

ANALYSIS OF EVOLUTION CHARACTERISTICS
OF A COASTAL SUPERCELL STORM BASED
ON DUAL RADAR WIND FIELD INVERSION

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Received on August 19, 2024

Presented by E. Bachvarova, Corresponding Member of BAS, on December 17, 2024

Abstract

Utilizing data from ground-based encrypted automatic stations, EC re-analysis datasets, and radar observations from Qingdao and Weifang, this study conducts an intricate analysis of the morphological evolution of a supercell storm structure in the coastal region of Qingdao on June 13, 2018. The methodology employed encompasses the application of dual radar wind field inversion techniques to delineate the dynamic progression of the storm. The findings reveal that the inflow jet positioned at the rear of the supercell induces the concurrent formation of anticyclonic and cyclonic vortex pairs to the south and north flanks of the storm system, respectively. Notably, the vigorous intensification of the cyclonic vortices augments the low-level atmospheric convergence. This enhancement is conducive to the facilitation of robust upward vertical motions, thereby leading to a marked elevation in the vertical stretching term. Concurrently, the amplification of the cyclonic vorticity fortifies the rear inflow jet itself. Upon the rear inflow jet's advancement to the front side of the supercell, it engages in a dynamic interaction with the ambient easterly winds. This interaction precipitates the genesis of a nascent convective cell at the juncture characterized by the storm bow's protrusion, culminating in a transformative alteration in the supercell's morphology. In a sequential pattern,

This work is financially supported by Natural Science Foundation of Shandong (ZR2023MD118, ZR2021MD010, and ZR2021MD062), East China Regional Phased Array Weather Radar Application Joint Laboratory (SDCXTD2023-1, 2018qdqxm05) and the Key Special Projects of Qingdao Meteorological Bureau (2023qdqxz02).

<https://doi.org/10.7546/CRABS.2025.02.07>

an anticyclonic storm initially exhibits a diminution in the upper atmospheric strata, subsequently extending its influence downward. The inception of the new convective cell on the front side of the supercell is notably instigated in the middle layer.

Key words: supercell storm, mesocyclone, extreme strong wind

Introduction. Supercell storms represent the zenith of isolated deep convective storm systems, distinguished by their exceptional organizational complexity, maximal intensity, and extended longevity relative to other convective disturbances. These meteorological phenomena are frequently the progenitors of extreme severe convective weather events, which have positioned them as a central subject of inquiry within the meteorological research community. The defining characteristic of supercell storms is the occurrence of a persistent and intense mesoscale rotation, typically referred to as a mesocyclone [1–8]. The scale vortices in bow shaped echoes serve as the predominant system that generates small-scale strong winds [9–14]. The presence of elevated convective available potential energy and significant vertical wind shear is conducive to the genesis of supercell storms. However, variable environmental conditions can precipitate marked disparities in the structural morphology of supercells, with corollary variations in the intense convective phenomena they induce. For instance, squall line-associated supercells often emerge in concert with incursions of dry and cold air masses, manifesting morphologically as bow-shaped structures [15–20].

Advancements in radar wind field inversion technology have substantially augmented our comprehension of the intricate three-dimensional wind field structures characteristic of these storm systems. This study scrutinizes the evolution characteristics of supercell storms through the lens of radar observations, employing dual radar wind field inversion to meticulously chart this evolution. Prior research leveraged dual radar for the inversion of wind fields in individual bow-shaped echoes, identifying the inverted rear inflow as a pivotal factor in storm intensification. The present study elucidates the characteristics of supercell storms' structural evolution using dual radar wind field inversion technology. It articulates the morphological evolution process with clarity.

Weather facts and background. Influenced by high-altitude cold vortex system, the Shandong province experienced a sequence of meteorological perturbations commencing on the afternoon of June 13, 2018, characterized by a progression of wind and hail events propagating from northwest to southeast. The meteorological disturbances were predominantly precipitated by severe thunderstorms and pronounced wind events. Observations recorded more than 200 instances of strong winds reaching Beaufort scale level 8 or higher, which included four strong wind events surpassing level 12, localized specifically within the eastern littoral zones of Qingdao. The peak wind gust recorded at Qingdao Station reached level 12 on the Beaufort scale (34.8 m/s), constituting an unprecedented

record for the month of June at this station since the year 1966. Furthermore, the Qingdao Olympic Sailing Base documented a maximum gust intensity of level 13 (39.1 m/s). These atmospheric anomalies were also associated with transient episodes of intense precipitation and hail occurrences.

The primary convective system instigating this coastal thunderstorm event was identified as a supercell storm. This particular supercell emerged through the confluence and intensification of a pre-existing, loosely organized cluster of convective storms situated upstream, in conjunction with several subordinate convective cells within the central and southern sectors of Shandong [3]. The incidence of thunderstorms and strong wind phenomena along the coastlines of Qingdao exhibits a direct correlation with the dynamics of the supercell storm, implicating it as the immediate causative agent of these weather events (illustrated in Fig. 1).

Dual radar wind field inversion. FUJITA [20] elucidated the critical relationship between the morphological evolution of bow-shaped echoes and the manifestation of extreme wind events at particular stages and locales. Utilizing radar data from Weifang and Qingdao in Shandong province, approximately 140 km apart, wind field inversion was conducted subsequent to velocity deblurring

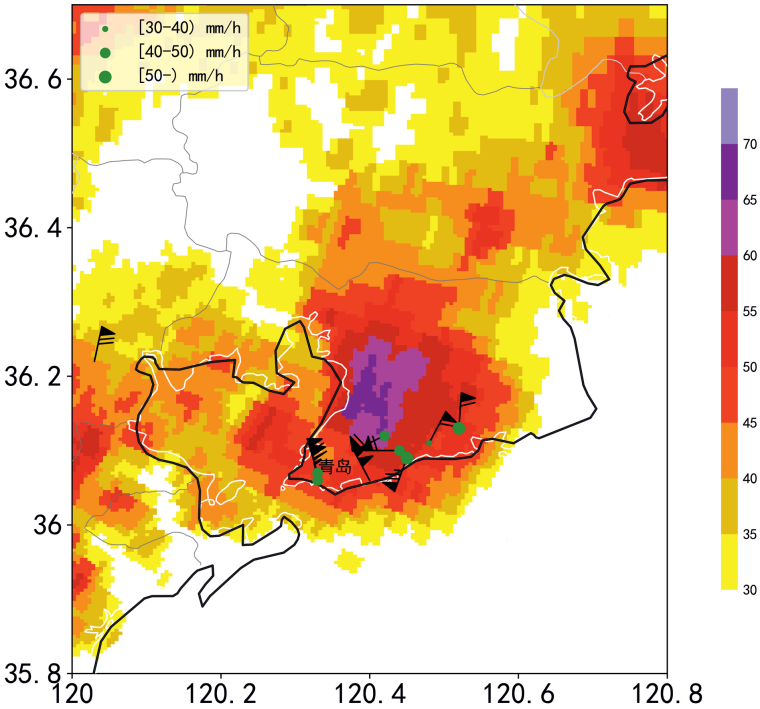


Fig. 1. Spatial distribution of gusts greater than force 8 at 17–18 CST (GMT+8, same below) and composite reflectivity at 17 CST on June 13, 2018 (green dots: 1-hour precipitation above 30 mm/h, shadings: composite reflectivity above 30 dBZ)

during the phase when a supercell storm's configuration underwent transformation. This allowed for an in-depth examination of the refined structure and the dynamic mechanisms underpinning its evolution. Due to the nature of radial velocity measurements acquired by radar, the observed radial winds in proximity to the junction of the two radar sites represent two vectors that approximate parallel alignment, rendering the inversion of tangential velocity imprecise. Consequently, the resultant velocity field in this region is deemed unreliable and has been excised from consideration [9].

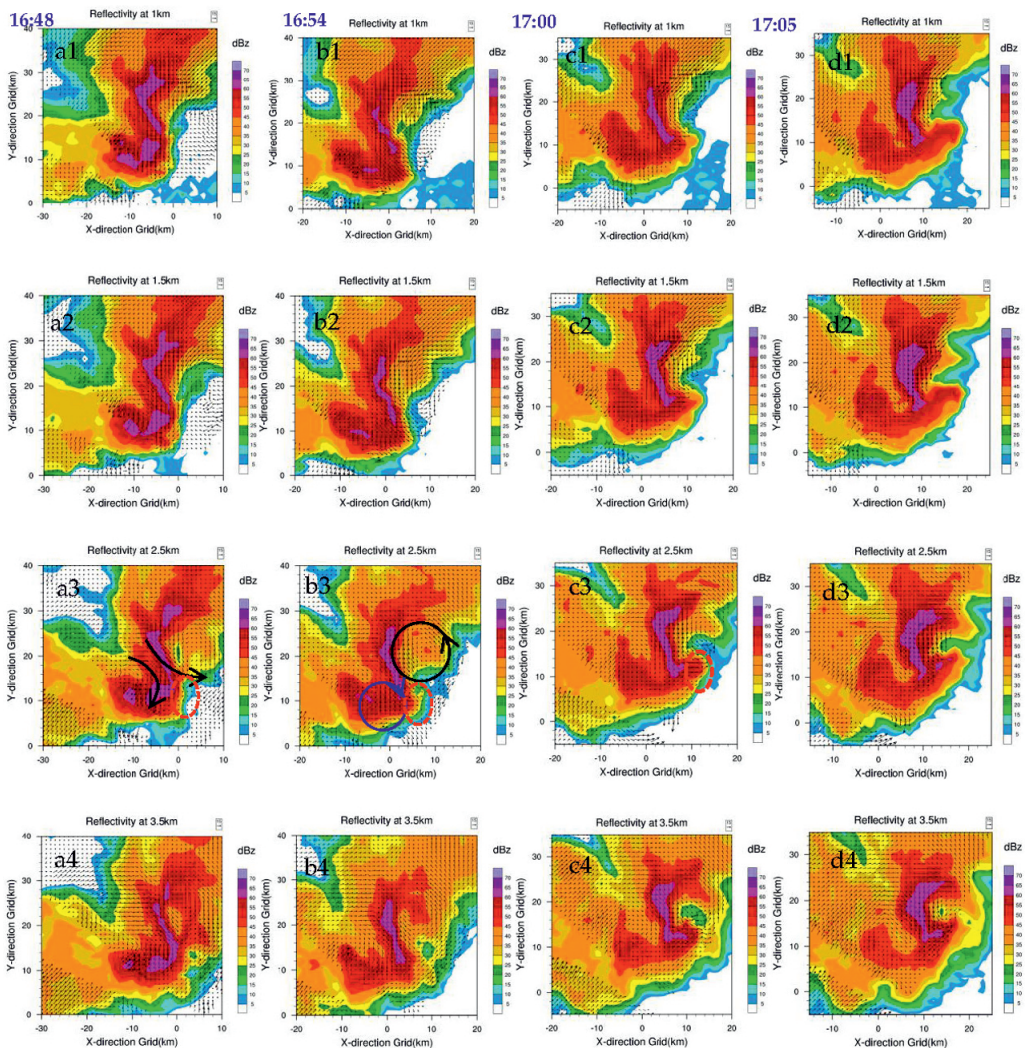


Fig. 2. Reflectivity factor (shadings) and the winds retrieved from the dual-Doppler radar.
 Red dashed line: the location of new convective storm; Black circle: mesoscale cyclone;
 Blue circle: mesoscale anticyclone; Black arrow in a3: airflow direction
 (a1–a4)16:48 CST (b1–b4)16:54 CST (c1–c4)17:00 CST (d1–d4)17:05 CST

Analyses of the dual radar wind field inversion outcomes reveal that at 16:48 (as depicted in Fig. 2a1–a2), the strong reflectivity factor within the lower layer, below 1.5 km, assumes an arc-like configuration. Concurrently, two distinct airflows are discernible within the wind field: a southward airflow enveloped by the storm and an easterly airflow present in the surrounding environment. Above the altitude of 2.5 km (Fig. 2a3–a4), situated over the bow-shaped echo, the rear inflow jet is positioned. This level is characterized by two pairs of mesoscale eddies, anticyclonic and cyclonic, flanking the rear inflow’s southern and northern boundaries, respectively. At this juncture, the northern anticyclonic vortex’s intensity and spatial extent surpass those of the southern cyclonic vortex, a disparity that is accentuated in the upper-level wind field. As the supercell storm progresses, the anticyclonic eddies on the southern flank exhibit a diminishing trajectory, evidenced by a reduction in both upper-level wind velocity and the intensity of the reflectivity factor. Conversely, the right-flanking cyclonic circulation demonstrates a trend of augmentation.

By 17:00 (Fig. 2c1–c4), the reflectivity factor of the southern anticyclonic vortex has attenuated to sub-60 dBZ levels. Meanwhile, the northern cyclonic vortex has undergone further evolution, rendering the apex of the bow-shaped echo increasingly pronounced at the front side, evincing a protrusive development (blue elliptical encirclement in Fig. 2a3–d3). This process precipitates the gradual encroachment of the rear inflow jet onto the supercell’s front side, catalyzing the genesis of a new convective cell within the middle layer (blue elliptical outline at an altitude of 2.5 km). The cyclonic eddies are burgeoning in intensity, with a more focused core, now surpassing the anticyclonic vortex centre in strength. By 17:05, the domain and vigour of the cyclonic eddies have become predominant, culminating in the formation of closed vortices. Initially, anticyclonic storms commence their dissipation in the upper atmosphere, with this weakening then propagating downwards. It becomes evident that the intensification of the rear inflow jet gradually yields a bow-shaped structure in the lower layer of the supercell, accompanied by the emergence of anticyclonic and cyclonic vortex pairs on either side. The robust development of cyclonic vortices enhances low-level convergence, favourable for the induction of augmented upward motion and an increase in the vertical stretching term. Simultaneously, the progression of cyclonic vorticity fortifies the rear inflow jet. When the rear inflow jet intersects with the supercell’s front side, it interacts with the environmental easterly winds, initiating a new cell (blue ellipse) at the locus of the storm’s bow protrusion, culminating in an alteration of the supercell’s contour. An anticyclonic storm first diminishes in the upper atmosphere, with this attenuation then extending downwards; the novel convective cell at the supercell’s front side is initially triggered within the middle layer.

Constructing a vertical transect of the storm along the northeast-southwest axis, an analysis of the supercell’s vigorous intensification phase (circa 16:42) re-

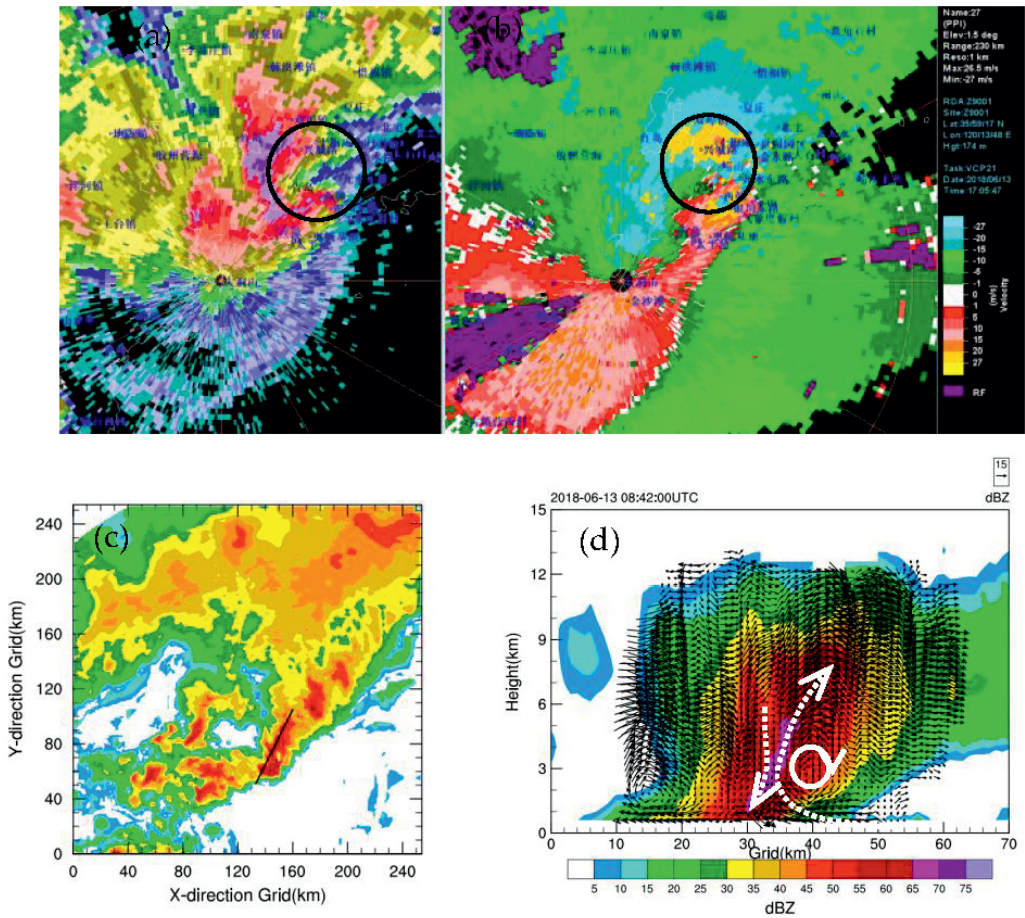


Fig. 3. Reflectivity factor (a) and radial velocity (b) at an elevation of 1.5° of Qingdao at 17:05 CST; Reflectivity factor at 16:42 CST (c) and the winds retrieved from the dual-Doppler radar (d) in the cross sections along the black line in (c)

veals an augmentation in the mesoscale vortex's vorticity. This intensification is observable on radar imagery as an enhanced rate of vortex rotation and the formation of smaller-scale intense vortices (as illustrated in Fig. 3). The supercell storm's strength is correspondingly magnified. Surveillance of mesocyclone activity via the Qingdao radar identified persistent mesoscale eddies within the lower layers concurrent with the supercell's development and maturity. The reflectivity factor imagery delineates an echo featuring a "bow-shaped" structure (Fig. 3a), and examination of the radial velocity map at a 1.5° elevation angle (Fig. 3b) reveals pronounced low-level rotation, indicated by the grounding of the area with high radial velocity values. These bow-shaped echo signatures are indicative of thunderstorms and strong winds at the surface.

An examination of the vertical wind field inversion at 16:42 (Fig. 3c, d) demonstrates the establishment of a significant discrepancy in velocity vectors

between the robust low-level easterly inflow jet and the upper-level westerly jet. This configuration fosters the genesis of horizontal vortex tubes within the middle and lower layers of the atmosphere. Within supercell storms, the existence of vigorous upward airflow contributes to the evolution of vertical vorticity, which is engendered by the impact of vertical ascensional motion upon the horizontal vortex tube.

The manifestation of this mesoscale vortex is also discernible in surface element variations. At 17:15, precipitation intensity peaked at a rate of 14.8 mm within a five-minute interval (Fig. 4). Accompanying such intense precipitation, there was a precipitous decline in ground temperature. Under the influence of the thunderstorm-induced high pressure and the formation of strong cold pools at the surface, a continuous rise in pressure would be anticipated. However, owing to the conjoint effects of mesoscale eddies and mesocyclones, surface pressure did not exhibit an increase but rather a decrease. The maximum wind gust, characterized as a southwest wind, was recorded at 17:16, persisting until 17:25. Subsequently, the weather condition transitioned into a cold strong wind emergent from the rear of the storm. Throughout the mesocyclone’s development phase within a supercell, its base elevation progressively diminishes, culminating in the establishment of a grounded mesoscale vortex. It is this interplay between mesoscale vortices and mesocyclones that precipitates the observed reduction in surface pressure.

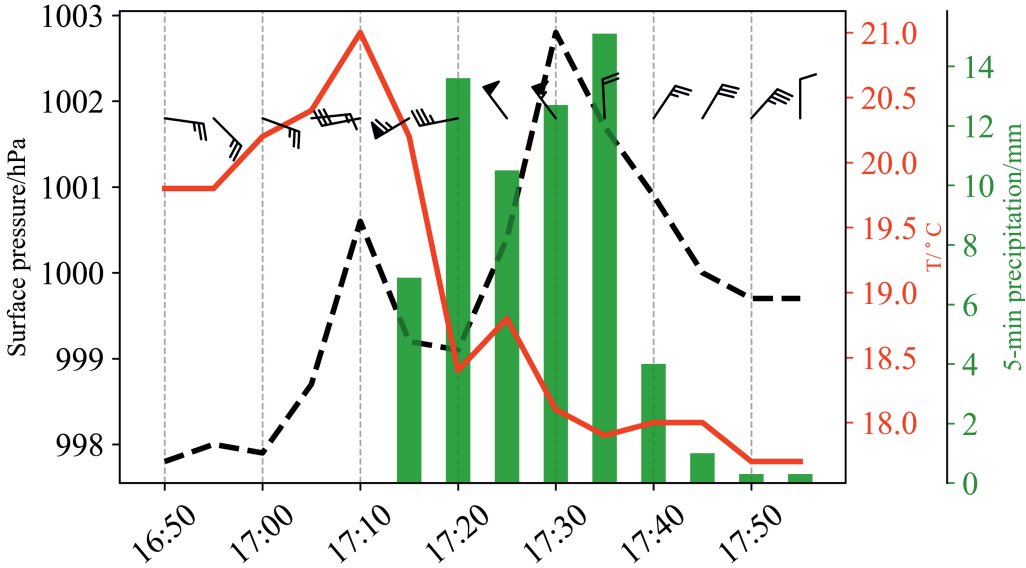


Fig. 4. Time series of temperature [°C] (red solid line), pressure [hPa] (black dotted line), precipitation [mm] (histograms) and wind at 1-min average [m/s] (barbed arrow)

Conclusion and discussion. Employing a combination of encrypted observations from automated terrestrial meteorological stations, reanalysis datasets provided by EC, and radar data acquired from Qingdao and Weifang, a compre-

hensive analysis was conducted on the structural attributes of supercells and the environmental conditions conducive to strong wind disasters along the Qingdao coastal area on June 13, 2018. The findings from this analysis are as follows:

1. An assessment of the ambient conditions over the eastern sector of the Shandong Peninsula suggests a highly favourable scenario for the genesis of supercell thunderstorms and the subsequent emergence of severe thunderstorm winds.
2. The vigorous intensification of cyclonic vortices serves to amplify low-level convergence, which is instrumental in fostering more pronounced upward motion and results in an escalation of the vertical stretching term; simultaneously, the evolution of cyclonic vorticity bolsters the rear inflow jet. Upon the rear inflow jet's incursion into the supercell's front side, it engages with the prevailing easterly winds, instigating the formation of a new convective cell (denoted by a blue ellipse) at the juncture where the storm's bow extends outward, thereby instigating a modification in the supercell's morphology. Initially, an anticyclonic storm exhibits a weakening phase commencing in the upper atmosphere, which then propagates to lower altitudes; the inception of the novel convective cell on the supercell's front side is initially observed within the middle atmospheric layer.
3. Pertaining to the supercell phase, the observed lack of a pressure drop can be attributed to the low-level decompression effects engendered by mesocyclones.

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