies have largely relied on surface wind observations (e.g., Bluestein et al., 2018; Moisseeva & Steyn, 2014; Sakazaki & Fujiwara, 2008), limiting our understanding of how diurnal boundary-layer wind turning varies with height. In this study, we address this gap using high-vertical-resolution wind measurements from a 356-m-high meteorological tower in Shenzhen. These observations enable us to characterize the vertical structure of diurnal boundary-layer wind turning and to examine whether the transition from CCW to CW rotation occurs within or above the observational range of the tower.

2. Data and Methods

2.1. Data

The study utilizes wind observations obtained from a 356-m meteorological gradient tower in Shenzhen, South China (113.89°E, 22.66°N), within the Pearl River Delta (PRD) area. As the tallest meteorological gradient tower

in Asia and the second tallest worldwide, the tower provides a unique platform for high-resolution vertical observations of the lower atmosphere and has been widely used in boundary-layer studies (e.g., Fu et al., 2025; He et al., 2022; Mai et al., 2025).

We analyze wind speed and direction measured at 13 vertical levels of 10, 20, 40, 50, 80, 100, 150, 160, 200, 250, 300, 320, and 350 m above ground level (AGL), spanning the period from April to June during 2018–2020. The observations have a temporal resolution of 5 min, allowing detailed depiction of the diurnal variation and vertical structure of boundary-layer winds.

To supplement observations above the tower, we additionally employ the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) global climate atmospheric reanalysis, ERA5, for the same period. ERA5 has a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and an hourly temporal resolution, and has been widely used in studies of boundary-layer winds (e.g., Chen et al., 2021; Du, 2023; Lima et al., 2022).

All data sets are analyzed in terms of diurnal anomalies, obtained by removing the climatological hourly mean at each vertical level or grid point. This approach effectively filters out migratory synoptic-scale disturbances and transient mesoscale disturbances, thereby isolating the diurnal component of boundary-layer winds relevant to this study.

2.2. Numerical Simulation Setup

Numerical simulations were conducted using the Weather Research and Forecasting (WRF) Model, version 4.2 (Skamarock et al., 2019). The model was configured with a single domain at a horizontal spacing of 4 km and no nesting. A vertically stretched grid with 54 levels was employed, with finer grid spacing within the boundary layer, and the model top was set at 50 hPa.

The Thompson aerosol-aware microphysics scheme (G. Thompson & Eidhammer, 2014) was used, together with the Yonsei University (YSU) planetary boundary layer scheme (Hong & Pan, 1996) to represent subgrid-scale vertical turbulent eddy mixing. This configuration has been demonstrated to perform well in simulating boundary-layer processes over South China (e.g., Du et al., 2021; Shen & Du, 2023; Yang et al., 2024). Radiative processes were simulated using the Rapid Radiative Transfer Model for Global Climate Models (RRTMG) longwave and shortwave radiation schemes (Iacono et al., 2008). The land surface processes were characterized using the unified Noah land surface model (Ek et al., 2003), coupled with the revised MM5 Monin–Obukhov surface-layer scheme (Chen & Dudhia, 2001). No cumulus parameterization scheme was adopted in this study.

To isolate the diurnal variation of boundary-layer winds, we conducted semi-idealized diurnal experiments following Chen and Du (2024). Initial and lateral boundary conditions for the numerical simulations were provided by the final operational global analysis data from the Global Forecasting System of National Centers for Environment Prediction (NCEP-FNL), available every 6 hr at a $1^\circ \times 1^\circ$ horizontal resolution. The simulations were initialized using the mean of the 0000 UTC NCEP-FNL fields averaged from each day of June 2020. Diurnally cyclic lateral boundary conditions were constructed from composite diurnal means for the same month. All meteorological input variables used in the diurnally repeating boundary conditions were derived from NCEP-FNL averages.

Each simulation spanned 30 days, with the first 20 days discarded as spin-up. Analysis was performed using the final 10 days of hourly model output, which were compared with tower observations and ERA5 reanalysis to examine the diurnal variation of boundary-layer winds.

To isolate the influence of urbanization on the vertical structure and diurnal variation of boundary-layer winds, two experiments were performed: a control run (Ctrl), which retains realistic land-use categories, and a sensitivity experiment (No-Urban), whereas all land surfaces were replaced with cropland to suppress land-use heterogeneity.

2.3. Measurement of Wind Turning

To quantify the rotation sense of wind hodographs, we introduce a rotation metric based on the vector cross product of perturbation winds at adjacent time steps. For two successive wind vectors $V_i = (u_i, v_i)$ and $V_{i+1} = (u_{i+1}, v_{i+1})$, the rotation measure is defined as

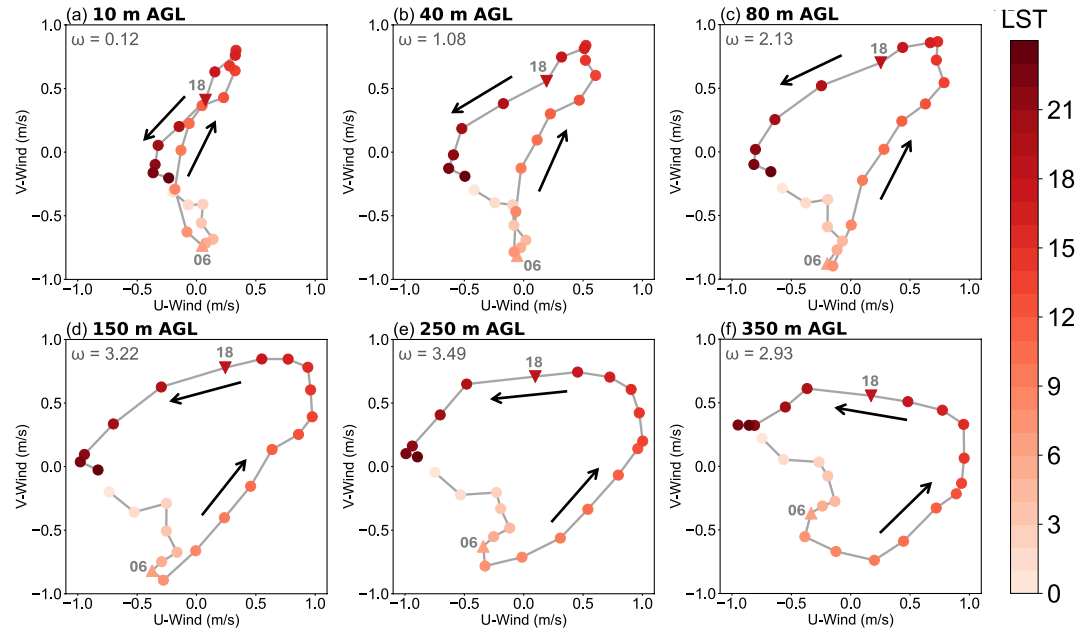


Figure 1. Diurnal variation (local standard time [LST]) of perturbation wind hodographs at six levels of the Shenzhen meteorological tower: (a) 10 m AGL, (b) 40 m AGL, (c) 80 m AGL, (d) 150 m AGL, (e) 250 m AGL, and (f) 350 m AGL. Hodographs are averaged over April–June for the period 2018–2020. Upright triangles denote wind vectors near sunrise (0600 LST), while inverted triangles denote sunset (1800 LST). Black arrows indicate the sense of hodograph rotation with time. The rotation metric ω is shown in the upper-left corner of each panel.

$$\omega_i = \mathbf{V}_i \times \mathbf{V}_{i+1} = u_i v_{i+1} - v_i u_{i+1} \quad (1)$$

where the sign of ω_i (with units of $\text{m}^2 \text{s}^{-2}$) directly reflects the rotation direction determined by the vector cross product following the right-hand rule (Figure S1 in Supporting Information S1): positive (negative) values denote CCW (CW) turning. To obtain an overall net rotation over the full diurnal cycle, we define a cumulative rotation metric as

$$\omega = \sum_{i=0}^{N-2} \omega_i \quad (2)$$

where $N = 24$ denotes the number of hourly time steps. Here, $\omega > 0$ indicates net CCW rotation, $\omega < 0$ indicates net CW rotation, and ω near zero (−1 to 1) implies an ambiguous or weak rotation sense. In this study, the wind-turning transition height is defined as the lowest height where ω changes from positive to −1.

3. Observations of the CCW Turning

Figure 1 shows the diurnal evolution of perturbation wind hodographs at six representative heights of the Shenzhen meteorological tower, averaged over April–June during 2018–2020. At all observed levels, the hodographs exhibit a clear anomalous CCW rotation with time, with the corresponding rotation metric ω being positive throughout the tower. Notably, this CCW turning is not confined to the near-surface layer but persists throughout the tower profile, extending up to at least 350 m AGL. This behavior contrasts with previous observational studies (e.g., Bluestein et al., 2018; Rotunno et al., 2018), which reported CCW turning primarily near the surface (<100 m AGL) and CW rotation aloft.

The vertical structure of the hodographs reveals a pronounced height dependence of the dominant wind oscillation components. At lower levels, perturbation winds are characterized primarily by meridional oscillations, whereas the amplitude of the zonal oscillation increases progressively with height. This transition indicates that near-surface diurnal wind variability is largely meridional, while zonal variability becomes increasingly important

aloft. Notably, the lowest level (Figure 1a) exhibits a relatively small rotation metric ($\omega \approx 0.12$), indicating weak CCW turning, whereas ω exceeds 1 at all higher levels. This weak rotation near the surface is associated with the reduced amplitude of the zonal wind component at the lower levels, which limits the development of a more complete diurnal rotation in the hodograph.

Despite the greater vertical extent of CCW turning relative to previous studies (e.g., Bluestein et al., 2018; Rotunno et al., 2018), the observed hodograph behavior remains broadly consistent with the combined effects of the Blackadar and Holton mechanisms. The Shenzhen meteorological tower is located in coastal South China, a region frequently influenced by nocturnal low-level jets during the warm season (e.g., Du & Chen, 2019a; Du et al., 2022; Li & Du, 2021), implying strong diurnal modulation of boundary-layer turbulent vertical mixing. Such conditions favor strong frictional adjustment following sunset, providing a dynamical basis for the meridional wind oscillations observed near the surface.

Consistent with this interpretation, wind speeds at lower levels decrease rapidly around sunset (approximately 1800 LST) and increase sharply near sunrise (approximately 0600 LST), reflecting the boundary-layer decoupling and subsequent recoupling with the surface. Friction acting on the wind can be regarded as two components: one associated with turbulent vertical mixing and the other associated with direct surface drag. While surface drag always acts to reduce wind speed, the contribution from turbulent mixing can either accelerate or decelerate the flow and induce directional changes, depending on the magnitude and direction of the vertical wind shear. After sunset, the rapid collapse of turbulent mixing sharply reduces the vertical exchange of momentum, diminishing downward momentum transfer from aloft. As a result, near-surface winds experience rapid deceleration, whereas winds aloft may accelerate due to reduced eddy stress from below. After sunrise, renewed turbulent mixing enhances vertical momentum exchange, strengthening the drag exerted by faster-moving air aloft and allowing near-surface flow to accelerate rapidly. This vertical contrast explains why the acceleration and deceleration of the meridional wind around sunrise and sunset are strongest at the lowest tower level (Figure 1a) and weaken progressively with height, with post-sunset deceleration becoming much less pronounced aloft (Figure 1f).

In contrast, the enhancement of zonal wind oscillations with height suggests an increasing influence of thermally driven processes away from the surface. Large-scale east–west thermal contrasts associated with the Chinese mainland to the west and the Pacific Ocean to the east, favor a diurnally varying pressure-gradient forcing, consistent with the Holton mechanism (e.g., Du & Yi, 2025). As frictional effects diminish with height, the zonal response becomes more prominent, resulting in more rounded hodographs at higher levels. Although the meridional wind exhibits a diurnal signal that may resemble a local sea-land breeze in phase, its evolution is primarily governed by Blackadar-type inertial adjustment associated with the diurnal modulation of boundary-layer mixing, rather than an independently forced north–south thermal circulation.

Overall, the CCW turning observed at the Shenzhen tower shares key similarities with that reported over the southern Great Plains of the United States (Bluestein et al., 2018), but exhibits a substantially greater vertical extent. This suggests that, in this region, frictional adjustment following boundary-layer decoupling may influence a deeper layer than previously documented.

4. Transition From CCW to CW

According to the mechanism proposed in Section 3, the anomalous CCW turning of wind hodographs cannot extend uniformly through the entire boundary layer. Instead, a transition from CCW to CW rotation is expected at a certain height, above which the influence of surface friction and turbulent adjustment weakens and inertial oscillations become dominant. Figure 2 further examines the vertical transition from CCW to CW turning using both ERA5 reanalysis and WRF-Ctrl results.

The ERA5 reanalysis (Figures 2a–2d) shows that anomalous CCW rotation of perturbation wind hodographs can also be identified at the tower location. At 1,000 hPa (Figure 2a) and 975 hPa (Figure 2b), the hodographs with positive ω exhibit a clear CCW turning with time of day, consistent with the tower observations presented in Section 3. With increasing height, however, the rotation sense gradually changes. At 950 hPa (Figure 2c), the hodograph displays mixed behavior, characterized by the coexistence of CCW and CW turning during different phases of the diurnal cycle, indicative of a transition regime. This is also reflected by the rotation metric ω changing sign from positive to negative at this level, indicating a transition in the dominant rotation sense. By 925 hPa (Figure 2d), the hodograph with large negative ω completes the transition and exhibits a pronounced CW

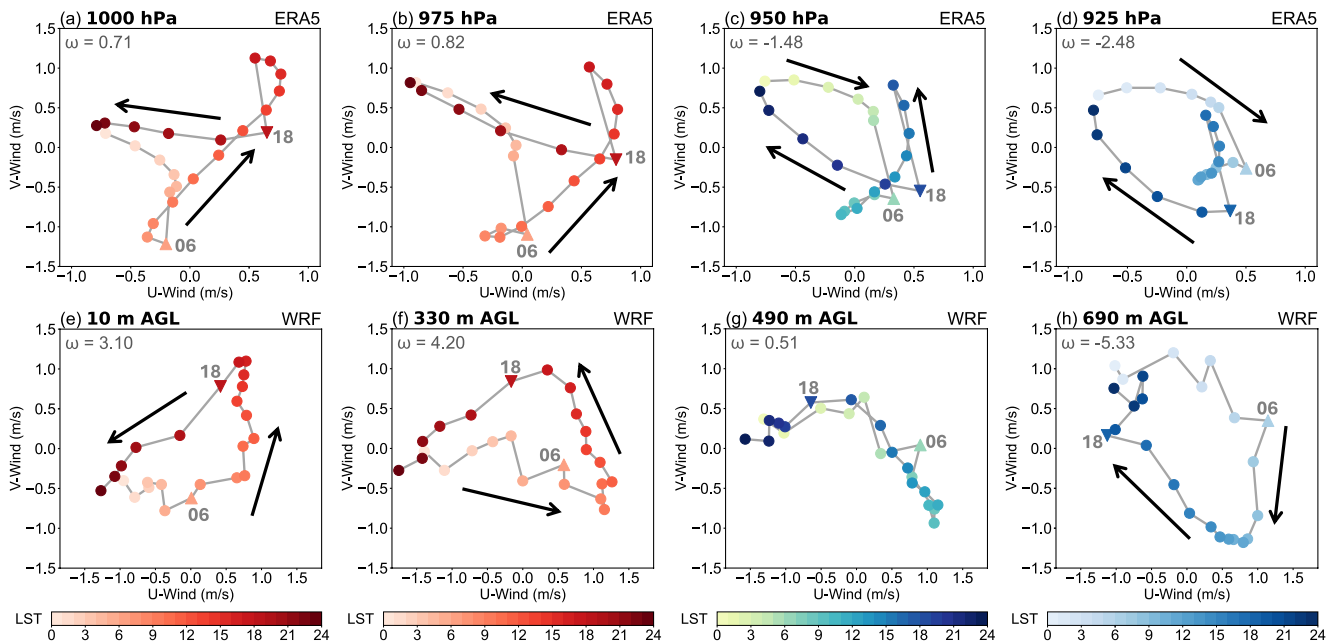


Figure 2. As in Figure 1, but for (a–d) ERA5 winds at 1,000, 975, 950, and 925 hPa, and (e–h) WRF-Ctrl simulations at 10, 330, 490, and 690 m AGL.

rotation, consistent with the typical inertial turning expected above the surface-influenced layer. These results suggest that the anomalous CCW turning is confined to a shallow near-surface layer, approximately below 500–800 m AGL, while the flow above undergoes conventional CW rotation, forming a distinct CCW-to-CW vertical mode.

The WRF-Ctrl simulations (Figure 2e–2h) further confirm this vertical transition, benefiting from their finer vertical resolution. At 10 m (Figure 2e) and 330 m AGL (Figure 2f), the hodograph with large positive ω exhibits a pronounced CCW rotation throughout the diurnal cycle. At 490 m AGL (Figure 2g), the hodograph enters a clear transition regime, in which the rotation sense is ambiguous, accompanied by a reduced ω ($|\omega| < 1$). Above this level, for example, at 690 m AGL (Figure 2h), the hodograph is dominated by CW turning, which becomes increasingly well-defined with height.

We note that the diagnosed transition height differs slightly between ERA5 and WRF-Ctrl, mainly due to differences in vertical resolution and coordinate systems (pressure levels in ERA5 vs. terrain-following coordinates in WRF). ERA5 is therefore not used to precisely diagnose the transition height, but rather to confirm the robustness of the overall vertical structure. Despite quantitative differences, both data sets consistently capture the transition from CCW rotation in the lower layer to CW rotation aloft and place the transition height near 500 m AGL.

The ERA5 and WRF-Ctrl results further supports the physical interpretation proposed in Section 3. At lower levels (Figures 2a and 2e), wind speeds decrease rapidly after sunset and increase sharply near sunrise, consistent with tower observations. In contrast, perturbation winds aloft (Figures 2d and 2h) exhibits the opposite diurnal behavior: wind speeds increase rapidly after sunset as the boundary layer decouples from surface friction and decrease after sunrise as turbulent mixing redevelops and downward momentum transfer is restored. This opposite diurnal response between the near-surface layer and the flow above the transition height provides strong evidence that the CCW-to-CW transition is fundamentally controlled by the vertical structure of frictional and turbulent processes within the boundary layer.

5. Mechanism of the CCW-to-CW Vertical Mode

To further clarify the physical mechanisms responsible for the CCW-to-CW vertical mode identified in Section 4, Figure 3, based on the WRF-Ctrl simulations, examines the horizontal and vertical structure of perturbation winds and their diurnal variation over both land and sea. Figure 3a presents a pronounced land–sea contrast of

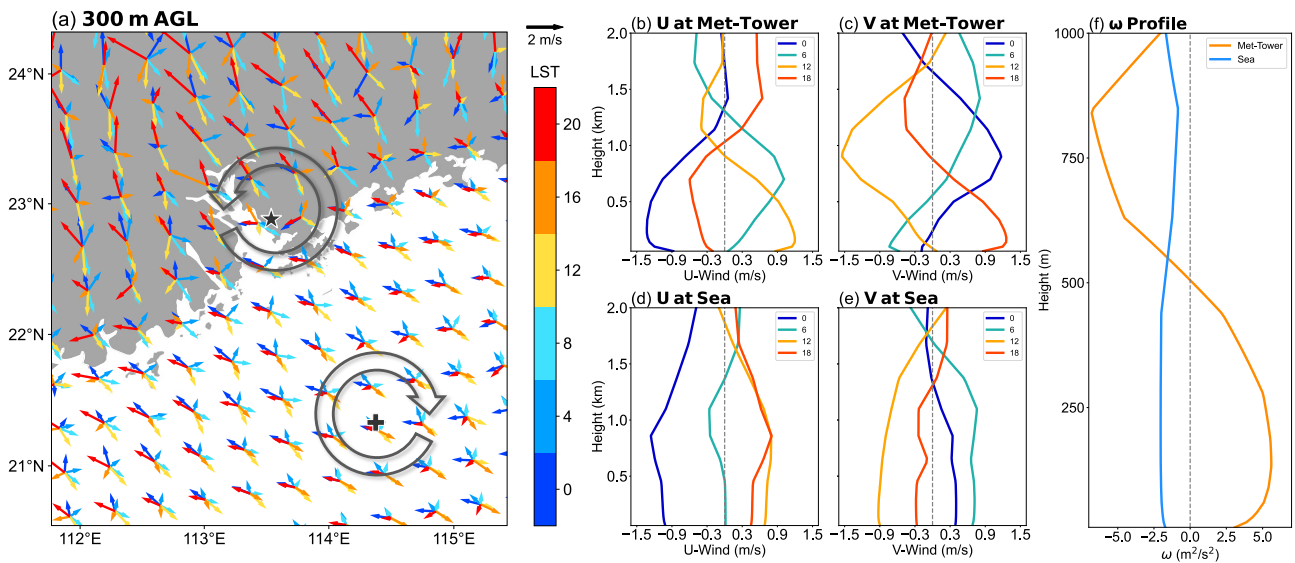


Figure 3. Horizontal and vertical structure of perturbation winds and their diurnal variation from WRF-Ctrl. (a) Perturbation wind vectors every 4 hr at 300 m AGL, with local standard time indicated by the color scale. Circular arrows indicate the sense of hodograph rotation with time. Shading denotes land areas. Vertical profiles of the (b) zonal (u) and (c) meridional (v) components of perturbation wind (abscissa) as functions of height (ordinate) and time (represented by four colors) at the Shenzhen meteorological tower (marked by the black star in [a]). (d, e) As in (b, c), but for the offshore location (114.5°E, 21°N), marked by the black plus in (a). (f) Vertical profiles of the rotation metric ω for the tower and offshore locations.

perturbation wind vectors at 300 m AGL. Over the ocean, perturbation winds exhibit a spatially coherent and temporally regular CW turning, with wind directions being nearly uniform across the region at any given time. This behavior is consistent with an inertial response under weak surface drag and turbulent mixing. In contrast, perturbation winds over land display more heterogeneous diurnal behavior. Near the Shenzhen meteorological tower, wind vectors show a clear CCW turning, while over much of the inland region the rotation sense is mixed and ambiguous, with both CCW and CW features appearing during different phases of the diurnal cycle. In addition, the perturbation wind speeds over land are generally larger than over the ocean, reflecting enhanced turbulent mixing on land, which amplify the diurnal variation of winds.

The vertical structure of these land–sea contrasts is demonstrated by the perturbation wind (Figures 3b–3e) and ω (Figure 3f) profiles. Below 2 km AGL, land-based profiles (Figures 3b and 3c) exhibit a strong vertical shear, indicating markedly different diurnal responses between lower and upper levels. Specifically, periods of acceleration aloft are accompanied by deceleration near the surface, and vice versa, producing a strongly curved wind profile. This behavior contrasts with the offshore profiles (Figures 3d and 3e), where winds at different heights vary almost in phase, yielding almost vertically aligned wind profiles indicative of weak surface drag and turbulent mixing. Consistently, Figure 3f shows that ω over the tower varies strongly with height, transitioning from positive to negative values. This pattern indicates a shift from CCW turning near the surface to CW turning aloft, with the transition ($\omega = 0$) occurring near 500 m AGL. In contrast, ω over the sea remains negative at all heights, suggesting persistent CW rotation throughout the boundary layer. In addition, to ensure the robustness of the WRF results, the corresponding horizontal and vertical structures of perturbation winds from ERA5 are also analyzed (Figure S2 and Text S1 in Supporting Information S1), which show good qualitative agreement with the WRF-Ctrl simulations.

As discussed in Section 3, the zonal wind component over land (Figure 3b) exhibits a clear thermally forced oscillation. At 0600 and 1200 LST, westerly perturbations strengthen below 1 km, and as daytime turbulent mixing intensifies, the level of maximum wind gradually descends toward the surface, reflecting enhanced downward momentum transport. After sunset (1800 and 0000 LST), the zonal perturbation reverses sign and the near-surface zonal wind decelerates, with the strongest deceleration occurring around midnight. Meanwhile, the meridional perturbation (Figure 3c), superimposed on a prevailing southerly background flow in this region, exhibits a diurnal variation strongly tied to the strength of vertical mixing. Near sunrise (0600 LST), southerly acceleration aloft coincides with southerly deceleration near the surface, indicating weak vertical coupling. By

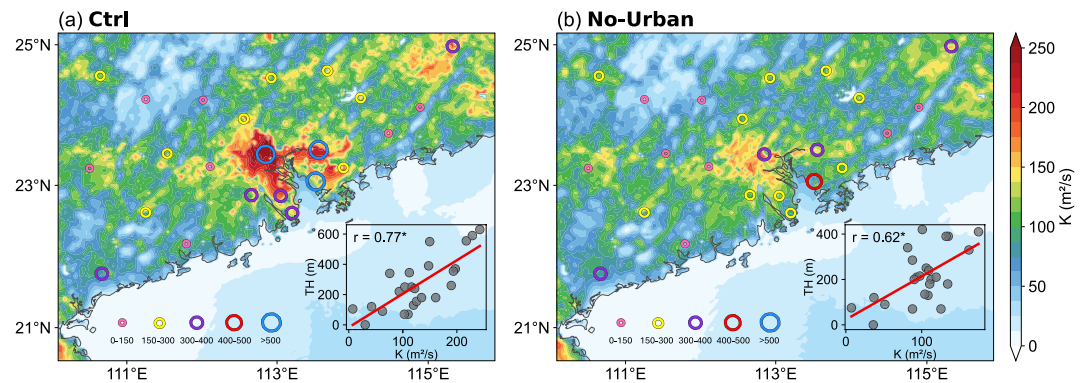


Figure 4. Horizontal distribution of the turbulent exchange coefficient (shading, K) at the 8th model level (~ 288 m) and the CCW-to-CW transition height for (a) Ctrl and (b) No-Urban experiments. Circles of varying sizes and colors indicate the transition heights: pink for 0–150 m AGL, yellow for 150–300 m AGL, purple for 300–400 m AGL, red for 400–500 m AGL, and blue for >500 m AGL. Insets in the lower right corner of each panel depict the relationship between transition height and K , with the red line representing the linear regression. The correlation coefficient (r) is shown in the upper left of each panel, and all correlations are statistically significant (* indicates $p < 0.05$).

midday (1200 LST), strong vertical mixing produces a pronounced southerly deceleration near 1 km that weakens toward the surface, while near-surface winds begin to accelerate northward. As turbulent mixing continues to intensify, near-surface southerly acceleration becomes increasingly prominent (1800 LST). At midnight (0000 LST), when turbulent mixing collapses, strong southerly acceleration develops near 1 km while near-surface winds decelerate southward, consistent with the climatological behavior of nocturnal low-level jets.

As shown in Figure 3, the anomalous CCW turning is not confined to the Shenzhen tower but appears across broader coastal land regions. Motivated by this result, WRF-Ctrl simulations are used to examine the spatial variability of diurnal perturbation winds over a broader area surrounding the tower. The results indicate that the CCW-to-CW transition height exhibits substantial spatial heterogeneity (Figure 4a), with higher values concentrated over the PRD and lower values dominating surrounding areas.

In the boundary layer, the turbulent eddy stress can be approximated as $K\partial V/\partial z$, where K is the time-varying turbulent exchange coefficient that depends on the static stability and vertical shear. Previous studies (e.g., Bluestein et al., 2018; Rotunno et al., 2018) have indicated that the vertical extent of CCW turning is roughly the nighttime Ekman depth $\sqrt{K/2f}$. This implies that stronger turbulent mixing can extend the vertical influence of frictional adjustment to higher levels. To quantify the role of turbulent vertical mixing, we further analyze K , and indicate that an expected clear positive relationship ($r = 0.77^*$, Figure 4a) occurs between K and the transition height: areas with larger K values tend to exhibit higher CCW-to-CW transition heights, while regions with weaker turbulent mixing generally show a shallower vertical extent of CCW turning.

Considering that boundary-layer and microphysics parameterizations are critical for simulating turbulent mixing, we further conducted three sensitivity experiments by replacing the boundary-layer and microphysics schemes used in the control run (Figure S3 in Supporting Information S1). The results show that, although the magnitude of K and the exact transition height vary somewhat across different parameterization combinations, the positive relationship between K and the transition height remains robust and statistically significant in all experiments. This indicates that the key conclusion is not sensitive to the specific choice of parameterization schemes. Detailed information on these sensitivity experiments is given in Text S2 in Supporting Information S1.

The spatial distribution of K further highlights the influence of urbanization. Over the PRD, where large metropolitan clusters are present, K is significantly enhanced relative to nonurban regions, reflecting intensified turbulent mixing associated with urban heat island effects (e.g., Baik et al., 2001; Lin et al., 2008; Pal et al., 2012).

To isolate the role of urban processes, a sensitivity experiment (No-Urban) was conducted in which all land surfaces were replaced by cropland. As shown in Figure 4b, the removal of urban land use leads to a pronounced reduction in K , particularly over the PRD. Correspondingly, the CCW-to-CW transition height decreases markedly in these urbanized areas, whereas changes in surrounding nonurban regions are comparatively modest.

Despite the reduction in K , a strong positive correlation ($r = 0.62^*$) between K and the transition height is still maintained. These results suggest that enhanced turbulent vertical mixing associated with urbanization plays a critical role in elevating the CCW-to-CW transition height over the Shenzhen tower region. Stronger daytime urban-induced turbulence deepens the layer influenced by surface friction through enhanced momentum exchange, while at night the thermal inertia of urban surfaces sustains residual turbulence near the surface and inhibits complete boundary-layer decoupling. As a result, a relatively deep layer remains subject to surface drag after sunset, allowing frictional adjustment to affect winds at higher altitudes than in nonurban areas. This expanded vertical extent of frictional influence provides a physical explanation for the unusually deep CCW turning of boundary-layer wind hodographs observed over the Shenzhen meteorological tower compared to previous observations in less urbanized regions.

6. Conclusions

Using high-resolution wind observations from the 356-m Shenzhen meteorological tower, this study provides the first direct observational evidence of an anomalous counterclockwise (CCW) turning of perturbation wind vectors with time throughout the lower boundary layer. In contrast to the classical clockwise (CW) rotation expected from inertial oscillations, CCW turning is observed at all tower levels up to 350 m AGL. By integrating tower observations with ERA5 reanalysis and semi-idealized WRF simulations, we further identify a unique vertical structure where the anomalous CCW turning in the lower boundary layer eventually transitions to the theoretically expected CW turning aloft ($> \sim 500$ m AGL), establishing a coherent CCW-to-CW vertical mode. To objectively characterize this behavior, a rotation metric ω is introduced to quantify the rotation sense of wind hodographs and to systematically identify the height of transition.

A key finding is that the CCW-to-CW transition height is exceptionally elevated over the coastal urban regions. While previous studies have documented CCW turning as a phenomenon largely confined to the near-surface layer (< 100 m AGL; e.g., Bluestein et al., 2018; Rotunno et al., 2018), our results reveal that the transition height can reach approximately 500 m AGL. Semi-idealized experiments further reveal pronounced spatial heterogeneity in this transition height and demonstrate a robust link to urbanization. After sunset, residual heat stored in urban surfaces sustains turbulent mixing within the near-surface layer, allowing surface friction to influence winds at greater heights. As a result, complete nocturnal decoupling between the surface and the overlying flow is prevented, effectively lifting the CCW-to-CW transition height. This mechanism provides a physical explanation for the unusually deep CCW turning observed in rapidly urbanizing coastal megacities such as the PRD.

These findings have important implications for understanding and predicting severe weather in coastal environments, as the diurnal variation of boundary-layer winds critically modulates low-level convergence, moisture transport, and vertical wind shear relevant to heavy rainfall initiation and development. By revealing how urbanization fundamentally alters the vertical structure of boundary-layer wind turning, this study provides new insights into the meteorological impacts of anthropogenic land-use change. Future work would expand this framework to other coastal regions worldwide to assess the generality of the CCW-to-CW vertical mode and its sensitivity to diverse geographical and climatic settings. Furthermore, the development of theoretical models and fully idealized numerical experiments would help isolate key dynamical processes and further clarify the mechanisms governing the diurnal variation and vertical structure of boundary-layer winds.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The Shenzhen meteorological tower data of boundary-layer winds are from <https://doi.org/10.5281/zenodo.14120603> (Fu, 2024). The ERA5 reanalysis data used in this study are available from the Copernicus Climate Data Store at <https://cds.climate.copernicus.eu/> (Hersbach et al., 2020). The NCEP-FNL reanalysis data used in WRF experiments are available from the NCAR's Data Support Section at <https://rda.ucar.edu/datasets/ds083.2/> (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of

Commerce, 2000). The setup for semi-idealized WRF simulation is detailed at <https://doi.org/10.5281/zenodo.18585227> (Liu, 2026).

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References

- Baik, J.-J., Kim, Y.-H., & Chun, H.-Y. (2001). Dry and moist convection forced by an urban heat island. *Journal of Applied Meteorology and Climatology*. https://journals.ametsoc.org/view/journals/apme/40/8/1520-0450_2001_040_1462_damcfc_2.0.co_2.xml
- Blackadar, A. K. (1957). Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bulletin of the American Meteorological Society*, 38(5), 283–290. <https://doi.org/10.1175/1520-0477-38.5.283>
- Bluestein, H. B., Romine, G. S., Rotunno, R., Reif, D. W., & Weiss, C. C. (2018). On the anomalous counterclockwise turning of the surface wind with time in the plains of the United States. *Monthly Weather Review*, 146(2), 467–484. <https://doi.org/10.1175/MWR-D-17-0297.1>
- Bryan, G. H., Kniviel, J. C., & Parker, M. D. (2006). A multimodel assessment of RKW theory's relevance to squall-line characteristics. *Monthly Weather Review*, 134(10), 2772–2792. <https://doi.org/10.1175/MWR3226.1>
- Chen, F., & Dudhia, J. (2001). Coupling an advanced land surface–hydrology model with the penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Monthly Weather Review*, 129(4), 569–585. [https://doi.org/10.1175/1520-0493\(2001\)129<0569:caals>2.0.co;2](https://doi.org/10.1175/1520-0493(2001)129<0569:caals>2.0.co;2)
- Chen, G., Du, Y., & Wen, Z. (2021). Seasonal, interannual, and interdecadal variations of the East Asian summer monsoon: A diurnal-cycle perspective. *Journal of Climate*, 34(11), 4403–4421. <https://doi.org/10.1175/JCLI-D-20-0882.1>
- Chen, Z., & Du, Y. (2024). The influence of topography on the diurnal rainfall propagation in the Bay of Bengal. *Journal of the Atmospheric Sciences*, 81(6), 1019–1032. <https://doi.org/10.1175/JAS-D-23-0225.1>
- Du, Y. (2023). Offshore migration of summer monsoon low-level jet on a diurnal scale. *Geophysical Research Letters*, 50(20), e2023GL103840. <https://doi.org/10.1029/2023GL103840>
- Du, Y., & Chen, G. (2019a). Climatology of low-level jets and their impact on rainfall over Southern China during the early-summer rainy season. *Journal of Climate*, 32(24), 8813–8833. <https://doi.org/10.1175/JCLI-D-19-0306.1>
- Du, Y., & Chen, G. (2019b). Heavy rainfall associated with double low-level jets over Southern China. Part II: Convection initiation. *Monthly Weather Review*, 147(2), 543–565. <https://doi.org/10.1175/MWR-D-18-0102.1>
- Du, Y., & Rotunno, R. (2014). A simple analytical model of the nocturnal low-level jet over the great plains of the United States. *Journal of the Atmospheric Sciences*, 71(10), 3674–3683. <https://doi.org/10.1175/JAS-D-14-0060.1>
- Du, Y., Shen, Y., & Chen, G. (2022). Influence of coastal marine boundary layer jets on rainfall in south China. *Advances in Atmospheric Sciences*, 39(5), 782–801. <https://doi.org/10.1007/s00376-021-1195-7>
- Du, Y., & Yi, S. (2025). The relationship scenarios between boundary layer jet and coastal heavy rainfall during the pre-summer rainy season of south China. *Journal of Meteorological Research*, 39(1), 26–40. <https://doi.org/10.1007/s13351-025-4138-x>
- Du, Y., Zhang, F., Sun, Y. Q., Wei, J., & Li, X. (2021). Practical and intrinsic predictability of wave-convection coupled bands over Southern China. *Journal of Geophysical Research: Atmospheres*, 126(22), e2021JD034882. <https://doi.org/10.1029/2021JD034882>
- Eigenmann, R., Metzger, S., & Foken, T. (2009). Generation of free convection due to changes of the local circulation system. *Atmospheric Chemistry and Physics*, 9(21), 8587–8600. <https://doi.org/10.5194/acp-9-8587-2009>
- Ek, M. B., Mitchell, K. E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., et al. (2003). Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *Journal of Geophysical Research*, 108(D22). <https://doi.org/10.1029/2002JD003296>
- Fang, J., & Du, Y. (2022). A global survey of diurnal offshore propagation of rainfall. *Nature Communications*, 13(1), 7437. <https://doi.org/10.1038/s41467-022-34842-0>
- Fu, D. (2024). Shenzhen-tower: Shenzhen-met (version Shenzhen) [Dataset]. *Zenodo*. <https://doi.org/10.5281/ZENODO.14120603>
- Fu, D., Du, Y., Mai, C., Li, M., & Li, C. (2025). Impact of boundary layer jets on cold pool characteristics observed from the 356-m high Shenzhen meteorological tower. *Journal of Geophysical Research: Atmospheres*, 130(19), e2024JD042926. <https://doi.org/10.1029/2024JD042926>
- Hong, S.-Y., & Pan, H.-L. (1996). Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Monthly Weather Review*, 124(10), 2322–2339. [https://doi.org/10.1175/1520-0493\(1996\)124<2322:nblvdi>2.0.co;2](https://doi.org/10.1175/1520-0493(1996)124<2322:nblvdi>2.0.co;2)
- He, J. Y., Chan, P. W., Li, Q. S., Li, L., Zhang, L., & Yang, H. L. (2022). Observations of wind and turbulence structures of super Typhoons Hato and Mangkhut over land from a 356 m high meteorological tower. *Atmospheric Research*, 265, 105910. <https://doi.org/10.1016/j.atmosres.2021.105910>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Holton, J. R. (1967). The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, 19(2), 199–205. <https://doi.org/10.1111/j.2153-3490.1967.tb01473.x>
- Hong, S.-Y., Noh, Y., & Dudhia, J. (2006). A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly Weather Review*, 134(9), 2318–2341. <https://doi.org/10.1175/MWR3199.1>
- Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., & Collins, W. D. (2008). Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *Journal of Geophysical Research*, 113(D13). <https://doi.org/10.1029/2008JD009944>
- Li, X., & Du, Y. (2021). Statistical relationships between two types of heavy rainfall and low-level jets in south China. *Journal of Climate*, 34(21), 8549–8566. <https://doi.org/10.1175/JCLI-D-21-0121.1>
- Lima, D. C. A., Soares, P. M. M., Nogueira, M., & Semedo, A. (2022). Global coastal low-level wind jets revisited through the new ERA5 reanalysis. *International Journal of Climatology*, 42(9), 4491–4507. <https://doi.org/10.1002/joc.7482>
- Lin, C.-Y., Chen, F., Huang, J. C., Chen, W.-C., Liou, Y.-A., Chen, W.-N., & Liu, S.-C. (2008). Urban heat island effect and its impact on boundary layer development and land–sea circulation over northern Taiwan. *Atmospheric Environment*, 42(22), 5635–5649. <https://doi.org/10.1016/j.atmosenv.2008.03.015>
- Liu, Z. (2026). Semi-idealized WRF simulation setup. *Zenodo*. <https://doi.org/10.5281/ZENODO.18585227>
- Luiz, E. W., & Fiedler, S. (2023). Can convective cold pools lead to the development of low-level jets? *Geophysical Research Letters*, 50(11), e2023GL103252. <https://doi.org/10.1029/2023GL103252>
- Mai, C., Du, Y., Li, M., Chen, G., Su, L., Li, C., et al. (2025). Cold pools detected by a 356-m meteorological tower in a monsoon coastal region. *Advances in Atmospheric Sciences*, 42(11), 2235–2246. <https://doi.org/10.1007/s00376-025-4446-1>

- Miao, J.-E., & Yang, M.-J. (2020). A modeling study of the severe afternoon thunderstorm event at Taipei on 14 June 2015: The roles of sea breeze, microphysics, and terrain. *Journal of the Meteorological Society of Japan*, 98(1), 129–152. <https://doi.org/10.2151/jmsj.2020-008>
- Moisseeva, N., & Steyn, D. G. (2014). Dynamical analysis of sea-breeze hodograph rotation in Sardinia. *Atmospheric Chemistry and Physics*, 14(24), 13471–13481. <https://doi.org/10.5194/acp-14-13471-2014>
- Mulholland, J. P., Nowotarski, C. J., Peters, J. M., Morrison, H., & Nielsen, E. R. (2024). How does vertical wind shear influence updraft characteristics and hydrometeor distributions in supercell thunderstorms? *Monthly Weather Review*, 152(7), 1663–1687. <https://doi.org/10.1175/MWR-D-23-0166.1>
- National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. (2000). NCEP FNL operational model global tropospheric analyses, continuing from July 1999. *NSF National Center for Atmospheric Research*, 866.498. <https://doi.org/10.5065/D6M043C6>
- Pal, S., Xueref-Remy, I., Ammoura, L., Chazette, P., Gibert, F., Royer, P., et al. (2012). Spatio-temporal variability of the atmospheric boundary layer depth over the Paris agglomeration: An assessment of the impact of the urban heat island intensity. *Atmospheric Environment*, 63, 261–275. <https://doi.org/10.1016/j.atmosenv.2012.09.046>
- Parish, T. R., & Oolman, L. D. (2010). On the role of sloping terrain in the forcing of the Great Plains low-level jet. <https://doi.org/10.1175/2010JA53368.1>
- Peters, J. M., Morrison, H., Nelson, T. C., Marquis, J. N., Mulholland, J. P., & Nowotarski, C. J. (2022). The influence of shear on deep convection initiation. Part I: Theory. *Journal of the Atmospheric Sciences*, 79(6), 1669–1690. <https://doi.org/10.1175/JAS-D-21-0145.1>
- Rotunno, R., Romine, G. S., & Bluestein, H. B. (2018). A simple model for the anomalous counterclockwise turning of the surface wind with time over the Great Plains of the United States. *Journal of the Atmospheric Sciences*, 75(9), 2971–2981. <https://doi.org/10.1175/JAS-D-18-0074.1>
- Sakazaki, T., & Fujiwara, M. (2008). Diurnal variations in summertime surface wind upon Japanese plains: Hodograph rotation and its dynamics. *Journal of the Meteorological Society of Japan*, 86(5), 787–803. <https://doi.org/10.2151/jmsj.86.787>
- Shapiro, A., Fedorovich, E., & Rahimi, S. (2016). A unified theory for the Great Plains nocturnal low-level jet. *Journal of the Atmospheric Sciences*, 73(8), 3037–3057. <https://doi.org/10.1175/JAS-D-15-0307.1>
- Shen, Y., & Du, Y. (2023). Sensitivity of boundary layer parameterization schemes in a marine boundary layer jet and associated precipitation during a coastal warm-sector heavy rainfall event. *Frontiers in Earth Science*, 10, 1085136. <https://doi.org/10.3389/feart.2022.1085136>
- Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., et al. (2019). A description of the advanced research WRF version 4. *NCAR Tech. Note Near/Tn-556+ Str*, 145(10.5065). http://pfigshare-u-files.s3.amazonaws.com/14057147/WRF_TechNote_Jan2019.pdf
- Stensrud, D. J. (1996). Importance of low-level jets to climate: A review. *Journal of Climate*, 9(8), 1698–1711. [https://doi.org/10.1175/1520-0442\(1996\)009<1698:iolljt>2.0.co;2](https://doi.org/10.1175/1520-0442(1996)009<1698:iolljt>2.0.co;2)
- Steyn, D. G., & Kallos, G. (1992). A study of the dynamics of hodograph rotation in the sea breezes of Attica, Greece. *Boundary-Layer Meteorology*, 58(3), 215–228. <https://doi.org/10.1007/BF02033825>
- Thompson, G., & Eidhammer, T. (2014). A study of aerosol impacts on clouds and precipitation development in a large winter cyclone. *Journal of the Atmospheric Sciences*, 71(10), 3636–3658. <https://doi.org/10.1175/JAS-D-13-0305.1>
- Thompson, R. L., Mead, C. M., & Edwards, R. (2007). Effective storm-relative helicity and bulk shear in supercell thunderstorm environments. *Weather and Forecasting*, 22(1), 102–115. <https://doi.org/10.1175/WAF969.1>
- Yang, H., Du, Y., Chen, Z., & Fang, J. (2024). Could developing frontal rainfall influence warm-sector rainfall? *Geophysical Research Letters*, 51(15), e2024GL110430. <https://doi.org/10.1029/2024GL110430>

References From the Supporting Information

- Hu, X.-M., Nielsen-Gammon, J. W., & Zhang, F. (2010). Evaluation of three planetary boundary layer schemes in the WRF model. *Journal of Applied Meteorology and Climatology*, 49(9), 1831–1844. <https://doi.org/10.1175/2010JAMC2432.1>
- Janić, Z. I. (2001). Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model. <https://repository.library.noaa.gov>
- Morrison, H., Curry, J. A., & Khvorostyanov, V. I. (2005). A new double-moment microphysics parameterization for application in cloud and climate models. Part I: Description. *Journal of the Atmospheric Sciences*, 62(6), 1665–1677. <https://doi.org/10.1175/JAS3446.1>
- Shimada, S., Ohsawa, T., Chikaoka, S., & Kozai, K. (2011). Accuracy of the wind speed profile in the lower PBL as simulated by the WRF model. *Inside Solaris*, 7, 109–112. <https://doi.org/10.2151/sola.2011-028>
- Srinivas, C. V., Venkatesan, R., & Bagavath Singh, A. (2007). Sensitivity of mesoscale simulations of land-sea breeze to boundary layer turbulence parameterization. *Atmospheric Environment*, 41(12), 2534–2548. <https://doi.org/10.1016/j.atmosenv.2006.11.027>