Abstract

Mesoscale convective complexes (MCCs) primarily form in the Great Plains of the United States and are significant producers of their warm-season rainfall. Their presence in the eastern states is rare. This study will analyze one such MCC that crossed Pennsylvania on 21 May 2004. The evidence led to the conclusion that conditions were conducive for MCC development. There was a cold front in eastern Canada and the Great Lakes States that was associated with tropospheric horizontal convergence. There was significant moisture and warm air advection. Potential vorticity (PV) maximums were apparent throughout the troposphere, which were incorporated with a baroclinic trough. Upward motion ahead of the trough triggered the MCC. Also, helicity and CAPE were considered because they are strong indicators of intense convection. The mature MCC consisted of a mesoscale vortex. The thunderstorms associated with a mature MCC produced downdrafts that created a mesohigh, and an outflow boundary. Meso-eta model simulations, surface and tropospheric observations, GOES-12 satellite, and NOWRAD radar were used as a means of observing the 21 May MCC event.

I. Introduction

A mesoscale convective complex (MCC) is a 200 to 300 km wide area of convection consisting stratiform rain, a mesoscale vortex, and in most cases thunderstorms on its leading edge. In North America, MCCs primarily occur in the Plains. They are primary producers of warm-season (May, June, July, and August) rainfall in this area. For example, Ashley et al. (2003a) found that in a 15-year period from 1978 to 1999, MCCs accounted for seven percent of the annual rainfall in eastern Kansas, southeastern Nebraska, and northwestern Missouri. They also observed that 20 percent of the warm-season rainfall in portions of Texas, Oklahoma, and Kansas, was the result of MCCs.

MCC formation usually occurs during the warm season, particularly in the months of May through August. However, there are events that occur in the late winter and early spring. In an examination of MCC events from 1978 to 1999, Ashley et al. (2003b) found that late winter and springtime MCC events tend to form in the Gulf Coast states (i.e. Texas, Louisiana, Mississippi, and Alabama). This is due to the close proximity of longwave troughs to the Gulf Coast States during this time of year. Ashley et al. (2003b) also found that the extent of the cirrus cloud shield, defined as having temperatures below -32°C, extended to Iowa during July demonstrating the northward migration of the MCCs through the spring and summer. June and July are the optimal months for the MCC’s cirrus cloud shield to pass over Pennsylvania.

Over North America, Maddox (1980) found that most of the initial thunderstorm development that proceeded MCC formation tended to occur in the late afternoon. This was
concurrent with the initial thunderstorm development for the global MCC population (Liang and Fritsch, 1997).

After an MCC develops, its average life is about 16 hours (Maddox, 1980). The MCC matures and its cold cloud shield often reaches its maximum extent in the early morning. More specific details on the stages and structural features of the MCC will be discussed in the forthcoming section.

The standard way to identify an MCC has been presented by Maddox (1980) (Table 1). Maddox also contributed the first description of the life-cycle of an MCC. Nearly all of the numerous studies conducted on MCCs across the world are based on this analysis. Table 1 describes the physical atmospheric characteristics of an MCC and emphasizes the need for infrared (IR) satellite images. Maddox’s criterion is based on the extent and temperature of the cirrus cloud shield associated with the MCC.

<table>
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<th>Physical Characteristics</th>
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| Size: A – Cloud shield with continuously low IR temperature ≤ -32°C must have an area ≥ 100,000 km²  
B – Interior cold cloud region with temperature ≤ -52°C must have an area ≥ 50,000 km²  
Initiate: Size definitions A and B are satisfied  
Duration: Size definitions A and B must be met for a period of ≥ 6 hours  
Maximum extent: Contiguous cold cloud shield (IR temperature ≤ -32°C) reaches maximum size  
Shape: Eccentricity (minor axis/major axis) ≥ 0.7 at time of maximum extent  
Terminate: Size definitions A and B not longer satisfied |

II. Mesoscale convective complex life cycle

a. Genesis stage

The genesis stage is often referred to as the development stage. It varies greatly among individual MCC events. In one composite MCC analysis by Maddox (1983), there were large values of precipitable water over a broad area. There is also strong evidence of warm advection due to southwesterly surface winds in the vicinity of the MCC (Fritsch et al., 1994). Rising motion usually accompanies the warm advection. The rising motion often breaks down into convective updrafts. The quantity omega, the time rate of change of pressure of an air parcel, is a direct measure of vertical motion. Omega values were negative for all parts of “Genesis Region” (GR) and for approximately all of the troposphere in Maddox’s (1983) composite analysis.

Maddox (1983) also observed lower tropospheric horizontal convergence in the GR for all of the MCCs in his composite study. Convergence contributes to upward motion and formation of convection. In some of the cases in his study, a northeast-southwest oriented surface front was located nearby. Horizontal convergence is particularly intense near fronts.
The surface southerly winds, to the south of the front, are partially responsible for advecting warm air into the region where the MCC is forming.

Potential vorticity (PV) is expressed as

\[ PV = -g \left( \zeta + f \right) \partial \theta / \partial p, \quad (1) \]

where \( g \) is the gravitational constant, \( \zeta \) is the vertical velocity, \( f \) is the Coriolis parameter, and \( \partial \theta / \partial p \) is the partial derivative of potential temperature with respect to pressure. PV maxima often coincide with short waves troughs. Short wave troughs are atmospheric waves embedded in the large-scale flow and thus propagate from west to east while leaning westward with increasing height (Aguado and Burt, 2001). Short wave troughs form in all levels of the troposphere. They promote thermal advection such that cold air advection occurs to the west and warm air advection occurs to the east of the trough (Aguado and Burt, 2001). Maddox (1983) observed warm-air advection in the GR due to a short wave trough. The warm-air advection usually occurred in the lower and middle troposphere. The most important contribution short wave troughs have to developing MCCs is their ability to lift the air and trigger convection. Therefore, in order to forecast MCC formation, it is pertinent to know the strength and location of the PV maximum associated with traveling short wave troughs.

As mentioned earlier, thunderstorm clusters are typically a precursor of MCC development. The average time for these thunderstorms to develop over the Great Plains is around 2000 UTC (Maddox, 1980). Parcels of air rise as they ascend in convective updrafts and cool. When the parcel achieves the same temperature as its surrounding environment, it has reached its level of free convection (LFC). As it continues to rise, the parcel of air becomes warmer than the environment and it becomes positively buoyant. The energy created in the process is called convective available potential energy (CAPE). The larger the CAPE values, the more buoyant the air, hence stronger convection (Emanuel, 1994).

Another property of the environment relevant to MCC formation is helicity, expressed as

\[ \text{Helicity} = \omega \cdot v_h. \quad (2) \]

This is the dot product of the absolute vorticity vector, \( \omega \), and the horizontal velocity vector, \( v_h \). Helicity is an important property of fluids and has been found to be essential in forecasting supercell thunderstorms (Lilly, 1985). Tsinober and Levich (1983) suggested that helicity had significant effects on three-dimensional fluid structures such as MCCs. MCCs tend to form in regions of large helicity.

b. Mature stage

Most MCCs mature during the early morning and on average the cirrus cloud shield reaches its maximum horizontal extent by 0730 UTC (Liang and Fritsch, 1997 and Maddox, 1980). The low-level jet (LLJ) is typically responsible for much of the moisture associated with the MCC. The LLJ transports moist air in the lower troposphere toward the MCC. This transport from the Gulf of Mexico is usually enhanced at night. It also has been noted by Tollerud and Rogers (1991) that the closer the MCCs are to the Gulf the longer they will live and the larger the cirrus cloud shield tended to be.
Mature MCCs contain a mid-tropospheric mesoscale vortex, which is induced by convective heating. The heated air locally creates lower pressure. A balanced cyclonic flow then occurs, which is strongly influenced by the Earth’s rotation (Fritsch et al. 1994).

The global average for the extent of the MCC’s cirrus cloud shield at the mature stage is $354,000 \text{ km}^2$. However, the cirrus shield can extend to $400,000 \text{ km}^2$ (Liang and Fritsch, 1997). According to Maddox (1980), the extent of the cirrus cloud shield only has to be $100,000 \text{ km}^2$ to be classified as an MCC. The location of the thunderstorms under the shield varies amongst MCCs. However, for many MCCs, the thunderstorms are located at the leading edge of the shield as it propagates. A stratiform cloud layer and the vortex are located behind the leading thunderstorms. The stratiform layer can produce very heavy rain.

Downdrafts have a significant role in the maintenance of an MCC. The cold-air from thunderstorm associated downdrafts is induced by evaporation from rain. A pool of cold, dense air is created at the surface. Because the air is sinking, pressure rises, hence the formation of a surface mesoscale high (Maddox, 1980, Keary and Rappaport, 1987, and Fritsch et al., 1994). It occurs directly under the middle-tropospheric vortex. Maddox (1983) noted an average pressure amplitude of two to four millibars (mb) in the mesohigh.

On the leading edge of the cold pool, surrounding warm air is forced to rise as the cold pool advances. This boundary is called the outflow boundary and may be the focus of additional thunderstorms. The vertical motion discussed earlier is dependent on the strength and the configuration of the outflow boundary (Fritsch et al. 1994).

c. Dissipation stage

Dissipation of the MCC begins with a breakdown of the mesoscale vortex. Often, the outflow boundary races well ahead of the mesoscale vortex. Similar to a typical thunderstorm, the updrafts diminish and downdrafts dominate (Emanuel, 1994).

Maddox (1983) noted several distinct conditions that led to the demise of the MCC. The LLJ no longer feeds moisture into the system. Cool air advection replaces the warm air advection in the lower troposphere. Very often the short wave trough will become vertically stacked. According to Liang and Fritsch (1997), MCCs often decay in the late morning or early afternoon. Specifically, Maddox (1980) found the average time to be 12:30 UTC.

III. Data and Methodology

In this study an examination was performed of the state of the atmosphere during the formation of the 21 May 2004 MCC. Our purpose was to determine whether the above conditions for MCC formation and maturation were satisfied.

The MCC’s trajectory was monitored via NEXRAD Doppler Radar. Images are available every 15 minutes. In addition, the extent of the MCC’s cirrus cloud shield was needed because of the MCC definition set by Maddox in 1980 (Table 1). The GOES-12 IR satellite images were used verify this definition.

Synoptic surface and upper level features were retrieved from The Pennsylvania State University Weather Station. It is important to take advantage of raw observations that include hourly station data and soundings from locations in the northeastern United States. Analysis of
the wind directions and heights allowed for observations of tropospheric conditions at 0000 and 1200 UTC.

A simulation of the event by the operational Meso-Eta Model was also available. The model run was initialized on 21 May at 0000 UTC. A software tool entitled GEMPAK was utilized to display model output.

IV. 21 May 2004 Observations

a. Synoptic conditions

A cold front dominated weather conditions at the surface in the northeastern United States at 0000 UTC. The front extended from eastern Canada, southward to Ohio and Pennsylvania, and the southern end was drifting southward. More than likely, this front was responsible for horizontal convergence in the troposphere (Maddox, 1983). Satellite images at 0015 UTC, NOWRAD radar at 0000 UTC, and surface observations displayed a broken line of convection. There was plenty of evidence that indicated the presence of abundant moisture. A weak but consistent southerly and southwesterly flow ahead of the front supplied moisture for the MCC. At 1000 mb, there was evidence of moisture advection from southwesterly winds (Fig. 1). Also at 0000 UTC, precipitable water amounts of 36 mm extended into New York. Maximum values of 40 mm were observed in central Indiana. In many MCC cases, deep moisture would be attributed to a LLJ (Tollerud and Rogers, 1991). However, in this analysis, no concentrated area of maximum winds was observed in the lower troposphere.

The 0600 UTC surface chart (Fig. 2), 0615 UTC satellite photographs and radar reveal an increase in convection immediately south of the front in Ohio over a six hour period. Abundant moisture continued to feed into the areas where convection was forming. The increased convection was indicated by an extension of 40 mm of precipitable water maximum into the area. This was caused by an extended period of horizontal convergence, forcing the warm, moist air to rise triggering the intense convection (Maddox, 1983). Also, a surface low pressure center developed on the front in southwestern Lower Michigan. Thunderstorms grew in eastern Indiana and western Ohio in response. Infrared satellite imagery displays the cold cloud top temperatures that were generated by cirrus clouds from the deep convection.

By 0700 UTC, thunderstorms ahead of the stationary front in Ohio and an area of thunderstorms moving eastward out of Indiana coalesced into a region of heavy convection (not shown). This convection moved southeastward. A squall line developed on its leading edge. According to satellite imagery at 0815 UTC, the convection could be designated as an MCC. The entire system moved into Pennsylvania at 0930 UTC. The radar showed evidence of a cyclonic circulation by 1130 UTC. This cyclonic circulation was indicative of a mesoscale vortex which was just west of State College, PA by 1200 UTC (Fig. 3).

The MCC passed over Pittsburgh, Pennsylvania at 0945 UTC. The 1200 UTC sounding (Fig. 4) revealed evidence of moist air at lower levels of the troposphere. In fact, at the surface Pittsburgh reported a temperature and dewpoint at 62°F. The Pittsburgh sounding remained exceptionally moist as far up as the tropopause. This indicated that copious amounts of moisture continued to be fed into the MCC.
The 1200 UTC surface analysis (Fig. 5) showed that the cold front has moved southeastward. The northern extent of the front had proceeded into central Maine and southern New York State. The front became stationary over northern Ohio. With the exception of the MCC, all other convection associated with the front had dissipated. By 1200 UTC, the MCC became the most significant weather feature in the Mid-Atlantic States (Fig. 3). Downdrafts from existing thunderstorms formed a cold pool and in turn a mesohigh (Leary and Rappaport, 1987). The cold pool and mesohigh formed over central Pennsylvania and northern West Virginia, where pressures exceeded 1020 mb. This mesohigh was located to the north and west of the outflow boundary, which was located in the eastern edge of the convective region. The cold pool had a role in maintaining existing and developing new thunderstorms. The cooler air pushed against the surrounding warmer air and forced it to rise. This rising motion caused thunderstorms to form (Fritsch et al., 1994). To confirm that this area of rain and thunderstorms had reached MCC status, the 1215 UTC satellite photograph (Fig. 6) depicted the expansive cirrus cloud shield of the MCC over Pennsylvania. This coverage and time of the maximum extent of the cirrus cloud shield would satisfy Maddox’s 1980 definition in Table 1.

The 0000 UTC 850 mb height field (not shown) displayed a longwave trough in eastern Canada that has extended into the Northeast. PV maximum values extended from Lake Michigan southward to central Illinois which indicate the presence of a shortwave trough (Fig. 7). There was a PV maximum identified at 700 mb and was centered over northern Lake Michigan. The northeast-southwest oriented PV maximum extended into Iowa and was moving east. This was indicated by strong negative (positive) PV advection to the west (east). The 500 mb analysis displayed evidence of a short wave trough over northwestern Ohio, eastern Michigan and Ontario, Canada at 0000 UTC (Fig. 8). At 0600 UTC the 850 mb short wave trough was located from south-central Ontario to southern Illinois. The 500 mb shortwave trough extended from southeastern Ontario to southern Illinois (Fig. 8).

The trough was baroclinic since it leaned westward with increasing height towards the colder air aloft. This was indicated by the trough positions at each level (Figs. 7 and 8). Baroclinic troughs tend to enhance rising motion and warm air advection needed for thunderstorm and MCC development (Aguado and Burt, 2001).

By 1200 UTC the longwave trough is steadily moving out of the Great Lake and New England states. Cooler air at 850 mb (Fig. 7) pushed into the northern Great Lake States from southern Canada. The temperature-dewpoint spread is small from the Midwest to New England. At 500 mb (Fig. 4), the temperature-dewpoint spread was less than 5°C over the Great Lake States and extending into Pennsylvania. These values suggest that higher moisture contents were available to maintain the MCC’s strength.

b. Mesoscale conditions

A description of the mesoscale conditions near the region where the MCC formed will now be provided. Features such as vertical motion, thermal advection, helicity and CAPE will be discussed.

Cross sections of the troposphere from 41°N and 90°W to 41°N and 75°W (not shown) were compiled to display rising motion and thermal advection of the troposphere at 0000 UTC. An area of warm-air advection dominated the lower troposphere. A layer of weak cold-air advection was above this. This thermal advection is over the state of Indiana where some of the MCC’s initial thunderstorms developed. Strong rising motion dominated the same area.
Thermal advection and rising motion are significant features MCC development. The 0600 UTC cross sectional analyses displayed increasingly high values of omega are occurring from the surface to the upper troposphere. Also, a vigorous region of mesoscale ascent occurred over the area where the MCC’s initial thunderstorms developed. Weak cold advection was occurring above 500 mb. Warm-air was advection occurred in below. There was a maximum value of warm air advection at 700 mb. Warm-air in the lower and mid troposphere and cooler air in the upper troposphere can render the atmosphere unstable to convection (Maddox, 1980). The warm advection coincided with the approaching short wave trough. Maddox (1983) conjectured that warm advection was enhanced ahead of these troughs.

Helicity (Figs. 9a and 10a) is often essential for thunderstorm development. Marginally high helicity values covered parts of western Pennsylvania, Ohio, and Kentucky at both 0000 and 0600 UTC. Values of over 70 m s\(^{-2}\) were present over this region. In general, helicity was greatest near the front. This could have an impact on the formation and maturation of the MCC.

Air is very buoyant where CAPE (Figs. 9b and 10b) is the highest. Thus, convection is favored in regions of large CAPE (Emanuel, 1994). Maximum CAPE values were also evident in south-central Indiana at 0000 UTC. The maximum values were apparent in western Ohio by 0600 UTC (Fig. 10b). Values rapidly decreased to the east and to the north at 0000 and 0600 UTC (Figs. 9b and 10b). Thus, the region where the MCC formed coincided with a region of enhanced CAPE.

V. Conclusions

Meso-eta model simulations, surface observations, NOWRAD radar, and GOES-12 satellite photos were used to analyze tropospheric and surface features near the region of MCC genesis.

It has been documented in most MCC case studies that development and structure are similar. This study used identical quantities as previous MCC case studies. These quantities include moisture advection, thermal advection, CAPE, omega, and PV maximum values. In addition to these quantities, this study used helicity. Helicity has been considered a factor in MCC development and maturity, but little is known of its exact impact.

The goal was to assess the synoptic conditions and mesoscale features relevant to the formation and maturation of the 21 May 2004 MCC. The following is a summary of the results of our observations:

- A northeast-southwest oriented front produced horizontal convergence in the region of the MCC’s development
- Initial thunderstorms formed to the south of the front
- Warm (cold) air advection dominated the lower (upper) troposphere
- Lower tropospheric winds provided moisture to the growing MCC
- Marginally high values of helicity appeared over the area of MCC formation
- High values of CAPE occurred in the areas of initial thunderstorm development and maturity
- PV maximum values indicated that a baroclinic short wave trough propagated into the region of MCC genesis
• MCC associated thunderstorm downdrafts produced a cold pool, a mesohigh, and an outflow boundary that initiated convection
• A mesoscale vortex developed in the mid-troposphere
• MCC reached maximum extent at approximately 1215 UTC

From these results, evidence has been found that the necessary components were present in the formation of the 21 May 2004 MCC. However, one piece of evidence that was not apparent, but was typically present in most MCC scenarios, was the presence of a LLJ. The abundant and steady moisture advection compensated for its absence. If this and other evidence found was indeed the case, it would verify the known criteria for the formation, classic structure, and strength of an MCC. More confidence can be put into forecasting MCCs because these criteria are understood.

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GOES-12 satellite images, NOWRAD radar images, surface, 850 mb, and 500 mb observations were provided from archives at The Pennsylvania State University Weather Station. Sounding data was provided by the Atmospheric Science Department at the University of Wyoming.

VI. Figure Legends

1. Analysis of 1000 mb mixing ratio and moisture advection for 0000 UTC 21 May 2004 centered on Pennsylvania. Winds are in m s\(^{-1}\) (full barb 100, short barb 5). Heavily solid lines mixing ratio (interval 2 g kg\(^{-1}\)); lightly solid lines moisture advection (interval 4 x 10\(^{-8}\) s\(^{-1}\)).

2. Surface analysis at 0600 UTC 21 May 2004 centered on western Pennsylvania. Solid lines isobars (interval 2 mb).


4. Sounding analysis at 1200 UTC 21 May 2004 for Pittsburgh, Pennsylvania. Left solid line dewpoint (degrees C); right solid line temperature (degrees C).

5. Surface analysis at 1200 UTC 21 May 2004 centered on western Pennsylvania. Solid lines isobars (interval 2 mb); dashed line outflow boundary; heavy solid arrow MCC path.

7. Analysis of 850 mb for 1200 UTC 21 May 2004 for United States. Winds are in m s\(^{-1}\) (full barb 100, short barb 5). Solid lines height (interval 40 m); dashed line 0000 UTC short wave trough position; heavily solid line 0600 UTC short wave trough position.

8. Analysis of 500 mb for 1200 UTC 21 May 2004 for United States. Winds are in m s\(^{-1}\) (full barb 100, short barb 5). Solid lines height (interval 60 m); dashed line 0000 UTC short wave trough position; heavily solid line 0600 UTC short wave trough position; dotted lines temperature-dewpoint spread below 5 deg. C.

9. Meso-eta model analysis of (a) helicity and (b) CAPE for 0600 UTC 21 May 2004 centered over Pennsylvania. Helicity interval 70 m s\(^{-2}\); CAPE interval 600 J kg\(^{-1}\).

10. Meso-eta model analysis of (a) helicity and (b) CAPE for 0600 UTC 21 May 2004 centered over Pennsylvania. Helicity interval 70 m s\(^{-2}\); CAPE interval 300 J kg\(^{-1}\).

VII. References


Liang, A.G. and J.M. Fritsch, 1997: The global population of mesoscale convective


