
The Multi-Scale Dynamics of an Extreme Precipitation Event in Chicago: Observations of Environment-Lake Breeze-Convection Interactions

Michael L. Kaplan ^a, Md Shamimul Hasan ^{b,c} and Yuh-Lang Lin ^{b,c*}

DOI: <https://doi.org/10.9734/bpi/crgese/v10/7925>

Peer-Review History:

This chapter was reviewed by following the Advanced Open Peer Review policy. This chapter was thoroughly checked to prevent plagiarism. As per editorial policy, a minimum of two peer-reviewers reviewed the manuscript. After review and revision of the manuscript, the Book Editor approved the manuscript for final publication. Peer review comments, comments of the editor(s), etc. are available here: <https://peerreviewarchive.com/review-history/7925>

Abstract

On 2 July 2023, a destructive, two-stage extreme precipitation event produced approximately 225 mm (9 in) of rainfall in less than 12 hours within a narrow corridor between O'Hare and Midway Airports in Chicago. Understanding how synoptic, mesoscale, lake-breeze, and convective processes combined to focus this rainfall is important for improving forecasts and flood preparedness in densely populated urban regions. This study aims to identify the multiscale dynamical and thermodynamic processes that organized the event before considering any urban enhancement. It also examines how three quasi-linear convective systems (QLCSs) interacted and evolved into a larger mesoscale convective system with mesoscale convective vortex (MCV) characteristics. The analysis uses ERA5 reanalysis, 13-km Rapid Refresh (RAP) analyses, Storm Prediction Center diagnostic fields, upper-air soundings, Chicago-area surface and Lake Michigan buoy observations, and NOAA NEXRAD radar data. These datasets are examined across meso-alpha to meso-gamma scales to diagnose the evolving jet-streak circulation, potential-vorticity structure, moisture transport, instability, surface convergence, and convective organization. The precursor environment featured an

^a Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512, USA.

^b Department of Physics, North Carolina A&T State University, Greensboro, NC 27411, USA.

^c Applied Science & Technology Ph.D. Program, North Carolina A&T State University, Greensboro, NC 27411, USA.

*Corresponding author: E-mail: ylin@ncat.edu, yuhlang2009@gmail.com;

upstream deep cold trough, a mid-to-upper-tropospheric jet streak with coupled potential-vorticity maxima, a stationary warm boundary and deformation zone, and a west-southwesterly low-level jet that transported abundant moisture towards northern Illinois. The first rainfall stage developed as three QLCs interacted over Chicago and formed a T-bone convective structure near Midway Airport, whereas the second stage followed upscale growth into a long-lived MCV-like circulation with persistent wraparound stratiform precipitation. These linked processes concentrated extreme rainfall over a small urban corridor even before urban heat-island and drag effects were isolated. The results show that extreme urban flooding can arise from close coupling among larger-scale atmospheric forcing, Lake Michigan-related convergence, and local convective evolution. Operational forecasters should therefore monitor transitions between jet-streak forcing regions, low-level moisture and convergence corridors, interacting QLCs, and emerging T-bone or vortical radar structures. Incorporating these signals into warning operations and urban flood-preparedness planning may improve early recognition of localized, high-impact rainfall events.

Keywords: Convergence; lake breeze; Mesoscale Convective Vortex (MCV); Quasi-Linear Convective System (QLCS); Urban Heat Island (UHI).

Abbreviations

<i>WMO</i>	: <i>World Meteorological Organization</i>
<i>KMDW</i>	: <i>Chicago Midway International Airport</i>
<i>KORD</i>	: <i>Chicago O'Hare International Airport</i>
<i>ERA5</i>	: <i>European Centre for Medium-Range Weather Forecasts Reanalysis v5</i>
<i>RAP</i>	: <i>Rapid Refresh analysis data</i>
<i>PV</i>	: <i>Potential Vorticity</i>
<i>MCS</i>	: <i>Mesoscale Convective System</i>
<i>MCV</i>	: <i>Mesoscale Convective Vortex</i>
<i>MUCAPE</i>	: <i>Most Unstable Convective Available Potential Energy</i>
<i>SBCAPE</i>	: <i>Surface Based Convective Available Potential Energy</i>
<i>QLCS</i>	: <i>Quasi-Linear Convective System</i>
<i>SPC</i>	: <i>Storm Prediction Center</i>
<i>CROCUS</i>	: <i>Community Research on Climate and Urban Science</i>
<i>CISL</i>	: <i>Computational and Information Systems Laboratory</i>
<i>CAPE</i>	: <i>Convective Available Potential Energy</i>
<i>PBL</i>	: <i>Planetary Boundary Layer</i>
<i>LCL</i>	: <i>Lifting Condensation Level</i>
<i>CIN</i>	: <i>Convective Inhibition</i>
<i>SBCIN</i>	: <i>Surface-Based Convective Inhibition</i>
<i>MSLP</i>	: <i>Mean Sea Level Pressure</i>
<i>RUC</i>	: <i>Rapid Update Cycle</i>

1. Introduction

The World Meteorological Organization (WMO) has for some time stated that climate change will intensify the atmospheric water cycle, a concept now widely accepted (World Meteorological Organization, 2021). This implies that greater global evaporation will continue to contribute to increases in extreme precipitation events and subsequent flash flooding. Many geographical regions have experienced such extreme precipitation events in recent years, including the Upper Mississippi River Valley watershed, including northern Illinois and the Chicago Metroplex (Fig. 1c) (Lincoln, 2023). In their National Weather Service Technical

Service Publication, Lincoln and Ford (2024) expand on earlier climatological analyses of extreme rainfall events within the Chicago metroplex by analyzing several extreme flooding events since 1950. Their analysis indicates that rainfall events exceeding 7.5 in (~187.5 mm) in a day or annual exceedance probabilities (AEP) > 1% are becoming more intense and more frequent, with less time between events. Their climatology expands on similar earlier studies of extreme precipitation in Chicago and northern Illinois (Balding & Ishii, 1993; Changnon, 1999; Changnon & Kunkel, 1999; Changnon & Westcott, 2002; Holmes & Kupka, 1997; Huff & Angel, 1989; Huff et al., 1955; Huff et al., 1958; Huff & Vogel, 1976; Merzlock, 1989; Nash & Chamberlain, 1954; Lincoln & Ford, 2024). Lincoln and Ford (2024) present evidence that these events have become stronger and more frequent when case studies from the last ~70 years are intercompared with those from the mid-20th century. Almost all of these events since the 1950s are coupled with summertime mesoscale convective systems (MCSs).

Recent urban flood-modelling work has similarly shown that climate-driven changes in extreme rainfall can alter simulated peak discharge and flood volume, underscoring the sensitivity of urban flood outcomes to precipitation forcing (Ghimire et al., 2023).

Long-record station analyses also show that rainfall regimes can exhibit non-stationary behavior, while the inferred timing of shifts may depend on the statistical method and temporal scale considered (Traore et al., 2026).

Convection-permitting studies over the United States further indicate that warming can alter both mesoscale convective-system rainfall structure and the regional distribution of mesoscale convective-system activity, reinforcing the need to consider convective organization when assessing heavy-precipitation risk (Cui et al., 2024; Haberlie et al., 2024).

When analyzing extreme events in a metroplex the size of Chicago over a long period, consideration must also be given to forcing signals beyond global-scale influences, such as the mesoscale impacts of the expanding metroplex and its changing surface characteristics. Kaplan et al. (2025) and Karim et al. (2025) presented evidence from observations and numerical simulation sensitivity studies indicating that both the Chicago metroplex and Lake Michigan affect the location and intensity of rainfall maxima during the propagation of multiple QLCSs over the metroplex in the warm season. These studies are broadly consistent with evidence from numerous simulations of the effects of urban heat islands and city mechanical forcing on precipitation worldwide (e.g., Steensen et al., 2022). Hence, a question remains as to whether city expansion over time, as well as changes in Lake Michigan water-surface temperatures, is at least partly, if not largely, responsible for the increased intensity and frequency of contemporary extreme precipitation events in Chicago. These local effects must be evaluated alongside global climate-forcing impacts when considering high-impact precipitation trends in large metroplexes such as Chicago.

Recent work on another major urban agglomeration has also demonstrated that synoptic background, nearby water bodies, and urban thermal effects can jointly influence mesoscale convective-system rainfall distributions, supporting the analytical separation of larger-scale forcing from local urban modification (Du et al., 2024).

The purpose of this study is to understand the evolution of the multiscale processes that led to the extreme precipitation event and that could be derived solely from meso- α - and finer-scale observations. Our hypothesis is that the downscale forcing dynamics and thermodynamics predispose the region to heavy rainfall even before urban modifications of those dynamics and the subsequent rainfall. This represents the fundamental synoptic dynamics that surround and

modify the forcing by Lake Michigan and Chicago's urban heat island and urban drag. This study will be followed by a subsequent manuscript presenting numerical simulations designed to distill Lake Michigan and urban-forcing effects on the larger-scale flood-producing environment. The knowledge gap in this problem lies in the urban modification of that downscale forcing; therefore, this manuscript focuses on how the non-urban environment predisposes local heavy-precipitation processes before urban effects are distilled. By identifying the implications of larger-scale environmental forcing for an extreme precipitation event, we can better distill urban modifications through multiscale numerical simulation sensitivity studies. In this first manuscript, we analyze the larger-scale dynamics and thermodynamics from observations of the 2 July 2023 flood, which represented an extremely high-impact event for the Chicago metroplex, totaling more than \$500 million in damage and flooding more than 70,000 basements (Lincoln & Ford, 2024) (Fig. 1b). Remarkably, as also shown in Fig. 1a, the total area of rainfall exceeding 7.5 in was relatively isolated to the Berwyn and Cicero subdivisions, where Community Research on Climate and Urban Science (CROCUS) field-network observations recorded the heaviest precipitation between Chicago's O'Hare (KORD) and Midway (KMDW) Airports. There were two periods of heavy precipitation, one from 1030-1730 UTC (~55% of the total rainfall) and one from 1830-2130 UTC (~45% of the total rainfall), which produced the heaviest precipitation depicted in Fig. 1a and were corroborated by cooperative and METAR precipitation observations in Figs. 1d-e. The study region is depicted in Fig. 1c. The first period unambiguously accompanied multiple transient QLCSS, whereas the second period was dominated by an upscale-building mesoscale convective vortex (MCV) with a broad, upstream-expanding stratiform rain shield. Also evident in Fig. 1a is that this small region of extreme precipitation, roughly centered on the Cicero and Oak Park neighborhoods, was embedded within a broader-scale and much weaker northwest-southeast-banded area roughly parallel to the lakefront, which was a recurring pattern in many of the cases analyzed by Lincoln and Ford (2024). Broader bands often interacted with or organized secondary orthogonal bands propagating over the metroplex from the Lake, although no two cases exhibited the same banded structures in their multi-decadal analysis of case studies. Doppler radar observations for the 2 July 2023 case indicated that a northwest-southeast QLCS, which contained several > 50 dBZ convective cells, slowly propagated southwestwards during the first QLCS episode after redeveloping near the Lake, i.e., along the Lake Michigan shoreline on the northeast side of the main downtown region. QLCS#2 then interacted with two other squall lines, one that had developed earlier from central Illinois (QLCS#1) and one from western Illinois (QLCS#3). Later, during the second heavy-rainfall period associated with the developing MCV, these QLCSS formed a pattern that we call a "T-bone" structure, when the dying QLCS from central Illinois, the QLCS from the northeast side of the city, and the QLCS from western Illinois all phased over the metroplex near Midway Airport (KMDW). Subsequently, that T-bone structure developed into a vortical structure that grew upscale, with a mesoscale baroclinic leaf-like stratiform region that developed over and persisted within the isolated region of very heavy precipitation centered near Berwyn, between O'Hare Airport (KORD) and KMDW. Thereafter, the MCV expanded greatly in scale as it propagated downstream over Lake Michigan and persisted for several more hours over and downstream from the Lake.

In the next section of this first manuscript, we describe the observational data employed in the analysis. In Section 3, we analyze the precursor meso- α -scale upstream environment using ERA5 and RUC analysis datasets and rawinsonde soundings, during which the incipient QLCS was organized upstream over central Illinois. Section 4 then includes additional upper-air analyses, detailed convective indices, Doppler radar analyses, and surface mesonet analyses over the metroplex to diagnose the meso- β/γ processes that focused the development of the T-bone through the interaction of the two other QLCSS with the remnant central Illinois QLCS

over the region of heaviest precipitation during the first precipitation period centered on KMDW. Section 5 repeats the analyses in Section 4 for the transition to the MCV during the second precipitation period. We then discuss the complex multiscale sequence of events in Section 6 in preparation for a second, forthcoming manuscript that focuses on numerical sensitivity studies of how multiple Lake Michigan breeze fronts/convergence zones and the urban heat island play key roles in the evolution of the multiple QLCSS and MCV that produced the extreme flood event of 2 July 2023.

1.1 Study Objective

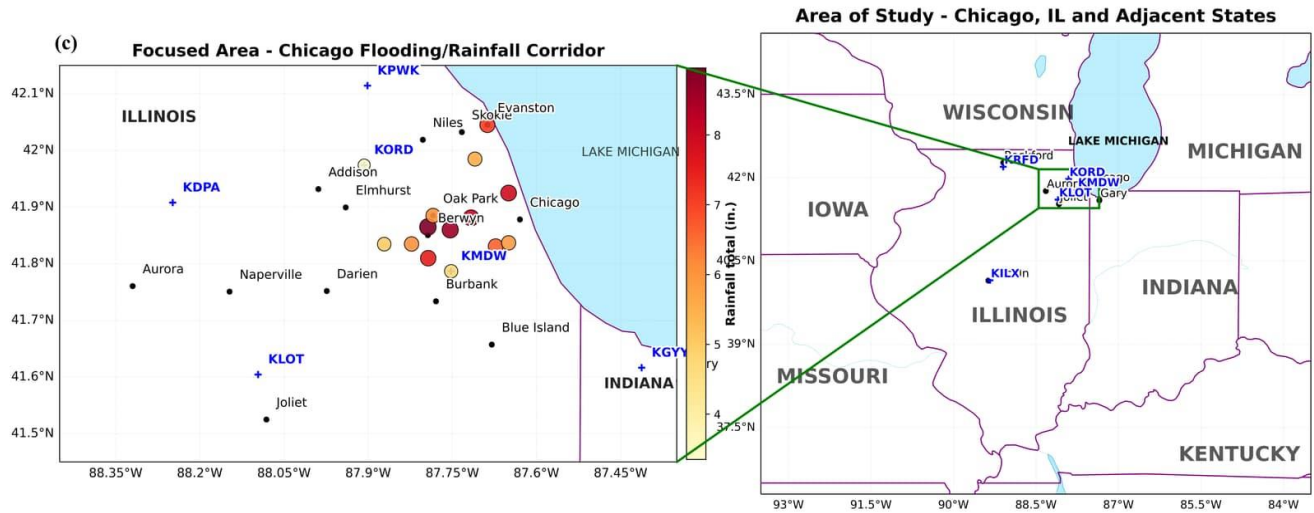
Accordingly, this study aims to diagnose, from observations, the meso- α to meso- γ dynamical and thermodynamic processes that organized the 2 July 2023 Chicago extreme precipitation event before isolating urban heat-island and drag effects in subsequent numerical sensitivity experiments.

2. Methods and Datasets

In this manuscript, only observed datasets were employed to analyze both the precursor large-scale environment and the evolution of radar and local surface processes. The larger-scale (meso- α) analyses were conducted using the ERA5 reanalysis (European Centre for Medium-Range Weather Forecasts, 2019). Rapid Update Cycle (RAP) 13-km datasets were employed for soundings over Chicago at Midway Airport (KMDW) (National Centers for Environmental Information, 2012). Additionally, RAP-derived stability and kinematic fields were extracted from the Storm Prediction Center's RAP archive (Storm Prediction Center, n.d.). Upper-air soundings at Lincoln, Illinois (KILX), were extracted from the University of Wyoming active radiosonde archive website (University of Wyoming, Department of Atmospheric Science, n.d.). Surface analyses were constructed over the Chicago metroplex, including buoy data over Lake Michigan from the MesoWest dataset (University of Utah, Department of Atmospheric Sciences, n.d.), which comprised primarily airport stations (Table 1). Doppler radar datasets were extracted from the NOAA NCEI Doppler Radar Archive (National Centers for Environmental Information, n.d.). Additional fields were extracted from the Plymouth State Weather Center Archives (Plymouth State University, n.d.) and the Weather.us radar website (Weather.us, n.d.).

Table 1. Chicago area airport stations employed in local analyses

Station	Name	Location
ORD	Chicago O'Hare International Airport	Chicago, IL
MDW	Chicago Midway Airport	Chicago, IL
PWK	Chicago Executive Airport	Wheeling, IL
UGN	Waukegan National Airport	Waukegan, IL
DPA	DuPage Airport	West Chicago, IL
06C	Schaumburg Regional Airport	Schaumburg, IL
ARR	Aurora Municipal Airport	Aurora, IL
JOT	Joliet Regional Airport	Joliet, IL
IGQ	Lansing Municipal Airport	Lansing, IL
IKK	Greater Kankakee Airport	Kankakee, IL
C09	Morris Municipal Airport	Morris, IL
DKB	DeKalb Taylor Municipal Airport	DeKalb, IL



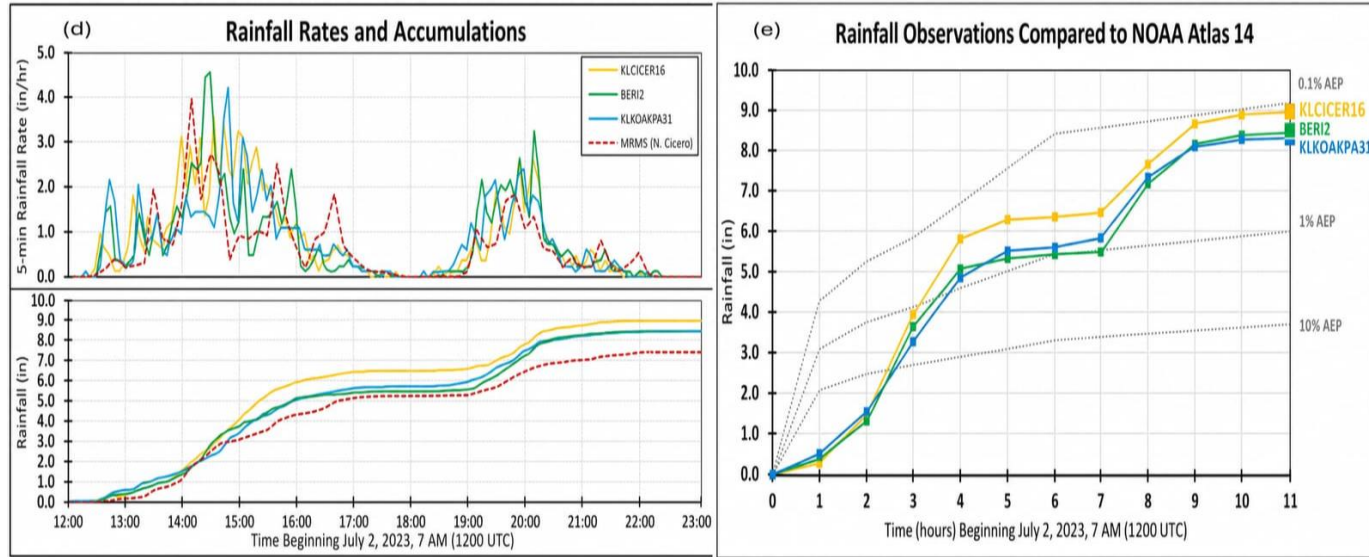


Fig. 1. (a) Observed precipitation on July 2, 2023, in Chicago from the CROCUS observational network as well as ASOS and COOP observers (J. Wang personal communication). (b) Impacts from flooding on 2 July 2023 [14]. (c) Study area and focused Chicago rainfall corridor. The right panel shows the broader regional domain, and the left panel highlights rainfall distribution, nearby cities, and weather stations around Chicago. (d) Rainfall rates (in hr^{-1}) and accumulations (in) at various cooperative surface stations in the Chicago area from 1200 UTC – 2300 UTC 2 July 2023. (e) Rainfall (in) observations compared to NOAA Atlas 14 data at multiple Chicago locations as in (d) from 1200 UTC – 2300 UTC 2 July 2023

3. Meso- α scale Precursor to the Chicago Heavy Rainfall Environment

3.1 Upper Tropospheric Quasi- and Semi-Geostrophic Organization of QLCS#1

The mid- to upper-tropospheric meso- α -scale flow on and immediately after 0000Z 2 July 2023 (00Z7/2) was dominated by unusually strong (for mid-summer) dual mid- to upper-tropospheric isobaric-layer PV maxima, a jet streak, a mid-continental baroclinic trough, and a mid-level cold pool, as depicted in the three-hourly fields extending to 09Z7/2 in Figs. 2-5, respectively. The broad trough axis, initially over the Central Plains, propagated east-northeastwards into the Mississippi River Valley by 06Z7/2 (Fig. 2). The jet streak propagated with the trough and contained two elongated maxima of mid- to upper-tropospheric isobaric-layer PV. Early in the period, the upstream trough PV maximum at 02Z7/2 in eastern Kansas (Figs. 2a-b) was stronger than the maximum in the jet's left-exit region. Over time, however, the downstream left-exit-region PV strengthened into an elongated, narrow filament over eastern Missouri and western/central Illinois, as shown by the 06Z7/2-09Z7/2 increase in positive horizontal mid- to upper-tropospheric PV advection just south-southeast of Chicago in Figs. 2c-d. The jet contained maxima of upward vertical motion (Figs. 4a-b) approximately in phase with the 300 hPa divergence maxima (Figs. 3a-b), extending from the trough axis downstream to the left-exit and right-entrance regions over Missouri/western Illinois and southeastern Illinois, respectively, early in the period. However, like the PV, the mid-level ascent maximum shifted from the right-entrance to the left-exit region over time and built downstream towards Chicago and northern Illinois in phase with the shift in divergence and mid-tropospheric height falls, with a roughly west-to-east orientation similar to the convective trend in Figs. 5c-e (Figs. 3c-d, 4c-e, and 6a-d). This ascent field ultimately contained two embedded maxima approximately in phase with the dual PV maxima: one associated with the upstream trough and one with the PV filament extending into the jet's left-exit region. Fig. 4e depicts the circulation orthogonal to the exit region, which, by 06Z7/2, exhibited a weak indirect structure. As shown in Fig. 5, active MCSs over Iowa, Missouri, and Illinois were roughly coincident with the larger-scale jet-induced dual ascending regions beneath the right-entrance and left-exit regions between 03Z7/2 and 09Z7/2 in Fig. 4. The jet's right-entrance region, with significant subgeostrophic curved flow (Figs. 3a-b and 4a-b), represented the more critical organizing circulation for the first MCS early in this period over southern and central Illinois. This MCS subsequently became QLCS#1 over central Illinois on or before 06Z7/2 and ultimately affected Chicago during the precursor period to the extreme precipitation event before 12Z7/2, as the QLCS strengthened beneath the left-exit region (Figs. 5a-f). However, the left-exit region gradually became dominant as QLCS#1 approached the Chicago metroplex.

After this early period of right-entrance-region lift before 06Z7/2, ascent in the left-exit region was more directly coupled to the QLCS as it moved poleward through Illinois. While the core of the mid-tropospheric PV maximum remained closely coupled to the trough, an expanding filament was clearly apparent extending into the jet's left-exit region as the main QLCS strengthened over central Illinois between 06Z7/2 and 09Z7/2 in Fig. 5. These dual PV maxima were mirrored in the ascent and divergence fields as the first precipitation event progressed. As shown in Figs. 3-4, after 06Z7/2, the divergence and upward motion migrated towards the left-exit region as the combined jet streak and trough approached northern Illinois. At 09Z7/2, the trough extended into northern Illinois and was accompanied by significant 300 and 500 hPa height falls. The deepening 500 hPa trough and vortical shear pattern extended into northern Illinois and were accompanied by strong mid-tropospheric cooling across the same region between 06Z7/2 and 09Z7/2 in Figs. 6c-d. The Xs in Fig. 6 denote the mid-level closed low. Additionally, accompanying convective outflow, diagnosed from the diffluent and

leftward-directed ageostrophic flow after 03Z7/2, can be seen approaching northern Illinois in phase with the main QLCS band, primarily in Fig. 4c. This convectively enhanced jet-exit-region circulation shifted divergence and ascent into the region just equatorward and west of Chicago by this period, primarily between 06Z7/2 and 09Z7/2 (again, note Fig. 4e). Also apparent is a splitting tendency in the PV-advection maxima in Figs. 2b-d. This splitting signal ultimately played a key role in the proliferation of multiple QLCSs that comprised a “T-bone” convective structure centered near KMDW during the first heavy-precipitation period.

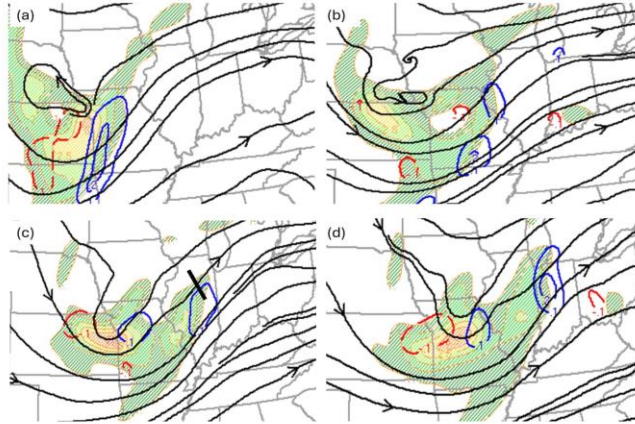


Fig. 2. RAP 400-250 hPa isobaric PV (shaded in PV units (PVU), where $1 \text{ PVU} = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$), PV advection (solid blue positive, dashed red negative in $\text{PVU} \times 10^3 \text{ s}^{-1}$) -and 300 hPa streamlines (black solid) valid at a) 0000 UTC, b) 0300 UTC, c) 0600 UTC, and d) 0900 UTC 2 July 2023. Thick black line on c) indicates the location of the cross section in Fig. 4e

3.2 Lower Tropospheric Jet, Deformation, and Moisture Transport Organizing QLCS#1

During the 0000 UTC - 0900 UTC period, the transition of upper-tropospheric divergence, ascent, and lower- to mid-tropospheric cooling from the jet streak’s right-entrance to left-exit region was in phase with, and coupled to, the movement of the 700 and 850 hPa low-pressure centers from the central Iowa-Missouri border to northern Illinois (note Figs. 2, 3, 7, and 8). As a result, two prominent signals created a favorable environment for strengthening QLCS#1 and organizing it into a well-defined squall line propagating toward Chicago from south-central Illinois. First, Figs. 7a and d at 700 hPa and Figs. 8a and d at 850 hPa show the significant low-level west-southwesterly jet accelerating from ~ 20 to 30 ms^{-1} and from ~ 15 to $\sim 25 \text{ ms}^{-1}$ maximum values, respectively, and extending poleward and downstream from southern and central Missouri to southern and central Illinois during 00Z7/2 through 09Z7/2. This strengthened the thermal/shear boundary and the shearing/confluent deformation zone depicted by the dashed black line in Figs. 8 and 9 across central Illinois, in phase with the upper-level divergence as it shifted north-northwestwards across the jet-streak exit region above the region of lowering heights that propagated into northern Illinois after 06Z7/2 at all tropospheric levels. The 700-850 hPa jet was also in proximity to the warm front across south-central Illinois, which was closely aligned with the shearing deformation, as the meridional gradient of the u-wind velocity component was significant in this location.

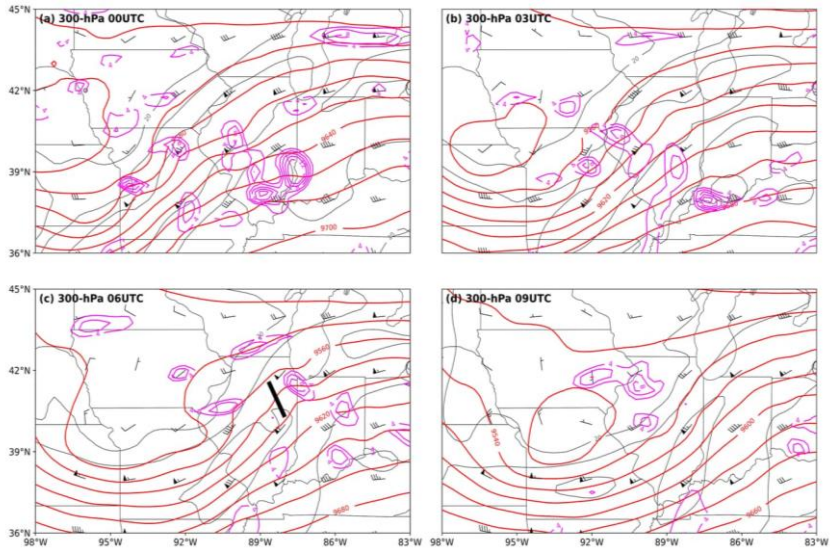
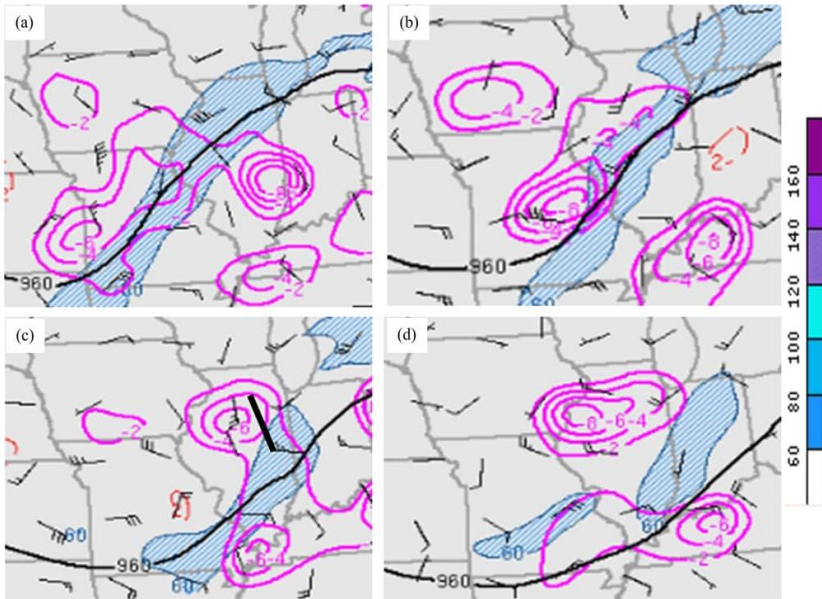


Fig. 3. ERA5 300 hPa height (red solid in m), wind barbs (ms^{-1}), isotachs (black solid in kt), and divergence (magenta in 10^{-4}s^{-1}) at a) 0000 UTC, b) 0300 UTC, c) 0600 UTC, and d) 0900 UTC 2 July 2023. Thick black line on c) indicates the location of the cross section in Fig. 4e



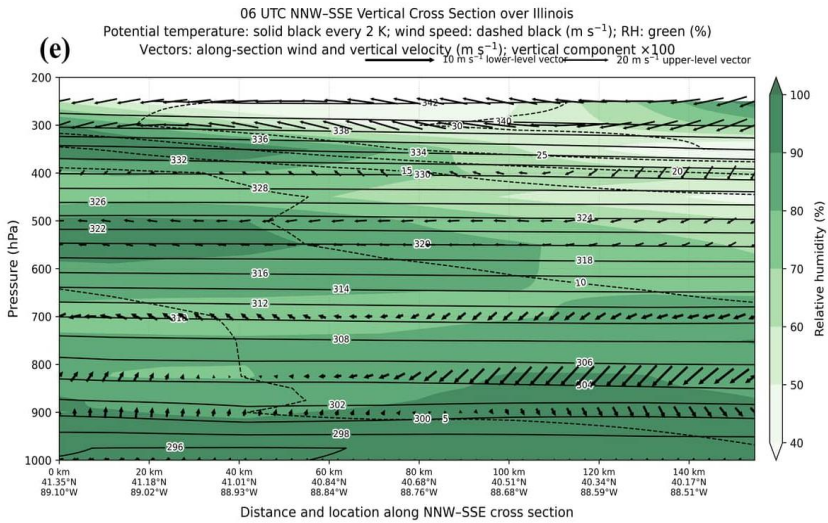


Fig. 4. RAP 300 hPa height (solid in m), isotach's (shaded in kt), ageostrophic wind barbs (kt), and 700-500 hPa mean omega (magenta in mbs^{-1}) valid at a) 0000 UTC, b) 0300 UTC, c) 0600 UTC, and d) 0900 UTC 2 July 2023. e) Total 3-D wind vectors and isotach's (black dashed in ms^{-1}) and relative humidity (green fill in %) at 0600 UTC 2 July 2023. Thick black line on c) indicates the location of the cross section in Fig. 4e

This prominent lower-tropospheric deformation zone, which became progressively more confluent with decreasing altitude, was derived largely from very warm continental tropical air that was advected downslope into the Central and Southern Plains before 00Z/7/2, thereby creating the mass perturbation that organized the low-level jet accelerations, i.e., the lee-trough meridional height gradient upstream over western Kansas and Nebraska and its attendant accelerating west-southwesterly low-level flow. Dry, warm air was advected into the upstream portion of this feature (note the 700-850 hPa meridional temperature boundary across central Missouri and central Illinois). In contrast, moist Gulf of Mexico air was advected first around its eastern periphery and then westward as well as poleward of the deformation zone. Both air masses propagated poleward in tandem toward north-central Illinois, as shown by the lower-tropospheric temperatures in Figs. 8a-d and the precipitable water (dashed black line) and water-vapor flux vectors (dotted black line) in Figs. 9a, c, e, and g and b, d, f, and h, respectively. The meridional confluence near the surface in the streamline fields of Figs. 9b, d, f, and g and the meridional shear of the zonal wind component in the 700 hPa-850 hPa layer in Figs. 8a-d were centered over central Illinois and were consistent with a confluent and shearing deformation zone supporting the warm-frontal boundary. This gradual strengthening of meridional-zonal shears within the surface-to-850 hPa layer occurred alongside increasing ascent downstream over north-central Illinois as ascent shifted toward the northwest side of the jet-exit region (Figs. 4c-e). These processes cooled the air in the lower to mid-troposphere across Iowa and northern Illinois, maintaining the deep-column height falls approaching the Chicago metroplex by 09Z/7/2 as a closed low in the height field, as shown in Figs. 6a-d. Consistent with these upper-air adjustments, Figs. 8e-h also show the west-east expansion of 1000 hPa height falls (evolving Xs), which began in south-central Illinois at ~03Z/7/2 and moved poleward to northern Illinois, including the Chicago metroplex, by ~09Z/7/2. These

height falls were poleward of a strengthening west-southwesterly low-level jet and equatorward of entrenched north-northeasterly low-level flow over north-central Illinois. The evolution of this strengthening west-east lower-tropospheric trough, the broad/large-scale thermal structure including the warm-frontal boundary at 700 hPa and below, and the predominantly meridional convergence zone supports the concept that QLCS#1 development and propagation were likely reflective of the aforementioned deep mass and momentum adjustments rather than local, earlier pre-existing MCS outflow boundaries from the flanking early convective features depicted in Figs. 5a-b over eastern Iowa and southwestern Indiana.

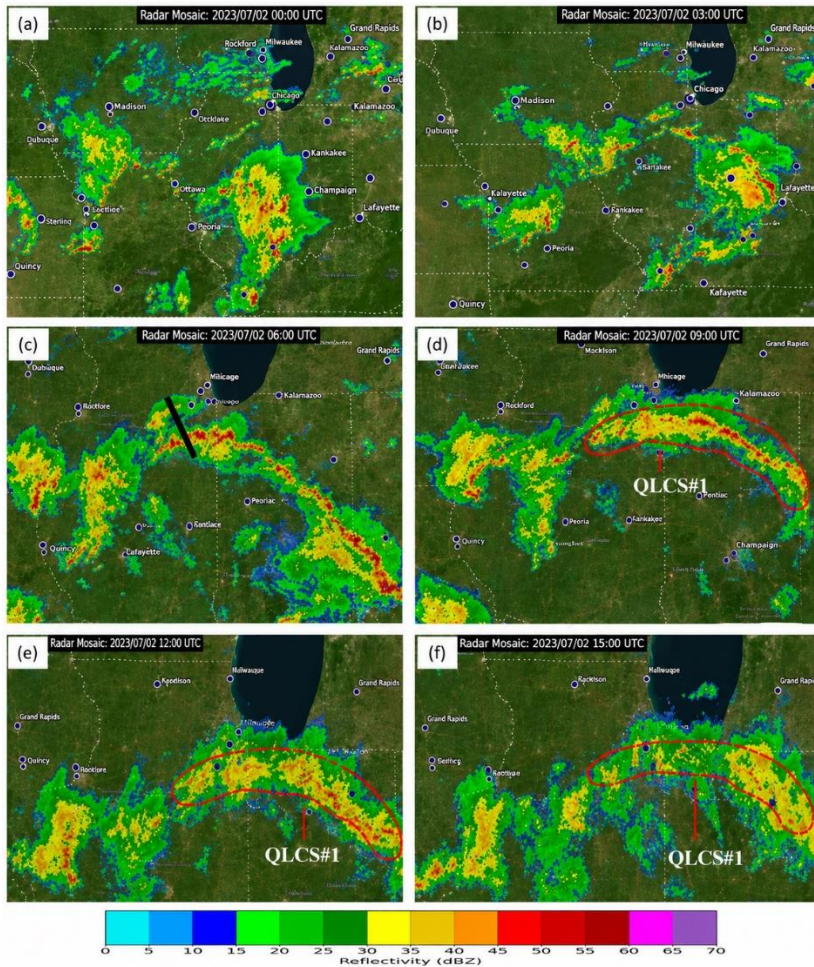


Fig. 5. NOAA NEXRAD Doppler radar composite imagery at a) 0000 UTC, b) 0300 UTC, c) 0400 UTC, d) 0500 UTC, e) 0600 UTC and f) 0700 UTC 2 July 2023. Note the organization and evolution of QLCS#1 poleward (Fig. d) towards Chicago from central Illinois. Thick black line in e) as in Figs. 2-4

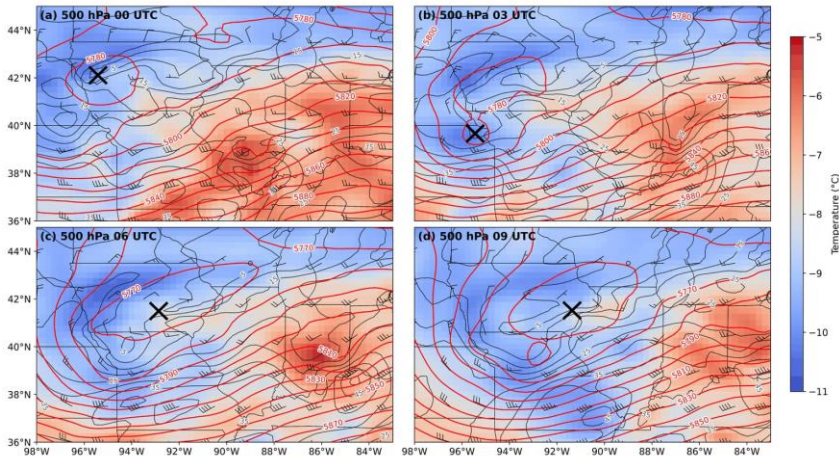


Fig. 6. ERA5 500 hPa height (solid red in m), wind barbs (ms^{-1}), isotach's (solid black in kt), and temperature ($^{\circ}\text{C}$) valid at a) 0000 UTC, b) 0300 UTC, c) 0600 UTC, and d) 0900 UTC 2 July 2023. Black X represents the upstream mid-tropospheric vortex center

By 09Z7/2 in Figs. 8d and 9g-h, the meridional shear of the zonal wind component and the lower- to mid-tropospheric closed low had moved just equatorward and southwest of Chicago, respectively. The west-east line of convection shown in the Doppler radar imagery in Figs. 5c-f represents QLCS#1, which strengthened as it approached the Chicago metroplex by 07Z7/2. In Figs. 9i-l, three features became increasingly collocated over time: (1) the strengthening mesoscale surface trough noted in Figure 8, (2) the surface confluence zone evident in the streamline field (black dotted lines), and (3) the organizing, zonally oriented precipitable-water maximum (black dashed lines). These features were in proximity to the central Illinois deformation zone on the equatorward side of the closed-surface low in Figs. 9g-h and were also near the lower- to mid-tropospheric cooling across north-central Illinois in Figs. 7 and 8 after 06Z7/2. In Figs. 9g-h, this moisture and surface-confluence feature began to rotate cyclonically, establishing a more southwest-northeast confluent structure at the surface. Hence, a plume of substantial moisture became collocated with cooling aloft along the deformation zone in central Illinois, which was the location of the west-east-elongating QLCS#1 depicted in Figs. 5c-e between 04Z7/2 and 06Z7/2 as this first of three QLCSs strengthened and propagated towards Chicago.

3.3 QLCS#1 Precursor Convective Environment, Triggering, and Subsequent Weakening

Consistent with these dynamical and thermodynamic adjustments was the early evolution of the QLCS#1 convective environment from 0000 UTC to 0900 UTC, depicted in Figs. 5a-f. The developing line of convection reflected the dynamical sequence described earlier and inferred from Figs. 2-4 and 6-9. Fig. 10 indicates that both the Lincoln, IL (ILX), 00Z7/2 sounding and the RAP surface-based convective available potential energy (SBCAPE) and most unstable convective available potential energy (MUCAPE) were already significant but not extraordinarily high, i.e., $>1000 \text{ Jkg}^{-1}$ over central Illinois at 00Z7/2 (black dashed zone in Figs. 10b-c). A key feature in the ILX sounding was the deep, well-mixed (adiabatic) layer

between 700 and 850 hPa (note the black arrow in Fig. 10a), indicating the transport of dry air from the southern Plains by the low-level jet beneath the mid-tropospheric cooling in the upper jet's entrance region, which ultimately shifted to that jet's exit region by 06Z7/2. At that time, a well-organized west-east line of convection can be seen consolidating over north-central Illinois, northeastern Missouri, and northwestern Indiana from the multiple earlier upstream MCSs flanking the upper-tropospheric jet in its left-exit and right-entrance regions in Figs. 5e-f. The convective line was closely aligned with the lower-tropospheric confluent deformation zone, developing 1000 hPa trough, and moist tongue depicted in Figs. 8 and 9, as well as with the transitioning/increasing upper-tropospheric divergence and ascent in the jet's left-exit region as height falls occurred over northern Illinois after 06Z7/2 in Figs. 2-4 and 6-8. Between 06Z7/2 and 07Z7/2, the line entered the equatorward side of the Chicago metroplex as the previously very strong reflectivity cores weakened (Figs. 5f and 11d).

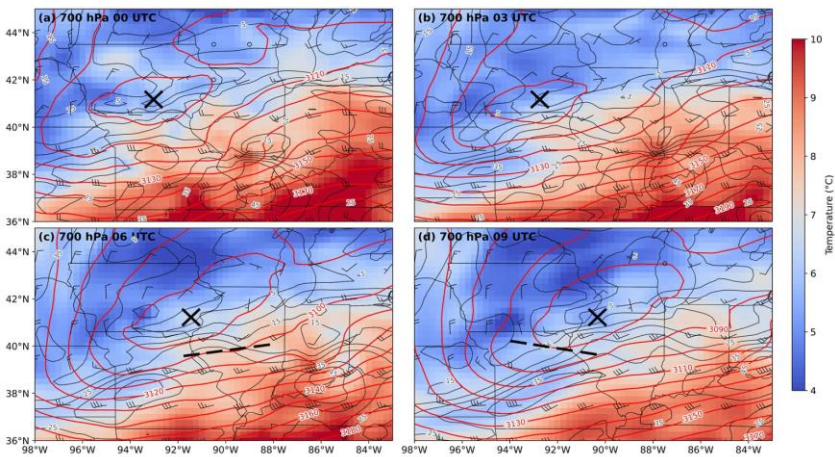


Fig. 7. ERA5 700 hPa height (solid red in m), wind barbs (ms⁻¹), isotach's (solid black in kt), and temperature (°C) valid at a) 0000 UTC, b) 0300 UTC, c) 0600 UTC, and d) 0900 UTC 2 July 2023. Black X represents the upstream vortex center and dashed black line the deformation zone location

Over the city, Figs. 9i-j show mean sea level pressure falls followed by rises between 00Z7/2 and 06Z7/2, reflecting (1) a dying line of unrelated convection that produced pressure rises and cooling over the city, followed by (2) a somewhat delayed inland penetration of cool Lake Michigan air and a shift at most locations to northeasterly airflow during the typical summertime late-afternoon lake-breeze penetration inland (cold-front symbol). During the 06Z7/2 to 09Z7/2 period, pressure falls reflecting the poleward motion of QLCS#1 are evident, along with nocturnal surface cooling and the development of south-southeasterly flow building poleward through the metroplex (Figs. 9k-l). Note the zonally oriented meso-trough over the city in Figs. 9k-l (dotted black line). Also evident in Figs. 9m-n, and consistent with the radar imagery in Figs. 5e-f, is the transition from relatively dry surface air over the southern part of the Chicago metroplex to a zonally oriented line of saturated surface air with increasing surface dewpoints as convection arrived (dashed white line). This was also consistent with the poleward shift of divergence aloft into the jet's left-exit region as QLCS#1 moved into the city and initially weakened while interacting with the drier urban environment. Between 06Z7/2 and 09Z7/2, Figs. 9k-l show the development of a confluence zone over the city corresponding

to the preceding mean sea level pressure falls, meso-low, and moistening, as the northeasterly flow along the lakefront began to penetrate back southwestwards and converge with the southerly flow near the center and south of the metroplex (dotted black line). This urban convergence was in phase with the poleward shift in upper-tropospheric divergence in the jet's left-exit region, which organized the regeneration of convection after 12Z7/2 farther northeast, leading to QLCS#2. At that time, confluent flow over the city replaced the previous 00Z7/2 surface ridging as the late-afternoon lake breeze subsequently propagated across the metroplex.

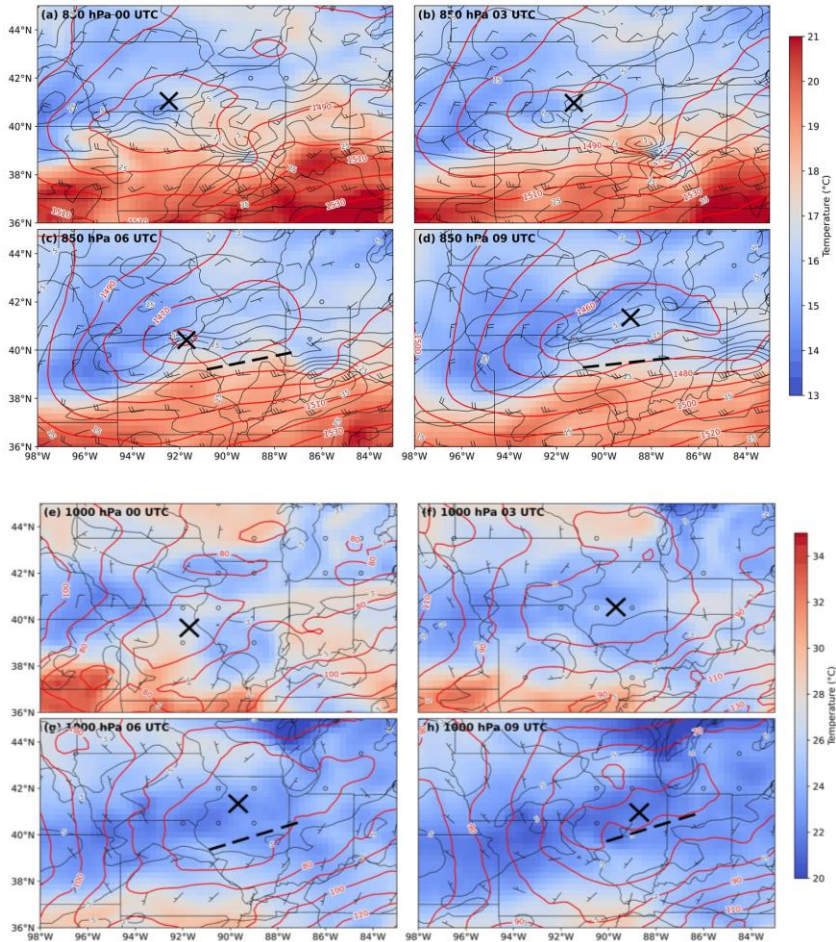
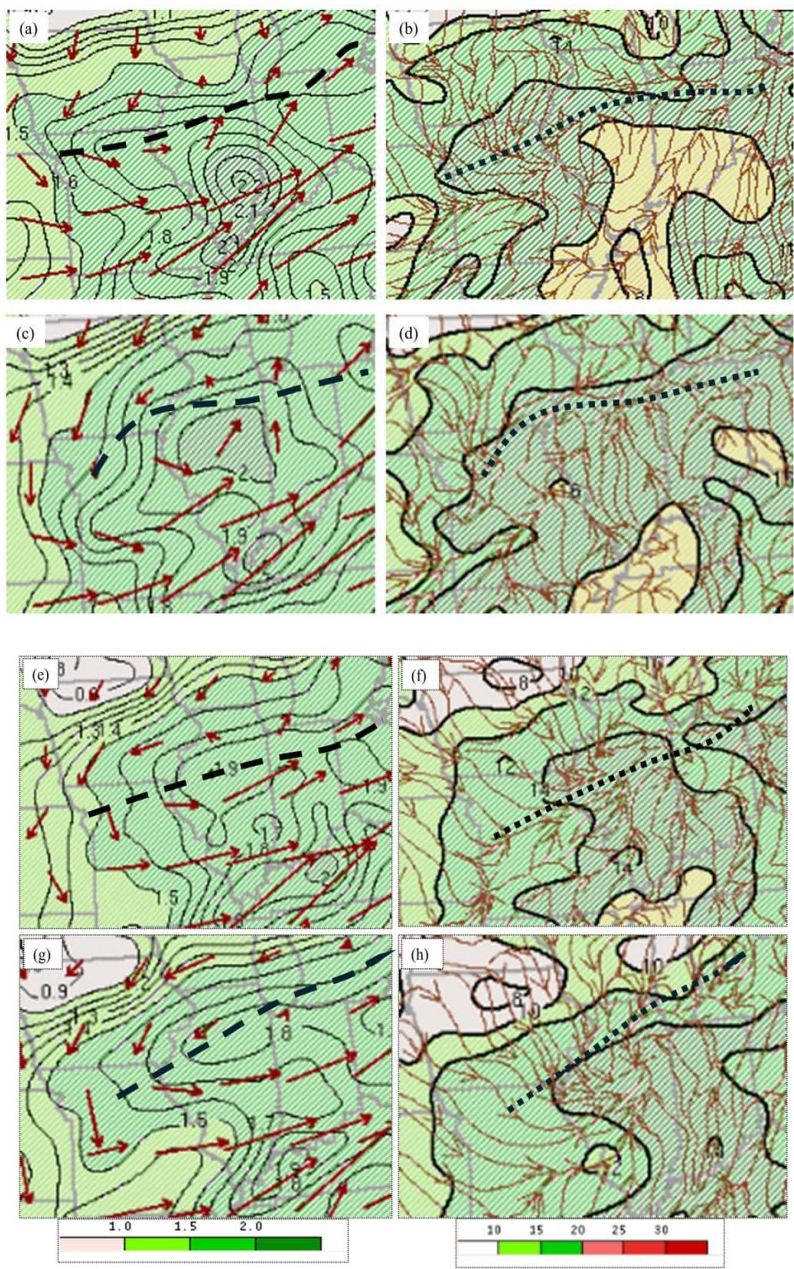


Fig. 8. ERA5 850 hPa height (solid red in m), wind barbs (ms^{-1}), and temperature ($^{\circ}\text{C}$) valid at a) 0000 UTC, b) 0300 UTC, c) 0600 UTC, and d) 0900 UTC 2 July 2023. ERA5 1000 hPa height (solid red in m), wind barbs (ms^{-1}), isotachs (solid black in kt), and temperature (shaded in $^{\circ}\text{C}$) valid at e) 0000 UTC, f) 0300 UTC, g) 0600 UTC, and h) 0900 UTC 2 July 2023. Black X represents the upstream vortex center and dashed black line the deformation zone location



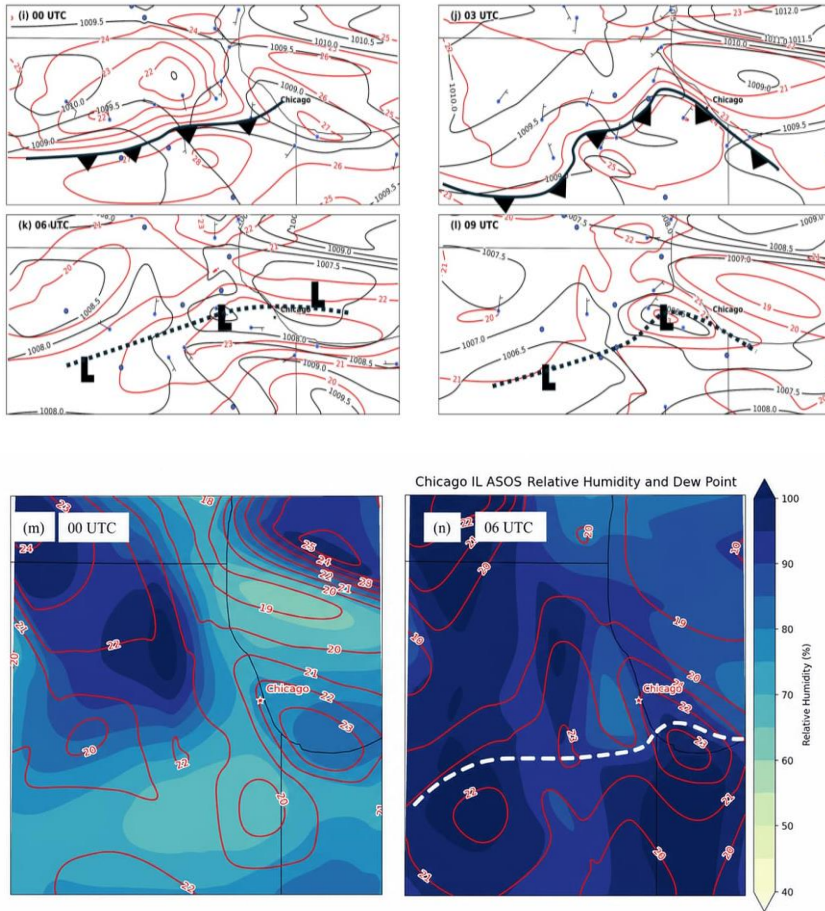


Fig. 9. RAP lower 400 hPa precipitable water (shaded and solid in in) and 850 hPa moisture flux transport vectors ($\text{g}^2\text{s}^{-1}\text{m}^{-3}\text{Kg}^{-1}$) (left) and surface streamlines (solid brown elongated vectors) and lowest 100 hPa mean mixing ratio (black solid in gKg^{-1}) valid at a-b) 0000 UTC, c-d) 0300 UTC, e-f) 0600 UTC, and g-h) 0900 UTC 2 July 2023. Chicago area airport METAR analyses of mean sea level pressure (black solid in hPa), surface wind barbs (kt), and surface temperature (red solid in $^{\circ}\text{C}$) valid at i) 0000 UTC, j) 0300 UTC, k) 0600 UTC, and l) 0900 UTC and surface Td (red solid in $^{\circ}\text{C}$) and surface relative humidity (shaded in %) at m) 0000 UTC and n) 0600 UTC 2 July 2023. Black dashed line on a), c), e), and g) is the axis of the precipitable water maximum and b), d), f), and h) the accompanying surface confluence and deformation zone organizing QLCS#1. Surface cold front on i) and j) is the advancing Lake Michigan front. Black dotted lines on k) and l) is the surface trough and imbedded meso-lows (L) where that cold front and remnant QLCS#1 trough converge. White dashed line on n) is the companion dewpoint front with the remnant QLCS#1 trough

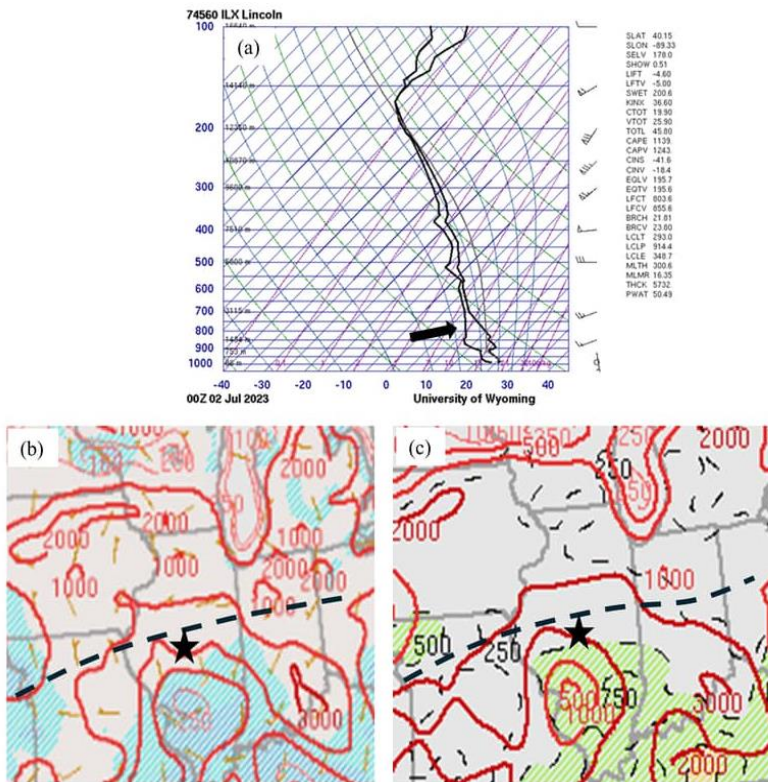
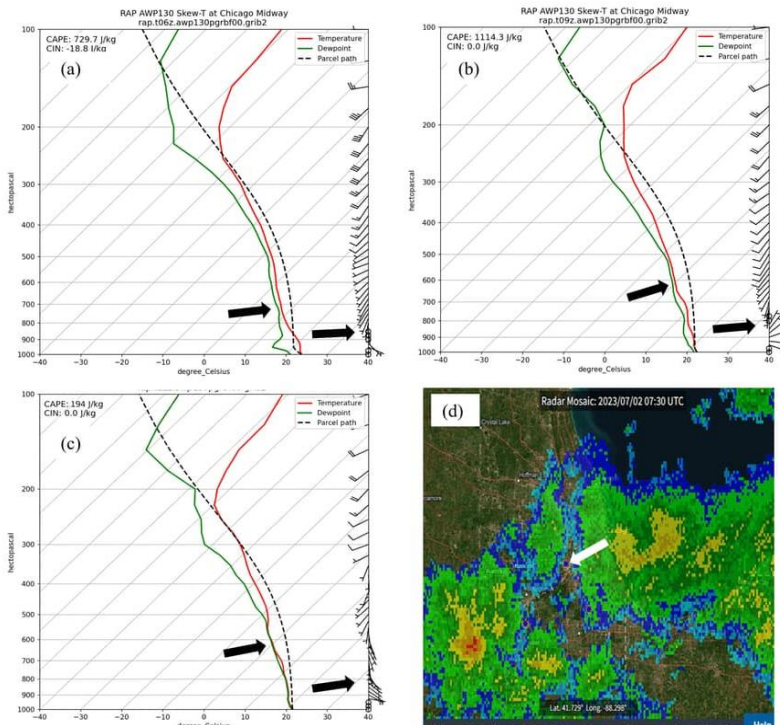


Fig. 10. a) Lincoln, IL (ILX) sounding b) RAP surface-based (SBCAPE) (red contours in JKg^{-1}), SBCIN (shaded at 25 and 100 JKg^{-1}), and surface wind barbs (kt) and c) RAP most unstable (MUCAPE) (red contours in JKg^{-1}), lifted parcel level (shaded in m), and surface wind barbs (kt) all at 0000 UTC 2 July 2023. Black arrow on a) is the loaded gun sounding region. Stars on b) and c) is the location of Lincoln, IL radiosonde site and dashed black lines the low-level deformation zone

Shortly after the line of convection accompanying the west-east-oriented and poleward-propagating QLCS#1 crossed the city, it split apart. Figs. 11d-f depict the collapse of convection during the 07Z7/2-10Z7/2 period as the middle of QLCS#1 dissipated over the city (white arrows in Figs. 11d-f). However, the low pressure accompanying that line remained a residual feature that became important for subsequent convective strengthening shortly after this period, when QLCS#2 began propagating toward the city from the northeastern Lake Michigan shoreline. Thus, QLCS#1 did not contribute directly to the first period of “heavy” precipitation but did so indirectly by creating surface pressure falls, confluence, and moistening before the arrival of QLCS#2 and, subsequently, QLCS#3, whose interaction organized the first period of heavy precipitation. During the weakening of QLCS#1, the RAP soundings in Figs. 11a-c at 06Z7/2-12Z7/2 indicate that, over KMDW, which should be representative of much of the city at the meso- β scale, a somewhat drier, subsaturated state existed in the column as QLCS#1 approached the city, with mostly veering south-

southwesterly airflow through the column and a very shallow layer of near-surface southeasterly flow (black arrows indicating early mid-level drying followed by incipient moistening and low-level inflow). This vertical wind shear was consistent with mid-tropospheric geostrophic warm-air advection early in the period, transitioning to cool-air advection, particularly in the lower troposphere, as backing occurred at low levels with the later arrival of the cold closed low aloft (Xs in Figs. 13a-b). Between 06Z7/2 and 12Z7/2, there was net cooling below 600 hPa as the easterly wind component built almost to that level and the mid-tropospheric westerly component slowly diminished. This reflected the arrival of the deep cold vortex across northern Illinois (Xs in Figs. 13a-b). It also reflected the inland transport of cooler air and diffuent near-surface airflow from Lake Michigan, which stabilized and moistened the environment at low levels below 650 hPa while MUCAPE increased aloft above 650 hPa, as also inferred from the onshore flow over the city in Figs. 9k-l. Thus, the column generally moistened and became more unstable aloft by 12Z7/2 (black arrows), indicating that the subsaturation that weakened QLCS#1 after 06Z7/2 was transitioning back towards a more favorable moist column for convective regeneration because of the arrival of the larger-scale closed low and immediately before the southwestward propagation of QLCS#2 between 11Z7/2 and 13Z7/2, as shown by the radars in Figs. 15a-d. This redevelopment of convection over the city was also consistent with the precipitable-water maximum and west-east low-level deformation zone (black dashed line) in Figs. 9f and g arriving over Chicago at this time, i.e., by ~09Z7/2 - 12Z7/2. Hence, the environment changed from favoring short-term QLCS weakening to favoring convective regeneration after 11Z7/2.



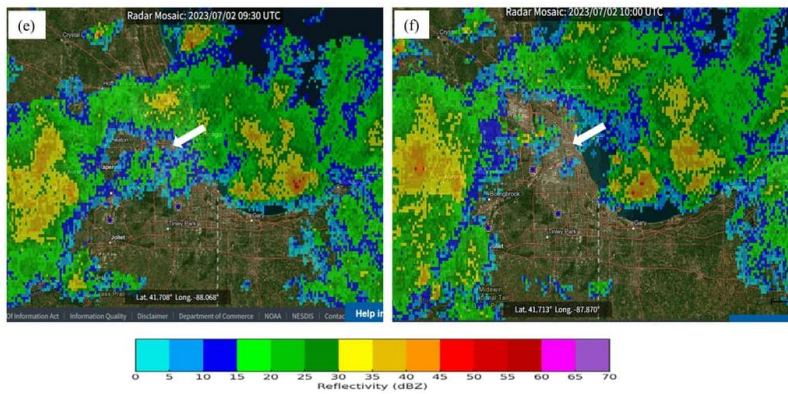


Fig. 11. RAP KMDW soundings valid at a) 0600 UTC, b) 0900 UTC, and c) 1200 UTC 2 July 2023. CAPE and CIN = MUCAPE and MUCIN. NOAA NEXRAD Doppler radar composite imagery at d) 0730 UTC, e) 0930 UTC, and f) 1000 UTC 2 July 2023. Black arrows on a)-c) represent the saturating part of the sounding above the main level of inflow wind. White arrows on d)-f) the collapse of QLCS#1's convection

4. QLCS#2-3 and T-bone Squall Line Development Leading to the First Period of Heavy-Precipitation Forcing

4.1 Upper-Tropospheric Forcing of QLCS#2 by the Arriving Vortex and Lower-Tropospheric Onshore Flow

The key period for the shift and rapid intensification of convection across north-central Illinois, primarily over the Chicago metroplex, was 11Z7/2-13Z7/2, as shown by the radar evolution later in this section and by the surface confluence near KMDW in Figs. 14 and 15. This period of convective intensification was consistent with the sounding in Fig. 11c, which indicated lower- to mid-tropospheric moistening after 09Z7/2 (black arrow). Between 12Z7/2 and 15Z7/2, the column became saturated up to 500 hPa, and the wind became nearly calm throughout the entire column, consistent with an environment likely to support an MCV (Davis et al., 2004; Schumacher & Johnson, 2009). Additionally, these RAP Chicago soundings and the surface-based (SBCAPE) and most unstable (MUCAPE) convective available potential energies supported the overnight maintenance of convective instability over the metroplex (Fig. 12). This reflected (1) slight diurnal surface cooling; (2) the strengthening of ascent and upper-level divergence across the city, as shown by the dotted black lines in Figs. 13a-d; (3) the movement of the 500-700 hPa vortex towards this region, with its relatively cool air sustained by ascent beneath the mid- to upper-tropospheric jet's left-exit region (dotted black lines); and (4) the poleward movement of the lower-tropospheric deformation/confluence zone and its precipitable-water maximum (Figs. 14e-f), which maintained a very moist column that gradually lost its elevated dry layer, with CAPE sustained by increasing vertically integrated moisture and cooling aloft (dashed and dotted black lines). The CAPE was no longer primarily a reflection of the relatively dry and unstable elevated mixed layer between 850 and 700 hPa evident in the KILX 00Z7/2 sounding in Fig. 10a (black arrow). That layer became more elevated after 12Z7/2 and appeared progressively less like the classical "loaded gun" sounding through this period, while increasing moisture propagated into the Chicago metroplex with the

poleward-propagating lower-tropospheric confluent deformation zone in Fig. 14f (dotted black lines). A closer examination of the evolving RAP soundings over the Chicago metroplex in Fig. 12 reflects this moist-neutral layer, which progressively became wetter while maintaining the weak-wind-shear profile more indicative of a weak vortex over the metroplex (black arrows). Figs. 13e-f (dotted black lines) support the 12Z7/2-15Z7/2 upper-tropospheric divergence in an extended west-east band in the jet's left-exit region, as well as upward vertical motion and the eastward propagation of the cold-core closed low at 500 hPa (Xs in Figs. 13a-d).

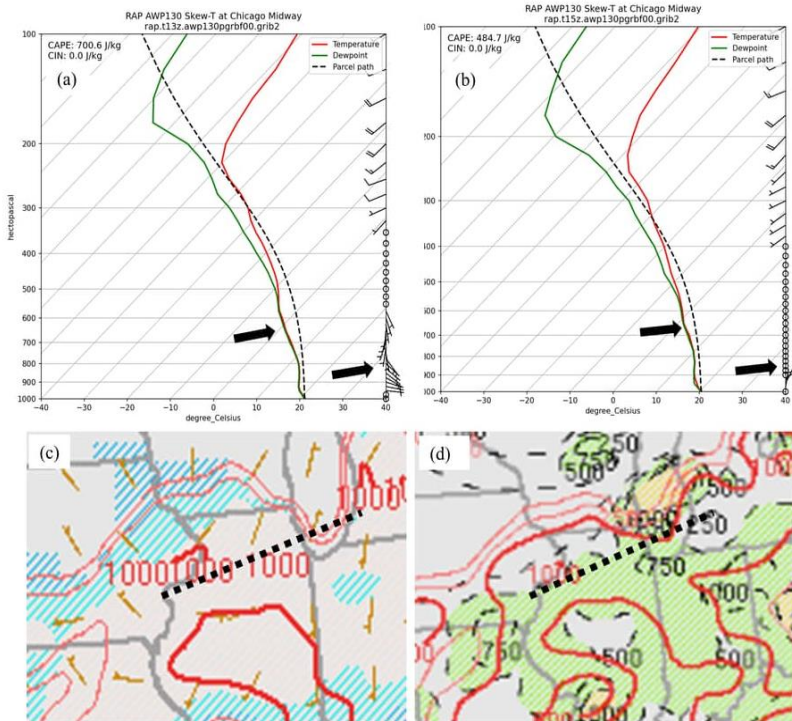
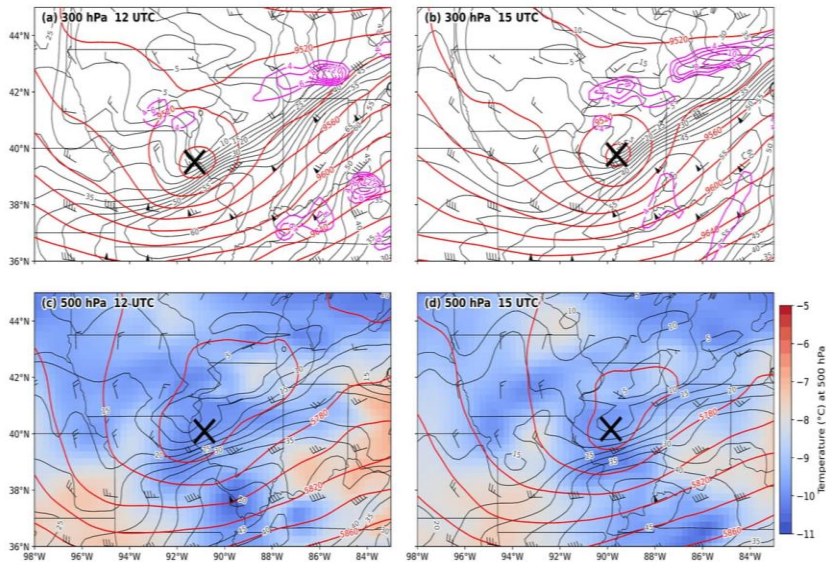


Fig. 12. RAP soundings over Chicago valid at a) 1300 UTC and b) 1500 UTC 2 July 2023. c) RAP surface-based (SBCAPE) (red contours in J kg^{-1}), SBCIN (shaded at 25 and 100 J kg^{-1}), and surface wind barbs (kt) and d) RAP most unstable (MUCAPE) (red contours in J kg^{-1}), lifted parcel level (shaded in m), and surface wind barbs (kt) all at 1200 UTC 2 July 2023. Arrows on a-b) the same as Figs. 11 a-c). Dotted black line on c-d) surface trough bisecting Chicago

4.2 Upper- and Lower-Tropospheric Cold-Vortex Forcing of QLCS#3 and T-bone Formation After Interaction with QLCS#2

In the lower troposphere (black Xs in Figs. 14a-d), the 850-700 hPa vortex became situated over the city by 15Z7/2, nearly in phase with the 500 hPa vortex, thus indicating very weak winds through the column over the metroplex, which was also consistent with the soundings in

Fig. 12. The deep west-east precipitable-moisture plume, in phase with the surface deformation zone, was aligned across the metroplex, with the 850 hPa moisture-flux transport vector oriented from southeast to northwest and directed nearly across the city (black dashed and dotted lines in Figs. 14e-f). This surface deformation zone likely reflected the initial pressure falls and convergence of the QLCS#1 trough at low levels (note Figs. 8h and 9l), which were subsequently enhanced by the jet's left-exit-region divergence aloft described earlier. Figs. 14g-n show the strengthening and evolving complexity of this trough during the first heavy-rainfall event spanning 11Z7/2-16Z7/2. A dual meso-low system developed, consistent with the evolution of the radar pattern into the "T-bone" configuration described in the next subsection. Beneath the arriving closed low aloft, a meso-low strengthened over the region between KMDW and the Lake Michigan coast on the southeastern side of the city. This was joined by another meso-low propagating into the metroplex from western Illinois in conjunction with the upper closed low and its trough/PV maximum. The pressure troughing over the city in Figs. 14g-n, together with the confluence zone (dotted black line), was first established around 07-09Z7/2 between the QLCS#1 trough and a second developing line of convection accompanying QLCS#2. It was then further joined by the meso-low and QLCS#3 propagating from western Illinois beneath the closed low aloft. This produced a "T-bone" pressure trough with surface confluence, where the northeasterly flow from QLCS#2 propagating southwestwards intersected the remnant QLCS#1 trough with southeasterly surface flow and the southwesterly surface flow accompanying the second meso-low and QLCS#3. This arc-shaped T-bone trough, and the convective squall-line intersections resulting largely from it, can best be described as two troughs formed by substantially different processes that intersected over the city. The first (QLCS#2) resulted from convection building upscale as onshore flow converged into the remnant QLCS#1 surface trough, whereas the second (QLCS#3) resulted from forcing by the upstream trough aloft. This can be inferred from the METAR data and Doppler-derived wind boundary in Figs. 14g-o, oriented west-southwest to east-northeast across the city.



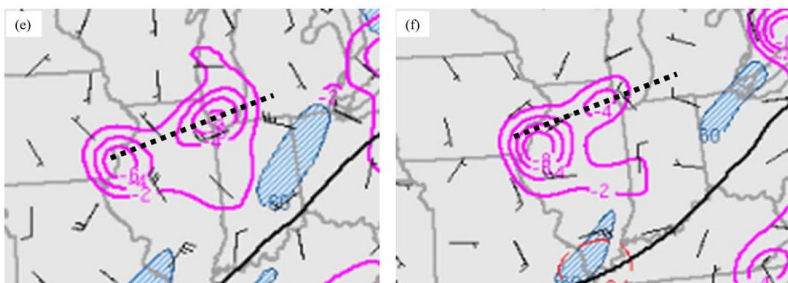
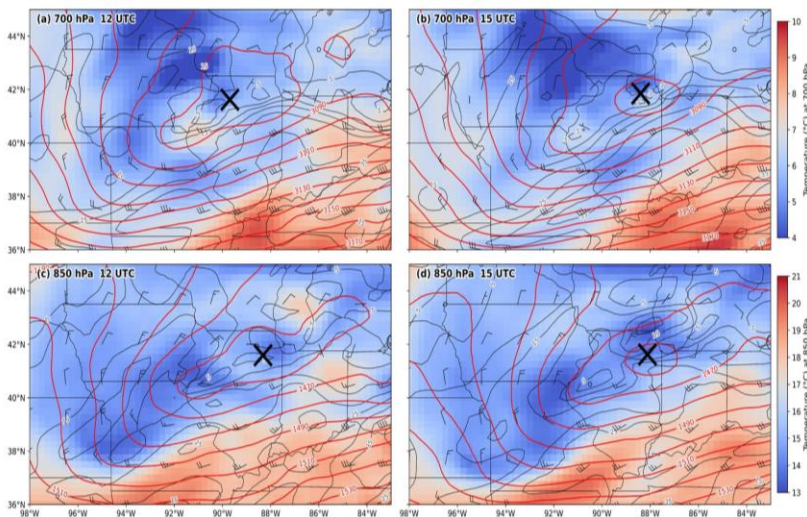
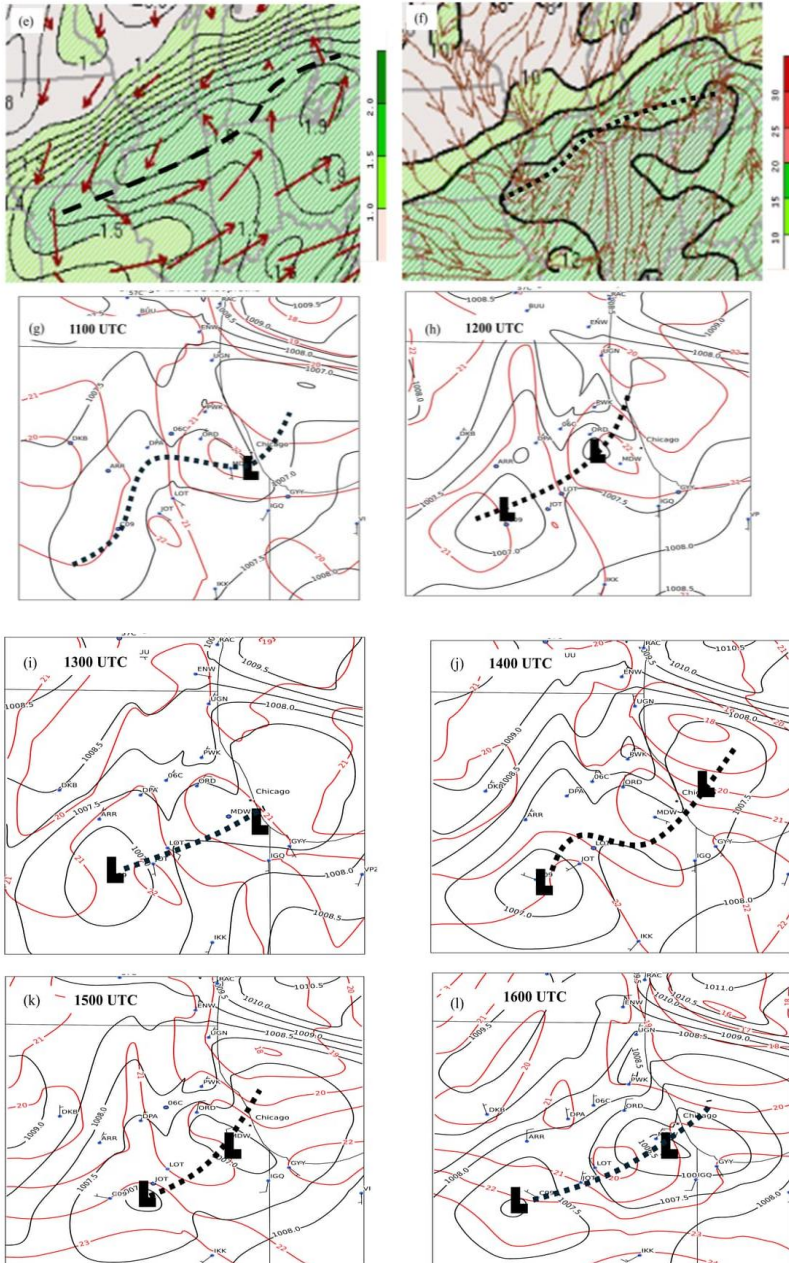


Fig. 13. As in Figures 2-4, respectively, at a-b) 1200 UTC – 1500 UTC, c-d) 1200 UTC – 1500 UTC, and e-f) 1200 UTC – 1500 UTC 2 July 2023. Black X on a)-d) is upper tropospheric vortex approaching Chicago. Black dotted line on e)-f) is the mid-tropospheric ascent location above the surface trough bisecting Chicago

Confluence in the T-bone over the city was therefore established among north-northeasterly, south-southeasterly, and west-southwesterly surface flows near KMDW. Eventually, the more eastern meso-low between KMDW and the Lake Michigan coast became the dominant of the two lows, taking over the T-bone mean sea level pressure structure by 15-16Z7/2 in Figs. 14k-l. At this time, the surface dewpoint and relative humidity, characteristic of a saturated surface layer, also took on a pattern consistent with the intensification of the more eastern meso-low and the confluence of west-southwesterly surface flow with north-northeasterly surface flow over the city during the most extreme rainfall within the first rainfall period (dashed white line in Fig. 14n).





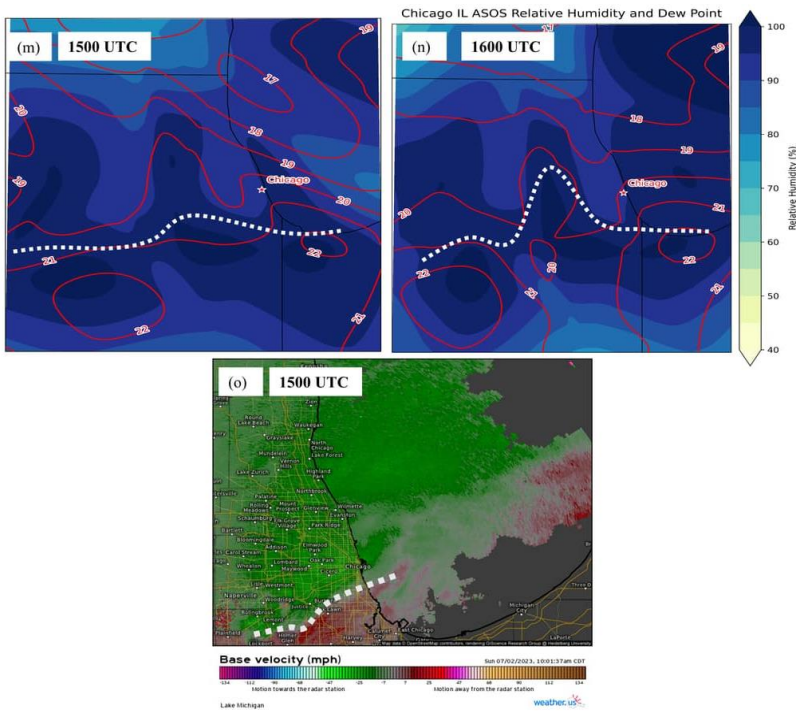


Fig. 14. As in Figs. 6-8, respectively, at a-b) 1200 UTC – 1500 UTC, c-d) 1200 UTC – 1500 UTC, and e-f) 1200 UTC – 1500 UTC 2 July 2023. Chicago area airport METAR analyses of mean sea level pressure (black solid in hPa), wind barbs (kt), and temperature (red solid in °C) valid at g) 1100 UTC, h) 1200 UTC, i) 1300 UTC, j) 1400 UTC, k) 1500 UTC, and l) 1600 UTC and surface Td (red solid in °C) and surface relative humidity (shaded in %) at m) 1500 UTC and n) 1600 UTC 2 July 2023. o) 1500 UTC base velocity from Chicago radar. Black X on a)-d) is the lower tropospheric vortex approaching Chicago. Black dashed line on e) is the axis of the precipitable water maximum and f) the accompanying surface confluence and deformation zone organizing QLCS#1. Black dotted lines on g)-l) is the surface trough and imbedded meso-lows (L) where that cold front and remnant QLCS#1 trough converge. White dashed line on m)-n) is the companion dewpoint front with the remnant QLCS#1 trough. Dotted white line on (o) is the surface trough and confluence zone based on Doppler radar signal

4.3 Radar Evolution Depicting the T-bone Structure

The radar imagery in Fig. 15 shows the most important period of convective reorganization across the city, producing the first and most significant component of the two extreme rainfall events. It shows the resurgence of convection that produced the first heavy-precipitation period as QLCS#1 gave way to QLCS#2 and QLCS#3, resulting in a T-bone radar configuration primarily between KMDW and the Lake Michigan coast on the southeastern side of the metroplex. The radar evolution after 1030Z7/2 began with a well-organized northwest-southeast band along the lakefront on the northeastern side of the metroplex (QLCS#2 in

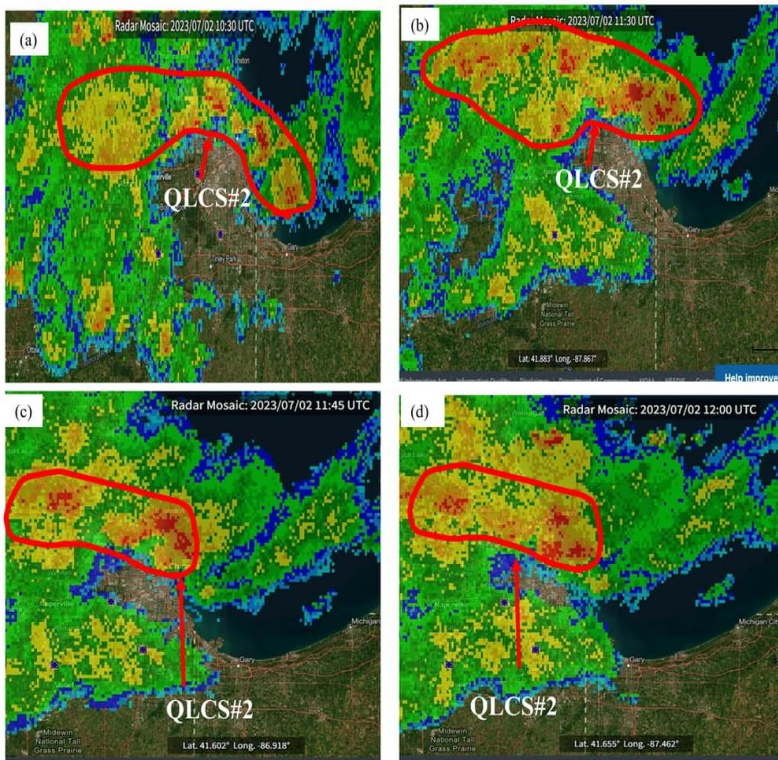
Figs. 15a-b). This represented the morning lake breeze converging into the remnant QLCS#1 trough indicated by the city-scale trough/meso-low in Figs. 14g-h (dotted black line). As this northwest-southeast convective band propagated very slowly southwestwards between 1145 UTC and 1315 UTC towards the remnant QLCS#1 city-scale trough, the detailed 15-minute radar images in Figs. 15c-i show the explosive phasing between this northwest-southeast line (QLCS#2) and a line propagating into the metroplex from western Illinois on the southwestern flank of the metroplex, i.e., QLCS#3, which was directly coupled to the closed low aloft. The 15-minute radar sequence in Figs. 15c-i indicates what appears on radar to be a collision of QLCS lines, reinforcing QLCS#2 convection and followed by the growth of the southwestern QLCS#3. The QLCS#3 line was near the second meso-low and the propagation of low-level southwesterly momentum arriving in the metroplex after 14Z7/2. Additionally, with the formation of this southwestward extension unifying both lines and completing the T-bone structure (black intersecting solid lines in Figs. 15i-l), another leading southwest-northeast line was generated and rapidly propagated into southwestern Lake Michigan ahead of the T-bone intersection. The key “T-bone” structure developed along the western flank of this second 40-50 dBZ area of convection. The T-bone extended the heavy rainfall accompanying the 40-50 dBZ echoes southwards over the western side of the city and, together with the line to its east, covered most of the Chicago metroplex. As shown in Figs. 14g-h, this T-bone radar signature reflected the geometry of the city-scale winds and surface trough in the METAR analysis in Figs. 14g-n, which was being rotated towards the southwest on its western flank, similar to the RAP low-level streamlines, precipitable-water plume, and moisture-flux vectors in Figs. 14e-f, notably the dashed and dotted black lines in those figures. In Figs. 15j-k and Fig. 18, after 1400 UTC, the “T-bone” gradually filled in with significant and more uniform > 40 dBZ echoes and drifted very slowly across the city towards the lakefront, establishing a period of some of the most intense rainfall in the region between and over KORD and KMDW, consistent with observations of the first rainfall event focused on the region around and over Berwyn inferred from Figs. 1a-b and d-e. The 14Z7/2-16Z7/2 period represented the focal point for continuous moderate-to-heavy rainfall over and near KMDW, as all these features consolidated into a region of fairly uniform but intense precipitation (>40 dBZ in Fig. 15k), with a surface north-northeast-south-southwest confluence maximum centered near or slightly south of KMDW and extending roughly west to east across the metroplex in Figs. 14j-l.

5. MCV Formation Organizing the Second Period of Heavy Precipitation over Chicago

5.1 Upper and Lower Tropospheric Circulation and Sounding Structures Indicating T-bone Evolution into an Offshore MCV

Figs. 16-18 depict the evolution of tropospheric stability and circulation as multiple QLCSs, evolved into a T-bone structure and then built into a deep circulation analogous to an MCV that strengthened over southwestern Lake Michigan. Figs. 16a-b indicate subtle warming in the saturated mid-troposphere (black arrows), i.e., 700-500 hPa during 19Z7/2-20Z7/2, as well as slight cooling below 700 hPa and increasing mid- and lower-tropospheric east-northeasterly flow backing to north-northwesterly flow during this period in the RAP Chicago soundings. SBCAPE and MUCAPE show a significant decrease as warming aloft and, most importantly, increasing wraparound cool lake airflow forced the largest instability equatorward and downstream of the metroplex (note the black arrow depicting transport of unstable air off the lake in Figs. 16c-d). Additionally, Figs. 17 and 18 support slight mid-level warming over the city, as 500 hPa warmed faster than the 700-850 hPa layer by 20Z7/2. During this period, the precipitable-water plume was almost stationary over the city, while the nearly vertically stacked vortex indicated deep, weak east-northeasterly airflow in Figs. 17f-g (note the black

dashed lines and X for the vortex location). Between the surface and 700 hPa, significant vortical structure existed by 18Z7/2 in Figs. 17d-e. Figs. 18b, d, e, and g provide an even stronger indication of the deep nature of the vortex structure extending downstream over southern Lake Michigan by 20Z7/2 (black Xs). Consistent with the reflectivity in Figs. 19f and h, the wraparound mid-tropospheric ascent over the city in Figs. 17g and 18g (dotted black line) indicated a persistent and slowly migrating region of moderate stratiform precipitation that comprised the core of the later second rainfall maximum near KMDW and in Figs. 1d-e. Fig. 17h indicates that the eastern meso-low, then moving over the lake, strengthened relative to the western one and slowly drifted offshore by 18Z7/2. The airflow over the entire metroplex adjusted to this dominant circulation and exhibited a typical cyclonic-circulation structure, with most meso- β -scale variability from the first heavy-precipitation event just 2-3 hours earlier absorbed into this broader-scale circulation between the meso- β and meso- α scales. This pattern continued through 20Z7/2 (Fig. 18h).



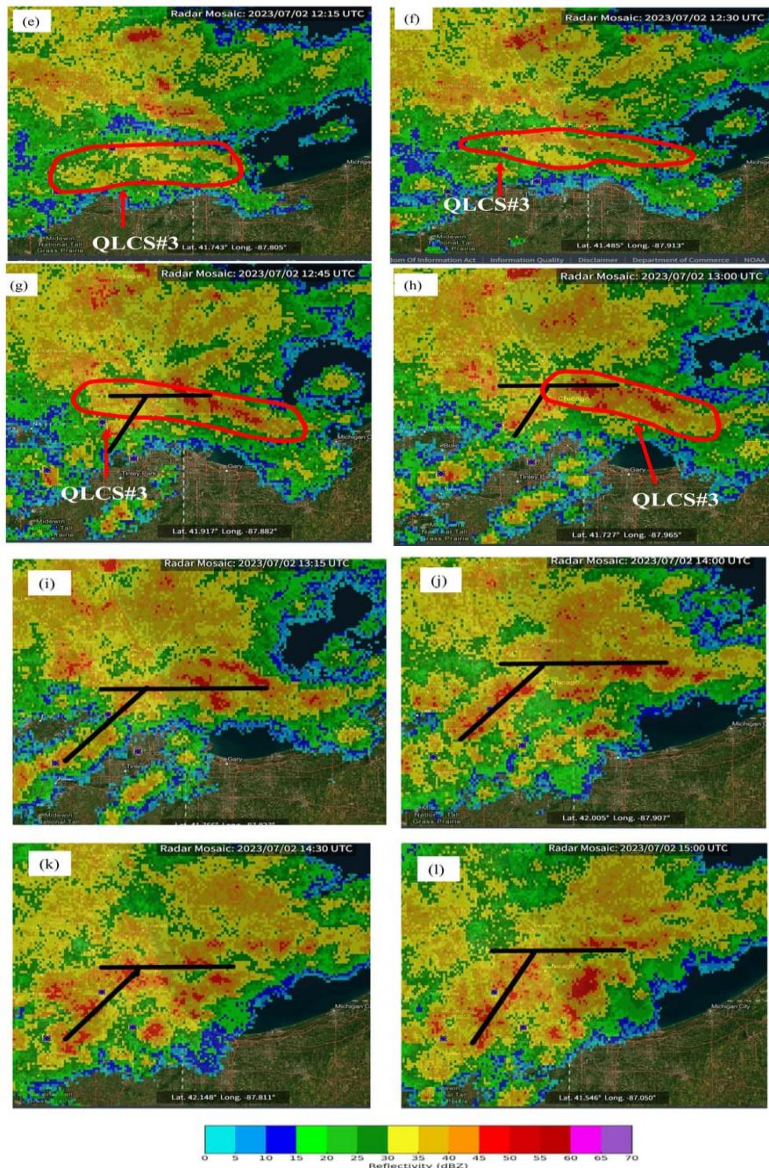


Fig. 15. NOAA NEXRAD Doppler radar composite imagery at a) 1030 UTC, b) 1130 UTC, c) 1145 UTC, d) 1200 UTC, e) 1215 UTC, f) 1230 UTC, g) 1245 UTC, h) 1300 UTC, i) 1315 UTC, j) 1400 UTC, k) 1430 UTC and l) 1500 2 July 2023. Northwest-southeast red circle represents QLCS#2 on a-d). Black solid line feature represents the “T-Bone” mentioned in the text on Figs. e-l) which represents the unification of QLCS# 2 and QLCS#3

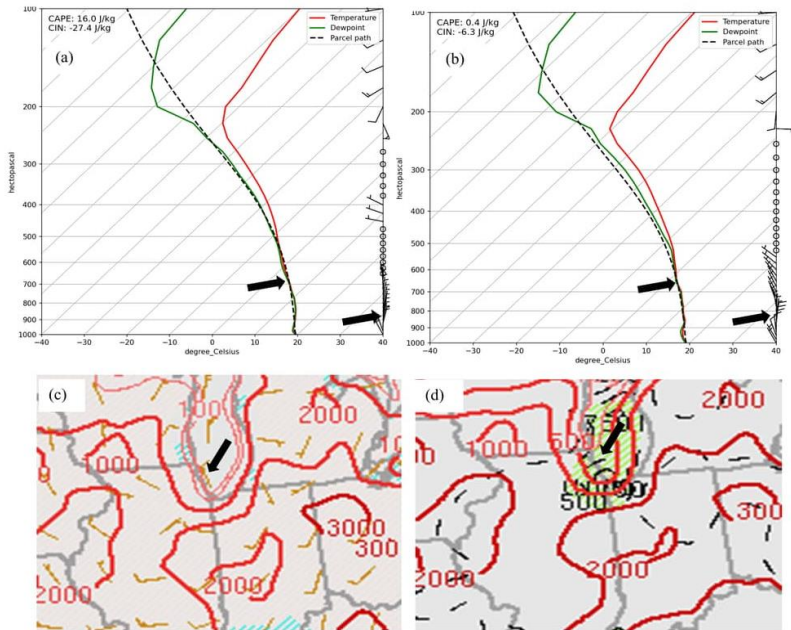
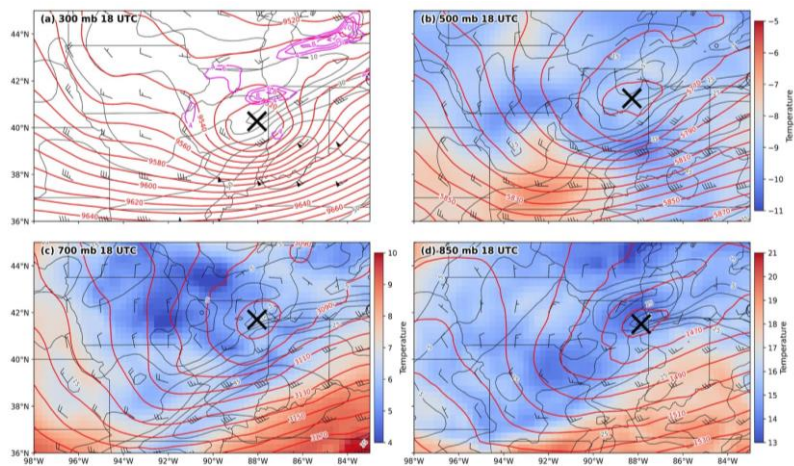


Fig. 16. RAP soundings over Chicago valid at a) 1900 UTC and b) 2000 UTC 2 July 2023. c) RAP surface-based (SBCAPE) (red contours in JKg^{-1}), SBCIN (shaded at 25 and 100 JKg^{-1}), and surface wind barbs (kt) and d) RAP most unstable (MUCAPE) (red contours in JKg^{-1}), lifted parcel level (shaded in m), and surface wind barbs (kt) all at 2000 UTC 2 July 2023. Black arrows on a)-b) same as previous soundings. Black arrow on c)-d) represents the direction and leading edge of stable airflow towards Chicago



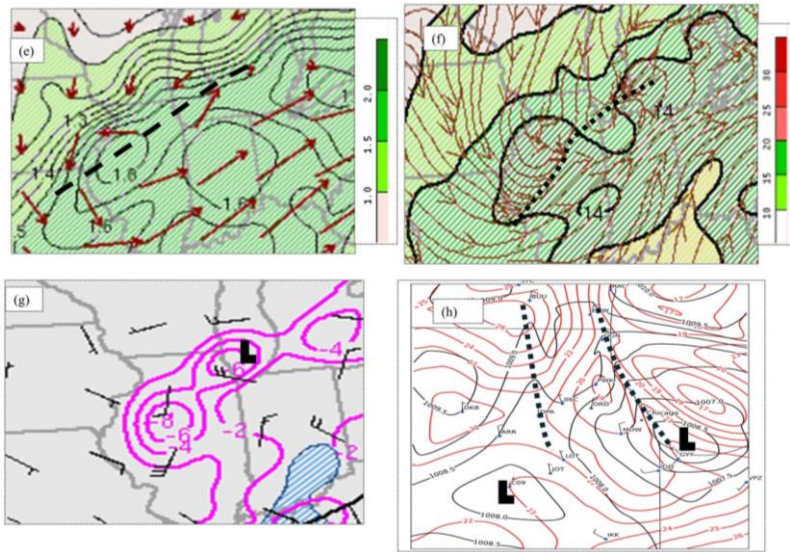
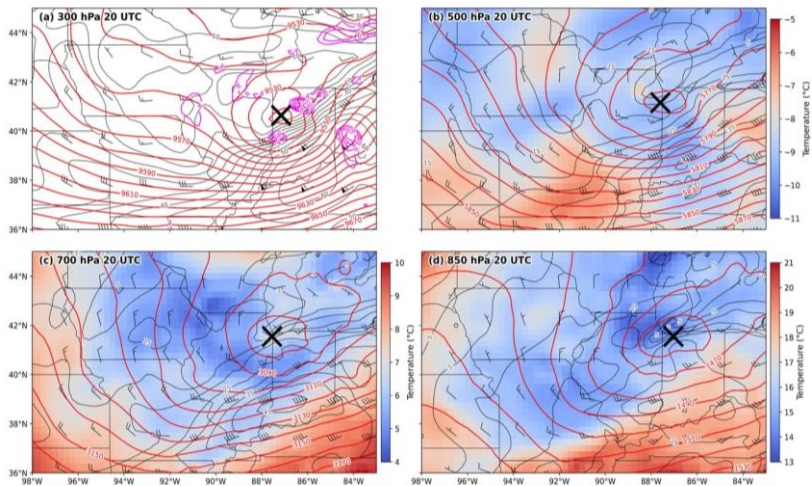


Fig. 17. As in Figs. 6-9, respectively, at a-h) 1800 UTC 2 July 2023. Black X on a)-d) is the center of the upper, mid-level, and lower tropospheric vortex approaching over Chicago. Black dashed and dotted lines on e)-f) the lower tropospheric moisture convergence zone. Black L on g) the developing mesoscale convective vortex location just southeast of Chicago. Black L is the same on (h) and black dotted lines inverted troughs over the city accompanying QLCS#2-3



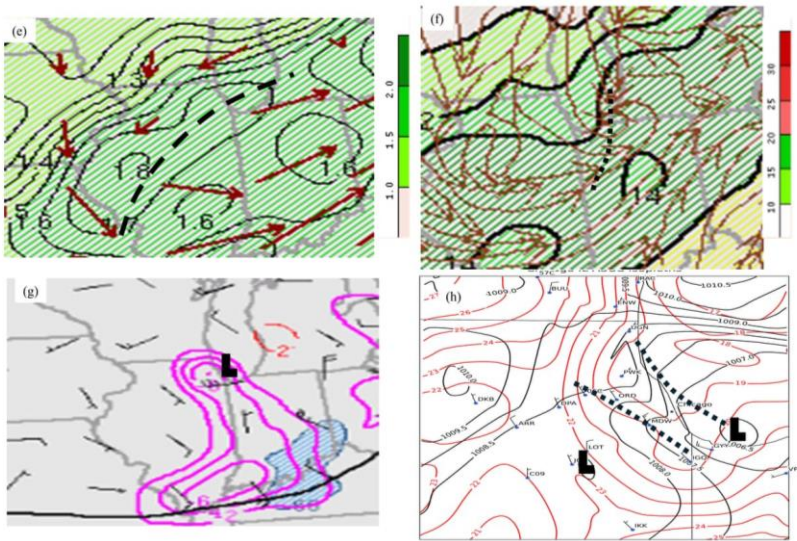


Fig. 18. As in Figs. 6-9, respectively, at a-h) 2000 UTC 2 July 2023. Black X on a)-d) is the center of the upper, mid-level, and lower tropospheric vortex approaching over Chicago. Black dashed and dotted lines on e)-f) the lower tropospheric moisture convergence zone.

Black L on g) the developed mesoscale convective vortex location just southeast of Chicago. Black L is the same on (h) and black dotted lines inverted troughs over the city accompanying merging and dying QLCS#2-3

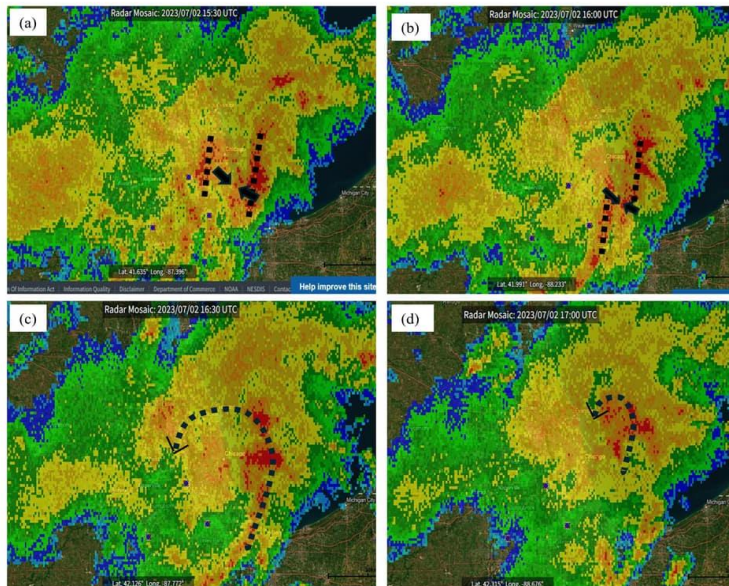
5.2 Convective Evolution from T-bone to MCV and Back-Building Precipitation Episode #2

Radar imagery in Fig. 19 from 14Z7/2 to 21Z7/2 clearly indicates that the T-bone slowly drifted eastwards across the city and, as it did so, five major changes occurred: (1) the western flank rotated equatorward like a major deformation zone separating northerly from easterly flow, thereby increasing lower- to mid-tropospheric vorticity; (2) the southern side of that deformation zone eventually thinned southwestwards and progressively filled in like a mini baroclinic-leaf system; (3) south-southeast of the location in (2), a dry surge progressed towards the vortex center over the lake from the southwestern side of the metroplex; (4) significant vortical structure organized over southwestern Lake Michigan, including mini-lines rotating around a central vortex; and (5) radar intensity gradually weakened and became more uniform, characteristic of continuous moderate stratiform precipitation with significant but progressively weaker dBZ levels. This surge in absolute vorticity and its mesoscale increase over southwestern Lake Michigan at mid-tropospheric levels, particularly during ~20Z7/2-22Z7/2, is shown in Figs. 20a-l, with evolving vorticity maxima in both ERA5 and RAP and a somewhat better-defined signal in the higher-resolution RAP. Additionally, the Chicago base-velocity data at 20Z7/2 in Fig. 20m show the following features, depicted by dotted white lines: (1) a central clear area surrounded by predominantly onshore flow; (2) mini-lines or additional onshore Doppler-flow signals; and (3) a continuation of the confluence zone lagging over the southern part of the metroplex. The green Doppler signal indicates multiple offshore surges of momentum moving back towards the radar, flanked by flow to the south or southwest, moving

away from the radar and indicating offshore motion, with a precipitation-free zone between the two surges moving back toward the radar. This likely indicates mesoscale convective vortex signature(s) offshore within the broader cyclonic circulation. As time progressed, the precipitation zone over the metroplex narrowed and weakened but departed the city only very slowly after 21Z7/2, thus ensuring a prolonged period of moderate-to-heavy stratiform precipitation that represented the end of the second major precipitation period, during which nearly half of the observed precipitation occurred near KMDW. All indicators of lower-tropospheric winds in Fig. 18 indicate a low-level jet from the east-northeast into the convective system after 15Z7/2, consistent with published studies of MCVs (Davis et al., 2004; Schumacher & Johnson, 2009).

6. Discussion

ERA5, RAP, Doppler radar, and surface observations indicate a complex multiscale evolution of the four organized convective features that constituted the two-component extreme precipitation event of 2 July 2023 over a small region of Chicago. A mid- to upper-tropospheric jet streak and cold trough with attendant dual isobaric PV maxima were critical to these convective features, forming an evolving mid- to upper-tropospheric divergence and ascent pattern. Early in the event, from ~03Z7/2 to 09Z7/2, an MCS formed in south-central Illinois in response to (1) divergence aloft within the jet's right-entrance region in proximity to (2) a low-level confluent deformation zone and (3) a low-level jet transporting large precipitable-water values beneath drier air aloft into that deformation zone, thus creating significant MUCAPE. As the central Illinois MCS strengthened and built upscale, the downstream mid- to upper-tropospheric PV, divergence, and ascent shifted to and strengthened within the jet's left-exit region. This transformed the MCS into the elongated west-to-east QLCS#1 over north-central Illinois as the low-level confluence zone intensified, transporting the moisture-rich west-east boundary/deformation zone poleward towards the metroplex with significant SBCAPE and MUCAPE.



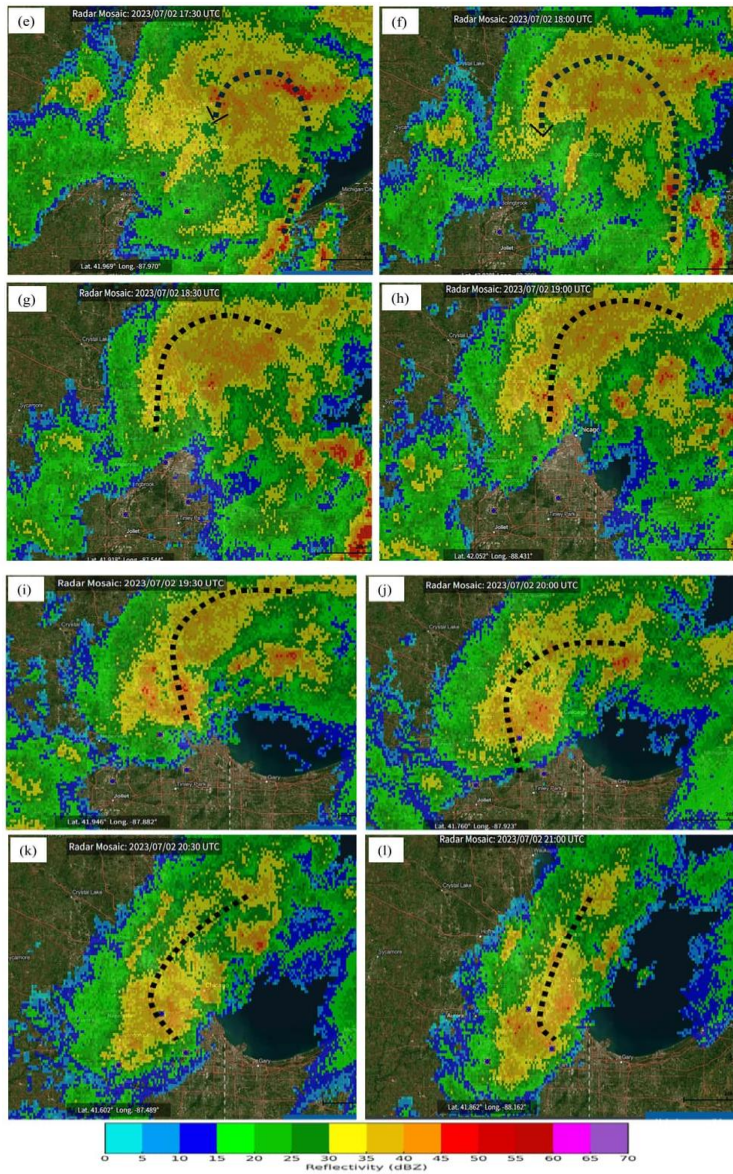
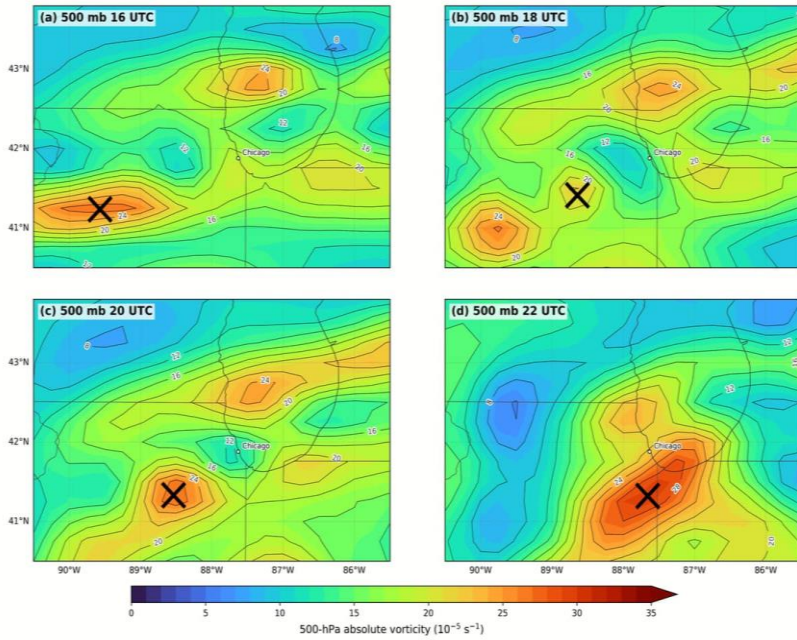
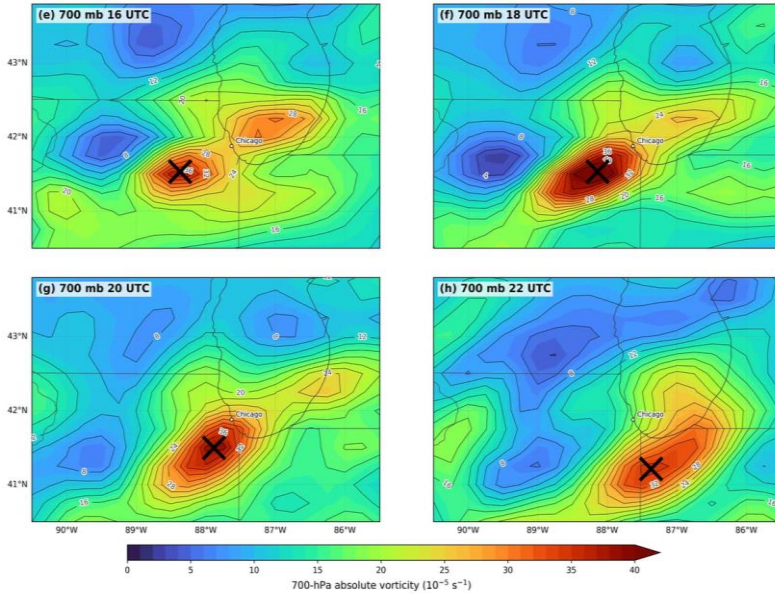


Fig. 19. NOAA NEXRAD Doppler radar composite imagery at a) 1530 UTC, b) 1600 UTC, c) 1630 UTC, d) 1700 UTC, e) 1730 UTC, f) 1800 UTC, g) 1830 UTC, h) 1900 UTC, i) 1930 UTC, j) 2000 UTC, k) 2030 UTC, and l) 2100 UTC 2 July 2023. Black dotted lines on all figures indicate evolving components of the mesoscale convective vortex and baroclinic leaf cloud system offshore and over Chicago, respectively

Evolution of 500-hPa Absolute Vorticity over Northern Illinois and Southern Lake Michigan



Evolution of 700-hPa Absolute Vorticity over Northern Illinois and Southern Lake Michigan



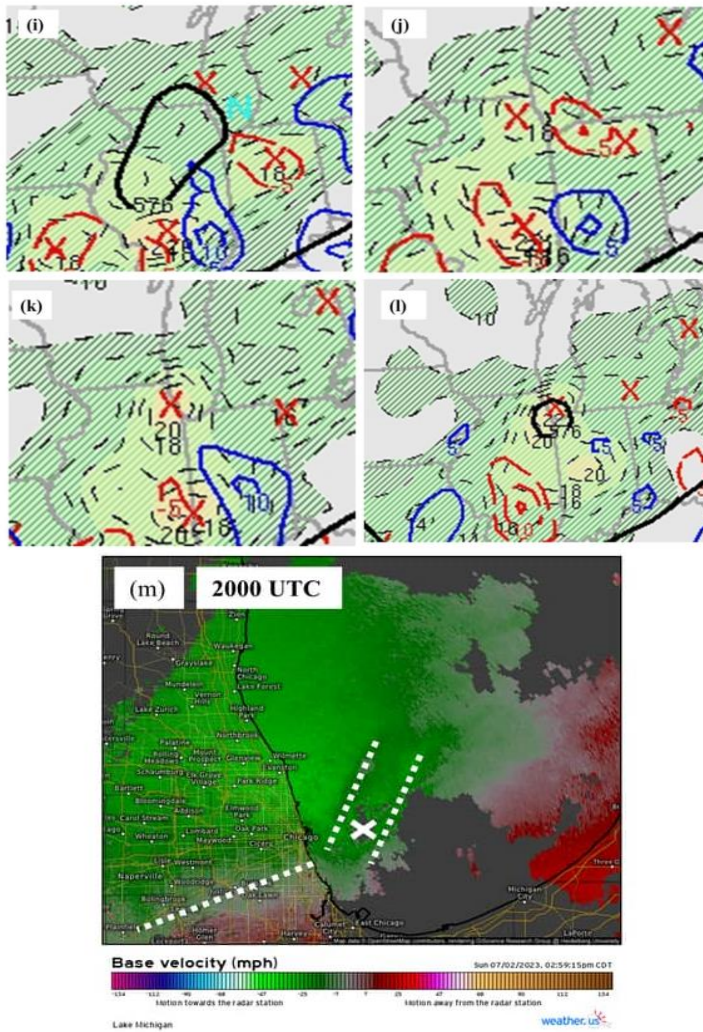


Fig. 20. ERA5 absolute vorticity (solid and fill in $\text{s}^{-1} \times 10^5$) at 500 hPa and 700 hPa valid at 1600 UTC (a&e), 1800 UTC (b&f), 2000 UTC (c&g), and 2200 UTC (d&h) 2 July 2023. RAP 500 hPa absolute vorticity (black dashed in $\text{s}^{-1} \times 10^5$), horizontal advection (red dashed positive and blue solid negative in $\text{s}^{-2} \times 10^8$), and height (m) valid at i) 1400 UTC, j) 1600 UTC, k) 1800 UTC, and l) 2000 UTC 2 July 2023. (m) 2000 UTC 2 July 2023 base velocity from the Chicago radar. Black X on a)-h) is the mid-lower tropospheric vorticity center accompanying the organizing mesoscale convective vortex also depicted with an X on i)-l). White X on m) the centroid of the offshore mesoscale convective vortex and accompanying dotted lines include confluence zones rotating around that system and lagging over the metroplex near the baroclinic leaf cloud system

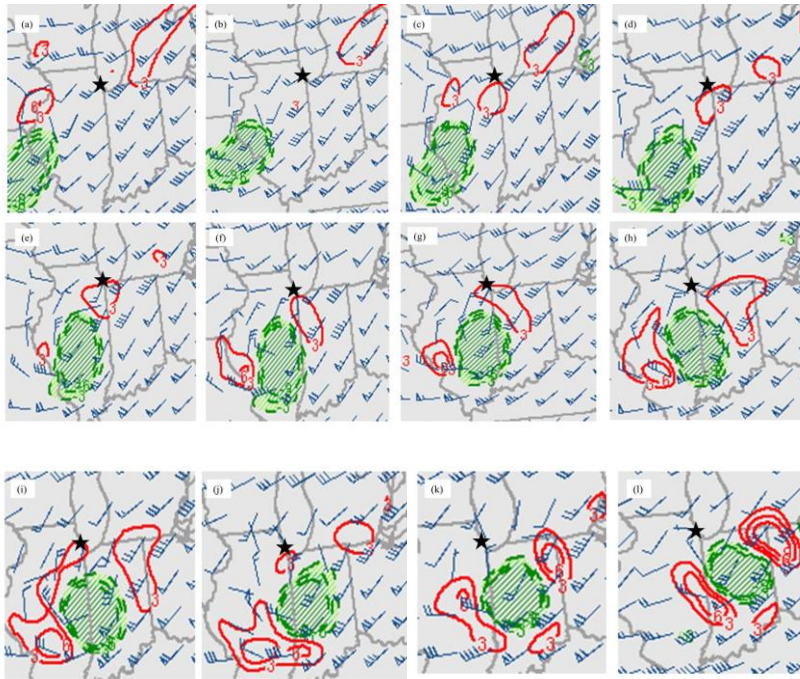


Fig. 21. RAP 250 hPa wind barbs (ms^{-1}) and fluid trapping parameter (solid red positive and dashed green (negative) in $\text{s}^{-1} \times 10^4$) valid at a) 1100 UTC, b) 1200 UTC, c) 1300 UTC, d) 1400 UTC, e) 1500 UTC, f) 1600 UTC, g) 1700 UTC, h) 1800 UTC, i) 1900 UTC, j) 2000 UTC, k) 2100 UTC, and l) 2200 UTC 2 July 2023

Following this initial organization of QLCS#1, from ~09Z7/2 to 12Z7/2 and after a brief weakening of QLCS convection over the metroplex, a surface boundary/trough/meso-low strengthened over the city in response to pressure falls beneath the jet's left-exit region and between the QLCS residual southerly flow/remnant trough and Lake Michigan-enhanced surface northeasterly flow. At ~11Z7/2 to 13Z7/2, the surface deformation zone of the poleward-propagating QLCS became nearly synonymous with the trough/meso-low over the middle of the metroplex, while vertically, between 850 and 500 hPa, the deep cold closed low propagated over the city beneath the jet's left-exit-region divergence maximum. During ~11Z7/2 to 13Z7/2, QLCS#2 developed on the metroplex's northeastern side and slowly propagated toward this city-scale trough. While elevated dry air dissipated in response to ascent and moisture advection, significant CAPE remained over the city in proximity to the deep moisture maximum coupled to the low-level confluence zone. Heavy precipitation developed, as inferred from radar, when the boundary between the southerly and northeasterly surface flows propagated southwestwards over the city. However, the most significant precipitation in the first event occurred near KMDW when a third QLCS rapidly propagated across the southeastern side of the metroplex and further energized QLCS#2 during the ~13Z to 15Z period. Convection built upscale from ~14Z7/2 to 16Z7/2 as this highly confluent meso- β -scale boundary between northeasterly, southeasterly, and southwesterly flow was deformed into a "T-bone" structure and was joined by an additional northeast-southwest-

oriented squall line equatorward of the T-bone feature. Surface pressure falls also indicated a meso-low near KMDW that eventually became dominant relative to a secondary, weaker meso-low on the southwestern flank of the metroplex during ~14Z7/2 to 16Z7/2. This defined the core of the initial heaviest precipitation period between KMDW and KORD, with the surface winds and pressure reflecting the T-bone radar structure. This first heavy rainfall event slowed the upper-tropospheric flow over Chicago, as shown in Figs. 21a-e, owing to mid-level latent heating; it also increased the fluid trapping of convection at this time. The westerly momentum decreased, and the flow became light and meridional (note the wind barbs near the star).

Shortly thereafter, at ~17Z-21Z, a second region of precipitation was organized over the city as the previous large, upscale-building precipitation area moved over southwestern Lake Michigan and developed a more vortical structure. The flow aloft over the city reflected this deep vortex as winds aloft increased from the northeast, static stability gradually increased, surface flow became more northerly, and the earlier complex surface-confluence boundary moved offshore (Figs. 21f-l). A narrowing but intense region of more uniform, moderate stratiform precipitation built west-southwestwards on the western flank of the offshore vortical feature, creating a narrow southwest-northeast heavy-rainfall region that resembled a mesoscale baroclinic-leaf precipitation zone coupled to the MCV during ~19Z7/2 to 21Z7/2 (white dotted lines in Figs. 19k-l). Within this back-building precipitation region over the city, the second period of heavy precipitation occurred between KMDW and KORD. Eventually, the precipitation ended when this wraparound feature slowly propagated east-southeastwards and dissipated after 22Z7/2.

This case study highlights how extreme precipitation events involving multiple MCSs can be organized by multiscale processes involving a large lake and semi-geostrophic baroclinic jet-front systems. Its novelty lies in going beyond idealized extreme-precipitation studies by linking adjustments across multiple scales of motion, thereby exemplifying the complexity of scale-interactive processes. However, urban heat-island forcing, which is not evaluated here, should be evaluated through numerical sensitivity studies in the companion manuscript. The findings of this study could have applications to operational forecasting because the analysis treats both larger- and mesoscale processes and their coupling in generating extreme precipitation at smaller scales. Additionally, the evolution of the T-bone structure into an MCV, creating dual episodes of heavy precipitation, may be relevant to mesoscale convective-system-induced flooding events.

In a subsequent manuscript, we will provide further detail on convective evolution over the city, focusing on the role of the Lake Michigan breeze convergence zones and their possible control of the multiple QLCs and the evolving MCV. We will focus on meso- γ -scale simulations that differentiate urban-canopy-scale forcing from more conventional land-surface representation to better diagnose how the urban heat island and city drag modify the Lake Michigan breeze forcing of convective evolution.

7. Conclusions

This study aimed to determine how observed meso-alpha and finer-scale dynamical and thermodynamic processes predisposed the Chicago metropolitan region to the extreme precipitation event of 2 July 2023 before considering any urban enhancement. Observations show the event developed within a favorable precursor environment characterized by an upstream deep cold trough, a mid-to-upper-tropospheric jet streak with dual potential-vorticity maxima, a low-level deformation zone, and a west-southwesterly low-level jet that transported

abundant moisture toward northern Illinois. As the upper-level divergence and ascent shifted from the jet streak's right-entrance region to its left-exit region, QLCS#1 strengthened and moved towards Chicago. The first heavy-rainfall period resulted from the interaction of QLCS#1 with two additional QLCs organized near the Lake Michigan breeze convergence zone and over western Illinois. Their merger over the metropolitan area produced a T-bone convective structure and focused rainfall within the corridor between O'Hare and Midway Airports. The second heavy-rainfall period occurred after this convective complex grew upscale and developed MCV-like characteristics over southwestern Lake Michigan, with persistent wraparound stratiform precipitation extending back across the city. Together, these two stages produced approximately 225 mm (9 in) of rainfall in less than 12 hours over a highly localized area. These results demonstrate that the observed synoptic and mesoscale environment was sufficient to organize and maintain the principal flood-producing systems before urban heat-island and drag effects were isolated. The most important forecast signals were the evolving jet-streak forcing, poleward moisture transport, persistent low-level convergence, interaction of multiple QLCs, development of the T-bone structure, and transition towards an MCV-like circulation. Because this observational study did not quantify urban effects, their contribution should be tested separately through numerical sensitivity simulations rather than inferred from the rainfall distribution alone.

8. Limitations

This study is based on a single extreme precipitation event over the Chicago metropolitan area, which limits the generalizability of the identified multiscale interactions to other events or locations. The observational design can diagnose associations among synoptic forcing, Lake Michigan-related convergence, and convective evolution but cannot isolate their individual causal contributions. Urban heat-island and surface-drag effects were not quantified separately. In addition, reliance on reanalysis, radar, sounding, surface, and buoy datasets introduces limitations associated with their spatial and temporal resolutions. Future numerical sensitivity studies and analyses of additional events are needed.

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Data Availability Statement

The ERA5 data used in this study are openly available from the NCAR Research Data Archive (<https://doi.org/10.5065/BH6N-5N20>) (European Centre for Medium-Range Weather Forecasts, 2019). RAP-based mesoscale analysis fields were obtained from the NOAA Storm Prediction Center (SPC) mesoanalysis archive (https://www.spc.noaa.gov/expert/ma_archive/) (Storm Prediction Center, n.d.). *The NEXRAD radar data used in this study are publicly available from NOAA/NCEI (NOAA National Weather Service Radar Operations Center, 1991).*

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammatically

ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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