A Long-Lived Mesoscale Convective Complex. Part II: Evolution and Structure of the Mature Complex

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ABSTRACT

An eight-day episode in August 1977 is described, wherein 14 mesoscale convective complexes (MCCs) developed in the central United States, including one to the immediate lee of the Rocky Mountains on each day of the episode. In Part I of this article, the daytime genesis of one of these systems was traced from its pre-convective roots in the mountains of central Colorado to its incipient MCC stage on the plains of eastern Colorado. In this paper, its continued nocturnal development into a large MCC over Kansas is followed. Satellite imagery shows that this system remained coherent for at least three days as it passed off the east coast and across the western Atlantic Ocean.

Analysis is focused on the mature stage of this and a second MCC in the episode in order to compare their major dynamic features to those of similar midlatitude systems reported in the literature, and also to previous studies of tropical mesoscale convective systems. Many of the important characteristics of midlatitude MCCs found by other authors are consistent with those studied here. In addition, significant similarities were found between the structure of these MCCs and developing tropical cloud clusters. It is concluded that the MCCs analyzed here are basically tropical in nature.

A number of previously unreported features are found common to the two MCCs studied here. Among these are a 50 kPa divergence/convergence couplet, hypothesized to be an adjustment of the flow around an "obstacle," and a ring of convergence at 20 kPa surrounding the large circular, divergent anvil region. Also, the high-speed upper-tropospheric outflow in the vicinity of the MCCs is shown to be shallow, indicating that the effect of these systems on the upper-tropospheric flow, in terms of changes in total kinetic energy, may not be as large as implied in previous work. Finally, computations show that while the two MCCs generated vertical velocities comparable to those associated with cyclogenesis, they transported virtually no heat meridionally, suggesting that MCCs are primarily driven by buoyant forces.

1. Introduction

During the summer months, nocturnal maxima of thunderstorm frequency and heavy precipitation occur over a broad region of the Central Plains (Wallace, 1975). More than 60% of all precipitation during the months of June, July and August falls between the hours of 2000 and 0800 local time within an area covering Nebraska, Kansas, Iowa and northern Missouri (U.S. Weather Bureau and U.S. Corps of Engineers, 1947). Evidence suggests that this precipitation frequently comes from mesoscale convective complexes (MCCs; Maddox, 1980, 1981) which originate as afternoon convection over, or immediately leeward of, the Rocky Mountains, and which then move eastward, growing in response to the high moisture content of the air over the Great Plains (Crow, 1969; Dirks, 1969; Wetz, 1973; Henz, 1974). In the accompanying paper (Cotton et al., 1983, hereafter referred to as Part I), the development of one such system has been documented from its convective-scale roots in the mountains of Colorado until it crossed the Colorado/Kansas border. In this paper, the subsequent evolution of the system is documented. We examine its growth into a large meso-α-scale (Orlanski, 1975) system over the Great Plains, emphasizing its structure at this mature stage. Following this phase the storm weakened and proceeded eastward across the country and over the western Atlantic Ocean.

Newton and Katz (1958) and Newton and Newton (1959) tracked mesoscale systems which survived for longer than a day as they traveled great distances across the United States. Generally, these systems were accompanied by synoptic-scale baroclinic waves and took the form of squall lines. However, the system studied here appears more comparable in structure to the MCCs studied by Maddox (1980), Bosart and Sanders (1981), Maddox et al. (1981) and Maddox and Doswell (1982). Those systems had a roughly circular anvil shape as seen by satellite. They existed for periods

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from 6 h to several days, during which they have been shown to produce significant precipitation and occasional severe weather, and to strongly modify the larger-scale environment.

The case to be discussed in this paper is set in the context of an eight-day episode, during which a series of MCCs developed and moved across the country, producing heavy rain and some flooding over an extensive region. In the following section, an overview of the entire episode is presented. In Section 3 we discuss the general evolution of the 4 August 1977 system from its initiation through its most intense mature stage, and to its passage across the western Atlantic. In Section 4, the structures of this MCC and the previous day's MCC, when each was in its mature stage over the Great Plains, are explored in some detail.

2. The episode: 3–10 August 1977

During the period from 3 to 10 August 1977, the eastern two-thirds of the United States was dominated by an approximately steady-state pattern of moist southwesterly low-level flow south of a weak, roughly stationary front, which extended from Colorado across northern Illinois and into New England. North of the front the airmass was slightly cooler and drier than the airmass to the south, with generally weak and variable low-level flow. Convective systems were observed to develop daily near the Colorado Rockies, and on most days also in the lower Missouri and Mississippi River basins, and move generally eastward along this stationary front, sometimes maintaining their identity for several days (see Fig. 1). The eight-day total precipitation distribution for the United States east of the Continental Divide (Fig. 2), based on the average accumulation within each 1° latitude/longitude block, illustrates the significance of the MCC activity during the episode. A coherent band of relatively heavy precipitation (exceeding 20–40 mm) resembles the MCC track density in Fig. 1: it originates over an extensive region along the eastern slopes of the Rockies, converges into a more intense and concentrated swath across the Central Plains and Midwest, and then broadens and diminishes to the south and east of the Great Lakes. Precipitation in this band from the High Plains to the eastward extent of the 40 mm isohyet ranged from about 130 to 500% of the mean amount for an eight-day early-August period, with the rest of the country having below or near-normal amounts (means based on Visher, 1954). The narrow band of excessive precipitation (exceeding 60–100 mm) from western Kansas to New York was aligned just to the south of the quasi-stationary surface front and marked the axis of numerous severe weather reports, including tornadoes, hail and damaging winds. Minor flooding occurred in a number of locations along this band; for example, on 6 August, Parke County in west-central Indiana received 175–225 mm of precipitation in 6 h and a total of 250–325 mm in 24 h.

The synoptic pattern which produced this episode has been discussed in Part I. Briefly, the episode began when an anomalously strong blocking ridge developed off the U.S. west coast and extended northward across eastern Alaska, with a broad, stationary cyclonic circulation downstream, centered over Hudson Bay. This development initiated a slow, steady flow of cool Canadian air southward to meet tropical air from the Gulf of Mexico and form the stationary front mentioned above. These features persisted throughout the eight-day period and are well reflected in the mean 50 kPa height field for the period and its departure from the climatic August mean, shown in Fig. 3. Weak short waves were observed circulating around the stationary 50 kPa low center over Hudson Bay. These were occasionally associated with particular convective systems during part of their lifetimes. The last and strongest

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**Fig. 1.** Tracks of the centroids of the 14 MCCs which developed during the episode of 3–10 August 1977. Circled number is the system number from Table 2. The date is given near the 0000 GMT symbol.
short wave triggered the end of the episode on 10 August when it pulled a surge of cool, dry Canadian air southward across the Great Plains to Texas. The mean 50 kPa height pattern shows that the Colorado Rockies were under a generally anticyclonic flow. This flow, which was more moist than normal, appears to have

originated at low latitudes over the eastern Pacific or possibly from Mexico. It reached Colorado as part of the circulation around the subtropical high pressure cell over New Mexico, which was only slightly stronger than average. It has long been known that a monsoon-like circulation brings moisture of tropical origin into Arizona and Utah (Bryson and Lowry, 1955; Hales, 1974). The moisture reaching Colorado from the south and west during this episode appears to have been the result of an extension of this monsoon flow into Colorado.

During the eight-day period, 14 cloud systems that reached MCC dimensions at some time during their existence, developed and propagated along similar paths across the United States. An MCC is defined according to the infrared (IR) satellite criteria adapted from Maddox (1980) and presented in Table 1. An IR image of a large MCC at its mature stage over eastern Kansas is shown in Fig. 4 of Part I. This system, which developed on the High Plains on the afternoon of 3 August, was the first in the series of 14.

Fig. 1 shows the tracks of the cloud-shield centroids associated with each of the 14 systems during the episode. Nine of the systems developed to the immediate lee of the Rocky Mountains, with at least one developing each afternoon of the episode. The remaining five systems developed west of the Mississippi River in Missouri or Iowa. The first three systems of the episode, including the two to be discussed in later sections, survived intact for at least three days, and can be tracked well into the Atlantic Ocean. Based on the analysis of satellite IR isotherm areas shown, these systems appeared to reintensify over the Appalachian Mountains on the afternoon of the second day of their life, and/or over the Atlantic Ocean, possibly in the vicinity of the Gulf Stream.

The third MCC of the episode, which developed on 5 August (system 3 in Fig. 1) followed a somewhat more southerly path than the first two, and seemed to follow the scenario for ideal evolution of a long-lived convective complex. It survived for at least three days, reintensifying three times apparently in response to

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**TABLE 1. Definition of Mesoscale Convective Complex (MCC).**

Based on GOES enhanced IR satellite imagery, the system must meet all of the following criteria (modified from Maddox, 1980).

1. A contiguous apparent blackbody temperature less than −32°C covering an area greater than 100,000 km².
2. An apparent blackbody temperature less than −53°C with an area greater than 50,000 km².
3. Area requirements 1 and 2 must be continuously met for at least 6 h.
4. At the time of maturity, the width/length ratio of the −32°C isotherm must be greater than 0.7. This is to distinguish MCCs from squall lines. The time of maturity is defined as the time at which the coldest apparent blackbody temperature is reached during the period described in 3.
favorable convective conditions: first over the High Plains, second over the Appalachian Mountains, and third near the Gulf Stream. Bosart and Sanders (1981) documented a mesoscale disturbance in considerable detail over a five-day period, during which it underwent three intensification cycles over land and another over the Atlantic. Such long-lived systems are probably not common events, however, since they require a rather specific combination of environmental factors to sustain them.

Some further statistics regarding the 14 storms in the episode are given in Table 2. Note that nearly all the MCCs listed reached their mature stage between 0600 and 1200 GMT, early morning local time (Central Standard Time = GMT - 6 h). A similar finding for a much larger sample of MCCs was reported by Maddox (1980). Bosart and Sanders (1981) noted this tendency in the intensification cycle of the disturbance they studied. One explanation for the nocturnal preference of these systems is the enhanced convergence produced by a low-level jet. Evidence of these jets was apparent in rawinsonde data south of many of these storms. Past studies have noted the link between the increase in inflow afforded convective storms by the low-level jet and the nocturnal thunderstorm phenomenon (Means, 1952; Pitchford and London, 1962; Bonner, 1963; Raymond, 1978). The correlation, both in space and time, between the climatological peak intensity of the low-level jet (Bonner, 1968) and the mature stage of many of the MCCs listed in Table 2 and documented by Maddox (1980) suggests a link between the two phenomena, although the physical relationship of cause and effect requires further study.

3. Evolution of the 4 August storm

In Part I it was shown that the convection developing over the central mountains of Colorado on the afternoon of 4 August 1977 occurred in a region of enhanced mid-level moisture, probably of tropical origin.
Table 2. Statistics of convective systems spawned during the 3–10 August 1977 episode which reached MCC dimensions.

<table>
<thead>
<tr>
<th>System no. (from Fig. 1)</th>
<th>Time of maturity (GMT) based on 3 h analysis</th>
<th>Area of −53°C isotherm ($\times 10^2$ km²)</th>
<th>Area of −32°C isotherm ($\times 10^3$ km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>0900 4 Aug</td>
<td>260</td>
<td>341</td>
</tr>
<tr>
<td></td>
<td>2100 5 Aug*</td>
<td>146</td>
<td>344</td>
</tr>
<tr>
<td>2</td>
<td>0900 5 Aug</td>
<td>215</td>
<td>336</td>
</tr>
<tr>
<td></td>
<td>0900 7 Aug*</td>
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<td>0600 6 Aug</td>
<td>221</td>
<td>380</td>
</tr>
<tr>
<td></td>
<td>2100 6 Aug†</td>
<td>74</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td>1200 8 Aug*</td>
<td>104</td>
<td>216</td>
</tr>
<tr>
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<td>101</td>
<td>136</td>
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<td></td>
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<td>99</td>
<td>152</td>
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<td>134</td>
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</tr>
<tr>
<td>14</td>
<td>0900 11 Aug</td>
<td>104</td>
<td>391</td>
</tr>
</tbody>
</table>

* Does not qualify as an MCC due to excessive width/length ratio.
† Does not qualify as an MCC due to short duration.

The convection grew and organized in a region which was to the anticyclonic side of an apparent weak subtropical jet stream. By 0000 GMT 5 August, a north–south line of convection had organized as it moved away from the Rockies and approached western Kansas. The first in a sequence of IR satellite pictures (Fig. 4a) shows the storm near this time. It was shown in Part I that this convection developed from orographic lifting along the eastern slopes of the Rocky Mountains, partly in association with a surge of cool air that had moved southward over the northeast Colorado High Plains earlier on 4 August.

By 0400 GMT 5 August (Fig. 4b), a second line of thunderstorms had appeared ahead of the initial convection and was oriented east to west across Kansas. Meso-analyses of 3 h surface data for the afternoon and evening of 4 August (Figs. 5a–d) indicate that this convective line occurred along a pre-existing discontinuity across southern Kansas, well to the south of the first Canadian cold front extending from eastern Colorado into eastern Nebraska.

Objective surface analyses for 0300 GMT (Fig. 6a) show that north of this discontinuity, the air over most of Kansas was very moist and in easterly flow, while to the south, the air was much drier, slightly warmer, and in south–southeasterly flow. (The objective analysis

Fig. 5. Meso-analyses of surface pressure reduced to sea level, at 3 h intervals for the afternoon and night of 4–5 August 1977. Contours are labeled in $10^{-1}$ kPa with the prefix 10 omitted. Surface discontinuities are also analyzed.
technique is discussed in Part I.) Analysis of hourly precipitation data has shown that this discontinuity closely followed the southern boundary of the precipitation which fell from the previous day's MCC. In fact, the area of mixing ratios in excess of $15-16$ g kg$^{-1}$ in Fig. 6a coincides very closely to the pattern of measurable precipitation from the first MCC.

The divergence field computed from the gridded winds at 0300 GMT (Fig. 6b) shows a coherent band of pronounced convergence extending from the Texas panhandle northeastward along the southern Kansas discontinuity. This convergence provided low-level forcing to help initiate the new convective line. In western Kansas, low-level convergence, coupled with pronounced terrain-induced vertical velocity and strong easterly moisture advection, provided ideal conditions for the continued growth of the mountain-generated component of the developing MCC. Though intense low-level forcing was also present around the southern and eastern periphery of the southern meso-$\beta$-scale (Orlanski, 1975) convective cluster that had developed in northeast New Mexico, there was insufficient moisture to sustain that system.

The maximum expansion rate of the MCC cloud shield occurred between 0300 and 0600 GMT as the orographic and southern Kansas convective groups lost their respective north–south and east–west linear structures. Activity in the southern Kansas line shifted northeastward along the discontinuity into northeastern Kansas, re-establishing a meso-high in that area by 0600 GMT (Fig. 5d). The continued development in this region was well south of the cold front in eastern Nebraska. While the southern component of the orographic convective line was weakening in the Texas panhandle, intense development continued near the eastward-propagating intersections of this line with the southern Kansas discontinuity and with the weak cold front in southern Nebraska (Figs. 5c–d), as indicated by the coldest IR cloud tops in those regions at 0400 MDT (Fig. 4b). The surface divergence field at 0600 GMT (Fig. 7) depicts marked convergence near and between these intersections. With ample fuel over central Kansas (as reflected in the equivalent potential temperature ($\theta_e$) field) to feed this region of strong low-level forcing, the intense convective centers near the intersections consolidated into a larger, more unified area of intense convection over central Kansas. This region became the apparent heart of the MCC, with a coherent circular area of cold convective outflow

grid points, proportional to 10 m s$^{-1}$ key vector in upper left); and for (b) terrain-induced vertical velocity [heavy contours (solid and at 5 mm s$^{-1}$ intervals for non-negative contours, dashed and at 10 mm s$^{-1}$ intervals for negative contours, hatched for $>-5$ mm s$^{-1}$)] and divergence (thin contours, $10^{-2}$ s$^{-1}$, dashed for negative contours, shaded for $<-2 \times 10^{-2}$ s$^{-1}$). Mesoscale features are from Fig. 5(c). Gridded terrain heights are shown in Part I, Fig. 22.
Three hours later at 1200 GMT (Fig. 4e), the system exhibited signs of decay as the $-53^\circ$C isotherm began to break up and shrink. The surface analysis at this time (Fig. 5f) shows a large meso-high entering Missouri. Although there were no indications of strong downdraft winds, the computed divergence field (not shown) indicated pronounced divergence throughout eastern Kansas and northern Missouri.

Because the entire genesis, intensification, and early weakening of the MCC occurred between the rawinsonde observation times of 0000 and 1200 GMT 5 August, the preceding discussion has necessarily focused on surface and satellite data. As described in Part I, the upper-level fields at 0000 GMT were relatively weak, with convergent, low-level easterly up-slope flow providing the dominant forcing for convective development on the High Plains. By 1200 GMT, a broad low-level jet evident at 0000 GMT through north Texas, Oklahoma, and southern Kansas veered from southerly to southwesterly, consistent with the mean nocturnal tendencies of the jet as described by Bonner (1968). Marked warm advection by this southwesterly airstream into the MCC had developed below 70 kPa by 1200 GMT, similar to the MCC cases reported by Maddox (1981), Maddox and

Persisting from before 0600 through 0800 GMT. The GOES-West image at 0645 GMT (Fig. 4c) shows the MCC during this stage.

The unified anvil produced by the MCC continued to expand in a circular fashion until about 0900 GMT (Fig. 4d). Note that the active anvil lobe centered on the northeastern Kansas/Missouri border appears somewhat independent of the larger, more MCC-like anvil centered over northern Kansas. Although IR temperatures of the convective outflow were not as cold as during the previous 3 h, the storm complex had reached its greatest size ($-53^\circ$C IR isotherm area) and was producing considerable precipitation at this time. Many areas had reported well over 25 mm of rain and Perry Lake in Jefferson County, northeastern Kansas, reported 107 mm of precipitation as a result of this system. The 0900 GMT surface divergence field (Fig. 8) shows an elongated convergence band along the southern periphery of the main MCC anvil and extending into northeastern Kansas between the two anvil segments. With the higher $\theta_v$ values centered over northeastern Kansas, convective activity in the southern and western portions of the MCC subsequently weakened rapidly.
Doswell (1982) and Bosart and Sanders (1981). Given the mean oscillatory nature of the low-level jet (Bonner, 1968), this dominant lower-tropospheric forcing probably maximized several hours earlier when the MCC was at its most intense stage.

As seen in Fig. 5, the second, stronger surge of Canadian air, associated with a developing weak cyclone over western Ontario, was rapidly approaching the area of the MCC during the evening and night of 4–5 August 1977. As this front reached the decaying MCC after sunrise on 5 August, new convection appeared to be triggered by the frontal lifting. Through the afternoon of 5 August, radar and satellite data show an area of thunderstorms linked loosely by a general area of thin cirrus which continued to propagate eastward along and ahead of the front. By the time the storm system reached western New York around sunset on 5 August, it had weakened considerably. By 1500 GMT 6 August, the remaining cloud system, consisting mostly of middle level clouds and rain showers, was moving off the coast of Maine. Satellite imagery was used to track the system further east. It appears to have intensified by the time it reached 50°W at 0600 GMT on 7 August (see Fig. 1). Following this, the satellite information deteriorates due to the high viewing angle, but the system, apparently associated with the surface front, was still visible until at least 0000 GMT 9 August.

Fig. 9. Radar composite chart for 1135 GMT 5 August 1977. Information extracted from the National Weather Service radar summary chart includes the scalloped areas of scattered rainshowers and thunderstorms, echo top heights (km MSL, denoted by dots), system movement (barbed arrows, full barb = 10 km h⁻¹), and cell movement (arrows labeled in km h⁻¹). The dashed lines enclose intense, dense convection organized into meso-β lines and/or clusters, as revealed by low-elevation PPI photographs from the three NWS radars located at the ×’s. Thin dashed lines INL-GGG and DDC-DAY denote cross sections for Figs. 11 and 12.

![Figure 9](image-url)

Fig. 10. 50 kPa height analysis (labeled in dam) for 1200 GMT 5 August 1977, with winds plotted (full barb = 5 m s⁻¹). Short-wave troughs are shown as thick dashed lines. Thin dashed lines INL-GGG and DDC-DAY denote cross section locations for Figs. 11 and 12.

4. Structure of the mature MCC

a. The 4–5 August storm

This section examines some aspects of the interaction of the MCC which developed late on 4 August 1977 with its environment, as deduced from rawinsonde observations at 1200 GMT 5 August, about three hours after the most extensive phase of the storm. Inferences about the nature of the circulation generated by the system are based on the evidence presented.

The radar structure of the MCC near 1200 GMT 5 August is shown schematically in Fig. 9, which was synthesized from the corresponding National Weather Service (NWS) radar summary chart and from low-elevation PPI photographs from three NWS radars. The scalloped boundaries depict the area within which widely scattered rainshowers and thunderstorms were occurring, while the dashed lines enclose smaller areas of denser, more intense convection that was organized into meso-β lines and/or clusters. The roughly circular shape of the storm, apparent from the satellite perspective, is confirmed by the radar depiction. Highest echo tops were located on the northwestern flank of the storm, where frontal lifting was probably enhancing the convection at this time (see Fig. 5f). The surface cold front was associated with a weak short wave at 50 kPa (Fig. 10), which had moved southeastward from the Canadian prairies over the previous 24 h. The MCC itself was located near the southern limit of the westerlies and very close to the subtropical anticyclone, in a region of rather weak vertical shear and anticyclonic horizontal shear.
Isentropic analysis of a north–south cross section is presented in Fig. 11. The analysis shows that the surface cold front in the vicinity of the MCC was associated with the polar front jet, located near the United States/Canada border at about 25 kPa. A lower-tropospheric cool pool over Topeka, well south of the polar front, in this and subsequent cross sections is consistent with the MCC case reported by Bosart and Sanders (1981).

A moisture analysis (not shown) suggests that the inversion feature at 40 kPa in the vicinity of the convection was a result of subsidence. Although the Topeka (TOP) sounding was contaminated by nearby convection, the soundings from Monett (UMN) and Omaha (OMA) reveal a significantly drier airmass above the inversion than below it. Further evidence of this subsidence can be seen in Fig. 12, an east–west cross section through Topeka for the same time. Between 20 and 40 kPa west of Topeka, the isentropes slope sharply downward toward the east. Since the wind was from the west in that vicinity, subsidence is the most likely result. East of the storm, in the upper troposphere over Peoria (PIA), one finds a rather shallow layer of high-speed westerly flow. Satellite film loops show that cirrus clouds spreading outward from the MCC anvil covered a broad area including most of the state of Illinois by 1200 GMT 5 August, leading to the conclusion that the MCC was the source of the high-speed air in the wind maximum. Further evidence to support this point is presented later.

Focusing further on the upper-level structure in the vicinity of the MCC, we look at the 20 kPa analysis as it evolved between 0000 and 1200 GMT on 5 August. Fig. 13a shows that the pre-MCC convection in eastern Colorado was developing in a region of largescale, weak anticyclonic flow, with weak vertical wind shear. Twelve hours later (Fig. 13b) a closed anticyclone had developed over the MCC, with a length scale similar to that of the storm. Also apparent from a comparison of Figs. 13a and b is an acceleration of the flow north of the storm. This manifests itself both in increased wind speeds and in the slight cross-contour component of the flow toward lower heights at stations north of the convection in Fig. 13b. Such acceleration has also been observed in association with other MCCs (e.g., Maddox et al., 1981). The anticyclone developed over the MCC as a result of a significant warming of the upper troposphere. This is evident from the 12 h change in the 50–25 kPa thickness presented in Fig. 14. The maximum thickness increase of over 60 m, corresponding to a mean warming in this layer of over 3 K, was centered over the MCC and was focused to the length scale of the MCC. The maximum thickness decrease of over 40 m in eastern Colorado marks the location at 0000 GMT 5 August of the convective line that evolved into the MCC and represents a cooling of over 2 K in the 50–25 kPa layer as the convection moved on to the east. The continuity implied by the scale, location and magnitudes of these extremes in

![Figure 11](https://example.com/fig11.png)

Fig. 11. North–south cross section at approximately 95°W for 1200 GMT 5 August 1977. Analyzed are wind speeds (dashed lines, m s⁻¹) and potential temperature (thin solid lines, K). Significant inversion features are located with heavy solid lines. The extent of the cross section covered by the MCC cloud shield (IR temperatures colder than −32°C) is indicated by the bar along the top, while the bars along the bottom show the extent of the meso-β radar features depicted in Fig. 9. Stations included are (INL) International Falls, MN; (STC) St. Cloud, MN; (OMA) Omaha, NE; (TOP) Topeka, KS; (UMN) Monett, MO; (GGG) Longview, TX. Their WMO numbers are indicated.
the upper-tropospheric 12 h thickness-change field points to the MCC as a dominant factor in the local environmental forcing.

Divergence in the vicinity of the MCC was calculated at two levels using the method of Bellamy (1949), which employs the rawinsonde data directly and requires no pre-analysis or interpretation of the reported winds. At 20 kPa (Fig. 15a), a broad closed region of divergence is seen in the vicinity of the system. Surrounding this is a ring of presumably compensating convergence. This convergent ring implies the existence of a subsidence field surrounding the MCC which extends far beyond the apparent visual limits of the storm’s influence. Other evidence of this subsidence has been discussed previously. At 50 kPa (Fig. 15b) the divergence pattern shows a divergence/convergence couplet located immediately upwind of the storm, and separated by a roughly east/west line of null divergence. This couplet is reflected in the wind field as a cross-contour flow (see Fig. 10) toward higher heights, and is probably a reflection of the adjustment process as flow encounters the “obstacle” of the MCC and decelerates as it diverts around or is entrained into the convective cells. This same divergence/convergence couplet at 50 kPa, resulting from cross-contour flow, is seen to be associated with a second MCC, which is examined in the following subsection.

b. A comparative case: The 3–4 August storm

To lend further support to the above analysis and for the purpose of adding generality to the conclusions drawn, a second MCC is examined. This system developed out of south-central Wyoming on the afternoon of 3 August 1977, the day before the storm studied in the previous subsection. Its evolution may be tracked using the surface analyses of Fig. 5, Part I, and Figs. 1 and 5 of this paper. This MCC also reached its most intense phase at about 0900 GMT. A satellite view of the storm at this time appears in Fig. 4 of Part I. We examine the system at 1200 GMT 4 August using rawinsonde data.

The schematic radar structure of this system, presented in Fig. 16, reveals the presence of two convective groups separated by an echo-free band across central Iowa. Based on satellite and radar analyses, the northern convection appeared weaker and somewhat shallower, but was expanding rapidly at 1200 GMT on 4 August. The convection which was associated with the original MCC, as represented by the large elliptical cold region on the IR image presented in Fig. 4 of Part I, evolved into the southern region of radar echoes; therefore our analysis is concentrated on this area.

The 50 kPa analysis at 1200 GMT 4 August, presented in Fig. 3 (Part I), shows a weak short wave
associated with this MCC; however, the thermal pattern at 50 kPa (not shown) indicated that there was little, if any, thermal support for this short wave. A weak stationary front at the surface, stretched east–west across northern Iowa, apparently was not influencing the southern convective group in a major way. A trough of low pressure in western Kansas and the Texas/Oklahoma panhandle region was apparently the dominant surface feature affecting this system.

A north–south-sectional analysis (Fig. 17) through the storm indicates that the surface stationary front in northern Iowa was linked with the polar jet, which
was in the same location as for the 4–5 August storm. A strong mid-level wind-speed maximum appears at Topeka (TOP) in Fig. 17. This feature appears on the 50 kPa analysis as a strongly ageostrophic wind vector moving cross contour toward higher heights. Although the Topeka sounding was taken within the MCC and was apparently affected by nearby convection, its wind profile is consistent with a sounding taken at Fort Riley, Kansas (FRI)\(^2\), about 75 km to the west, and is therefore considered representative of scales much larger than that of the individual thunderstorm. The temperature and moisture profiles of the soundings at Fort Riley, Omaha (OMA) and Monett (UMN) reveal a strong subsidence inversion feature in the vicinity of 50 kPa, very similar to that observed near the 4–5 August storm; and again, this evidence is supported by the slope of the isentropes in the east–west cross section shown in Fig. 18. Within the general area of isentropes sloping downward, which lay across most of Kansas above 50 kPa, the most concentrated area of implied subsidence is centered in the region of the mid-level wind maximum over Fort Riley and Topeka. The moisture analysis of Fig. 18 also shows an intrusion of dry air at the same level into the otherwise nearly saturated Topeka sounding. A simple interpretation of this feature which qualitatively explains the observed flow is that dry air generated by the subsidence above 50 kPa west of the storm was being entrained into and/or funneled between convective elements, possibly to become part of thunderstorm-scale or mesoscale downdrafts.

Another prominent feature seen in Fig. 18 is the layer of high-speed air east of the storm near the tropopause. This feature is more sharply defined than the corresponding wind maximum associated with the 4–5 August storm (Fig. 12). As with that case, satellite film-loop data identify this as anvil-level outflow from the MCC. The horizontal extent of the outflow on this day can be seen in Fig. 19, on which is plotted the wind vectors at the upper-tropospheric level of maximum wind speed. One can identify a roughly triangular region of predominantly anticyclonic flow which covers a 600 000 km\(^2\) area bounded by a line from southwestern Arkansas to western Pennsylvania, to central Iowa and back to Arkansas. This triangle encloses an apparent jet stream feature which is separated from the polar jet in southern Canada by a col in the wind speed, and which seems to emanate from the

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\(^2\) For example, the 50 kPa wind at Fort Riley (WMO number 72455) was 310° at 27 m s\(^{-1}\), at Topeka 351° at 34 m s\(^{-1}\).
MCC. The feature is discernable as far east as Pittsburgh, and can be identified in each of the soundings within the triangle by a shallow high-speed “spike” in the wind velocity profile near the tropopause. Examples of the wind profiles are presented in Fig. 20. Other examples can be inferred from the cross section wind speed analyses at Monett (UMN, Fig. 17) and Dayton (DAY, Fig. 18). The most striking aspect of the profiles shown in Fig. 20 is the shallowness of this jet feature—it is entirely confined above 30 kPa. Below that level there is very little wind shear, with winds being light throughout. These profiles serve to clearly distinguish
the MCC-generated “jet” from the polar jet, in which the wind shear is distributed evenly throughout the troposphere [see, for example, the wind speed analyses over International Falls (INL) on Figs. 11 and 17].

Because of the shallowness of the MCC-produced “jet”, the total kinetic energy added to the atmosphere is not comparable to that of a true jet streak. As a result the net long-term effect of such features on the large-scale atmospheric flow is not likely to be as large as one might suspect from looking at analyses of 20 kPa flow anomalies alone.

The divergence pattern at 20 kPa (Fig. 21a) shows a very similar pattern to that for the 4–5 August storm. A concentrated area of divergence was centered over the MCC and was surrounded by a band of convergence. The “jet” feature discussed above originated in the divergent region and extended eastward into an area of convergence over Indiana and Ohio. At 50 kPa (Fig. 21b) one finds a divergence/convergence couplet similar to that associated with the 4 August storm. As with the 4 August storm, the pattern reflects a cross-contour flow toward higher heights to the rear of the storm. In this case the greater magnitudes of both the divergence and convergence maxima are a result of the use of the apparently somewhat anomalous high-speed Topeka wind vector in the computation.4

4 Use of the Fort Riley wind in place of the Topeka value results in only a minor reduction in magnitudes of the maxima. Of course both vectors cannot be used together since the Bellamy (1949) method requires uniform station spacing, i.e., that of the standard synoptic network.
c. Discussion

The previous subsections have presented analyses of two MCCs which displayed a number of similar characteristics. Both storms were roughly circular in shape and were loosely organized into groups of smaller-scale thunderstorm clusters and lines. Each system was situated on the warm side of a nearby surface frontal discontinuity. In the mid-troposphere a subsidence inversion was present in the immediate environment of both MCCs. Finally, at jet stream level both storms displayed a shallow, high-speed, anticyclonic, divergent outflow region whose influence was noted far beyond the immediate vicinity of the convection. This latter feature is probably the most prominent and easily identified “signature” of the two systems studied here, and has also been noted in a study of a large number of MCCs by Maddox (1981).

To better address the circulation involved in the MCCs, Fig. 22 shows the divergence profiles in the vicinity of both MCCs studied. These profiles were calculated in 5 kPa layers using full-resolution tracking winds obtained from stations arranged in a polygon surrounding each MCC, again using the technique discussed by Bellamy (1949). The corresponding $p$-velocity profiles, derived through mass continuity, are also included in Fig. 22. Because of the relatively weak winds through most of the troposphere in the vicinity of the MCCs, we chose to apply a constant divergence correction for each layer in order to yield vertical velocities of 0 at 10 kPa, as discussed by O'Brien (1970). While virtually no correction was necessary for the data at 1200 GMT 5 August, the uncorrected 10 kPa vertical velocity at 1200 GMT 4 August is about the same value as the corrected maximum at 25 kPa, which is about half of its uncorrected value. The similarity of the corrected profiles supports their credibility. The area within the polygon selected for 1200 GMT 4 August was 512 000 km$^2$, and 523 000 km$^2$ for the following day’s MCC. Also shown on Fig. 22 for comparison are composite calculations of divergence and vertical velocity for tropical cloud clusters in their developing, pre-cyclone stage, as presented by McBride and Zehr (1981) for two separate data sets, one from the western Atlantic and one from the western Pacific. The area within which McBride and Zehr calculated divergence is about 20% larger than that used for the MCCs, similar enough so that qualitative comparison of these curves is possible.
The outflow layer as delineated by the wind speed profiles in Fig. 20 corresponds exactly to the divergent layer shown by the MCC divergence profiles in Fig. 22. The smoother, less detailed nature of the cloud cluster profiles can be attributed to the large number of soundings and storms combined into these composite profiles; nevertheless, the similarities between MCC and cloud cluster divergence structures stand out clearly. Both have general convergence throughout the lower and middle troposphere, with a narrow layer of relatively strong divergence centered at 20 kPa associated with the storm outflow. The vertical velocity profiles have their maximum upward values in the upper troposphere for both storm types, with the peak being sharper and slightly higher for the MCCs. The primary differences between the MCC and cloud cluster profiles appear to be the mid-level divergent layer beneath a stronger 50–30 kPa convergent layer for the MCCs, with the resultant vertical velocity profiles having a lower-level maximum as well as the upper-level maximum (though similar features in cloud clusters may be masked by the compositing technique). It should be remembered that the MCC profiles represent the storms in the early stages of decay. These differences between the MCC profiles and the developing cloud cluster profiles may therefore reflect the particular stages of evolution of the systems. Maddox's (1981) composite vertical velocity profile for the vicinity of the mature MCC bears more resemblance to the cloud cluster profiles here.

The evidence of Fig. 22, suggesting a similarity between MCCs and tropical cloud clusters, is corroborated by some of the other observations presented earlier in this paper. The convective organization as seen by radar is similar to the structure found in tropical cloud clusters. Studies of these tropical systems (McBride and Zehr, 1981; Williams and Gray, 1973; Ruprecht and Gray, 1976) show that they are associated with anticyclonic flow in the outflow layer near the tropopause, as are the MCCs. They show that a local warming is generated in the mid- to upper-troposphere by tropical convective systems, resulting in a "warm-core" storm structure. Similar warming associated with the MCCs is evidenced by the upper-tropospheric thickness increases found as the storms intensified. They also show tropical cloud clusters to be surrounded by a subsiding clear region of suppressed convection. Evidence for a similar subsidence phenomenon associated with two MCCs has been presented above.

Of course, tropical cloud clusters exist in an essentially barotropic environment and rely primarily on buoyant accelerations to drive them. We have shown that the MCCs of this episode favored a proximity to east-west surface frontal discontinuities. The north/south temperature gradient associated with these weak summertime fronts is not large, and by definition it is confined to the cool side of the boundary. While the MCC convection in the episode was concentrated on the warm side of the discontinuities, the fronts must nevertheless be considered a possible source of energy for the MCCs. They may provide a mechanism to enhance upward vertical motion, which could initiate, strengthen or maintain convection. The vertical motion values at 30 kPa for the MCCs in Fig. 22 is equivalent to uniform 5–6 cm s⁻¹ upward motion over a square 700 km on a side. This is a rather large synoptic-scale value, such as one might find in the warm sector of a developing midlatitude wintertime cyclone (e.g., Pålmen and Newton, 1969). However in this case, if the surface front, and the baroclinic processes associated with cyclogenesis along a front, are important to the production of these large MCC-generated vertical velocities, one would expect to see some of the manifestations of cyclogenesis, such as falling surface pressures and the north–south exchange of heat that develops as the front deforms and the storm "wraps up". As seen from Figs. 5, in both Part I and here, there is not a consistent drop in surface pressure associated with the MCCs. The fronts do not appear to deform in the vicinity of the storms except where they intersect the outflow boundaries of meso-β-scale convective clusters.

To address more quantitatively the question of a north–south heat exchange, a process which is necessarily associated with the production of vertical velocity in baroclinic storms (when the temperature gra-
dient is concentrated in the north–south direction), we have calculated the meridional heat transport for the two MCCs studied. Fig. 23 presents the vertical profiles of average meridional sensible heat transport by the two storms, along with the profile from a mature winter cyclone centered at the same location. Each profile was constructed by calculating a nine-station mean temperature for each 5 kPa layer from the surface to 10 kPa. Each individual station’s deviation $T'$ from that mean was then multiplied by the meridional wind component $V$ (equivalent to $V'$ since the zonal average $V$ is zero) and the nine values of $VT'$ were averaged arithmetically. The results show that the winter cyclone generated a strong northward transport of heat through the troposphere while virtually no northward heat transport was produced by the MCCs. In fact, throughout most of the troposphere, except near the surface, there was a slight southward transport of heat by these systems. The low-level transport can be better attributed to the effects of the low-level jet than to the surface front. From Figs. 22 and 23, one is led to the conclusion that a weather system which displaces as much mass vertically as a baroclinic system without transporting significant sensible heat poleward must be operating in a predominantly barotropic environment and must be basically driven by buoyant accelerations (re: the tropical cloud cluster).

5. Summary and conclusions

The evolution of a large mesoscale convective complex (MCC) is studied from a point subsequent to its smaller-scale evolution over the mountains and plains of Colorado on the afternoon of 4 August 1977, as documented in Part I. We follow its intensification through its mature stage in eastern Kansas, and its later progress across the United States and into the Atlantic Ocean. MCCs are meso-α-scale convective systems distinguishable from squall lines by the roughly circular shape of the large, contiguous, cold cloud shield observable by satellite (Maddox, 1980, 1981). Two MCCs have been examined in detail near their most intense stage. From the study of these two cases, which display a number of similar characteristics, it is concluded that they are basically tropical in nature and that their dynamics are dominated by buoyant accelerations. Some of the specific findings which support this conclusion are:

1) The MCCs developed a warm-core, divergent, anticyclonic flow pattern in the upper troposphere which was not present prior to the development of convection. Similar structure is observed in tropical cloud clusters. This finding is in agreement with the analysis of Maddox et al. (1981).

2) Maps of divergence near the tropopause show large divergent areas centered on the MCCs, which are surrounded by a band of convergence which lies well beyond the visible limit of the storm. This implies subsidence in the clear region surrounding the MCCs. Evidence of subsidence is also found from analyses of soundings at stations surrounding the MCCs where the classical subsidence stable layer is seen in the mid-troposphere.

3) Mid-level divergence maps show a convergence/divergence couplet centered upwind in both MCCs and separated by an east–west line of null divergence. This feature is found to be a manifestation of a cross-contour flow toward higher heights, which seems to represent the adjustment as mid-level air encounters the “obstacle” of the MCC.

4) Divergence profiles of the two MCCs are similar to tropical cloud cluster divergence profiles as reported in the literature; they display a deep layer of general convergence through the troposphere and a narrow layer of intense divergence near the tropopause. The shallow divergent layer corresponds to a layer of high-speed anvil outflow which extends well beyond the visible limits of the storms.

5) Calculations show that the MCCs developed vertical velocities comparable in magnitude to developing midlatitude winter cyclones, but without any of the characteristic features associated with cyclogenesis, such as decreasing surface and northward transport of sensible heat.

The MCCs in the episode studied here all reached maturity during the nighttime. While being beyond
the scope of this paper, we suspect that the unique features of these systems may be largely controlled by several characteristics of the nocturnal period:

- The presence of a nocturnal inversion.
- The presence of a low-level jet.
- The absence of shortwave radiational heating and the greater role of longwave radiational cooling.

The nocturnal inversion effectively decouples all but the most vigorous convection from the friction layer, which may inhibit the tendency for convection to assume a particular mode of organization such as the squall line configuration. The nocturnal jet provides a steady, high-speed influx of low-level moisture just above the nocturnal inversion. Finally, Gray and Jacobson (1977) and McBride and Gray (1980) presented evidence that a variety of organized mesoscale convective systems, such as tropical cloud clusters, attain an early morning maximum intensity, as was the tendency for the MCCs studied here. They attribute this diurnal modulation to the day versus night variations in tropospheric radiational cooling (and the resultant divergence profiles) between the weather system and the surrounding relatively cloud-free region. In the case of the continental MCC, the difference between cloudy and cloud-free regions would be much greater than for maritime systems since the surface energy budget would also be strongly modified.

The weak baroclinic features that were found in the vicinity of these MCCs, such as surface fronts, appeared to act primarily to trigger and direct the release of the buoyant instability. MCCs may be compatible with a certain amount of baroclinicity, but it is hypothesized that as baroclinicity increases (particularly vertical wind shear), the convection tends to organize itself more into the classical squall structure (Palmén and Newton, 1969), or into the more comma-shaped cloud patterns described by Reed (1979). This hypothesis remains to be tested. Finally, it is uncertain to what extent the differences in the two MCCs studied here (primarily the well-defined mid-level jet in the one case) represent the natural variability of such systems or simply non-representativeness of the observations.

Among the many avenues yet to be explored regarding MCCs, detailed studies of their convective organization by radar is essential. Under some conditions it is possible for a squall line (as observed by radar) to generate a nearly circular cloud pattern of anvil cirrus. Therefore in future studies the satellite-based definition of MCCs (Table 1) should be augmented with radar information. Dynamic investigations of the influence of baroclinicity on storm structure and further exploration of the interaction of MCCs and the low-level jet should also prove illuminating. It is particularly in these latter two areas that dynamic characteristics may be found which will more closely define to what extent MCCs may actually be considered mid-latitude cloud clusters.

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