# Mesoscale Convective Complexes:
# An Overview

By

Harold Reynolds

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## 1. What is a Mesoscale Convective Complex?

Prior to 1980, the study of convective activity at the mesoscale level had been limited to tropical phenomena like cloud clusters, squalls and hurricantes, midlatitude squall lines and land-sea breeze systems. In 1980, Robert A. Maddox introduced the concept of the mesoscale convective complex (MCC) after a careful study of satellite IR images over the central United States during 1978. The MCC was contrasted with the mid-latitude squall line and found to be a unique entity, forming under different synoptic conditions and having completely different characteristics. With these differences in mind, he created an admittedly arbitrary and somewhat artificial definition in order to promote further research.

A mesoscale convective complex must have a continuous cloud shield with IR temperatures ≤ -32°C which covers an area ≥ 100,000 $km^2$ and have a cold cloud shield with a temperature ≤ −52°C covering an area ≥ 50,000 $km^2$, conditions that ensure that “the system is active and that precipitation is falling over a wide area”. These must last for more than 6 hours so that “the system's circulations are likely to be sampled (at some point in its life cycle) by several synoptic upper air soundings”, at least in the central United States. Finally, the eccentricity of the cloud shield must be ≥ 0.7 at the time of its maximum extent, a criterion “arbitrarily specified to preclude classification of linear-type systems as MCCs.”

Augustine and Howard (1988) subsequently argued for the elimination of the -32°C cloud shield criterion. They pointed out that the majority of an MCC's rainfall occurs within the cold cloud region and that there is a distinct linear relationship between cold cloud and warm cloud areas. They also said that the determination of the -32°C cloud cover for a particular mesoscale storm system is too subjective because “a contiguous -32°C area is often associated with several storm systems, which may be at different stages of their life cycles”, while the -52°C criterion “appears to delineate individual mesoscale systems well”.

McAnelly and Cotton (1989) pointed out that there is a 2°C discrepancy in the IR temperatures of the MB enhancement curve, so that earlier MCC definitions are apparently in error by 1-2°C. Cotton et al (1989) continued with both of the latter conclusions, requiring that the area of cold cloud shield with temperatures ≤ −54°C be ≥ 50,000 $km^2$. However, both they and Augustine and Howard stated that this definition was unsatisfactory because no dynamics were involved. Cotton et al attempted to rectify this problem by proposing the following definition of a mesoscale convective complex:

> A mature MCC represents an inertially stable mesoscale convective system which is nearly geostrophically balanced and whose horizontal scale is comparable to or greater than $\lambda_R$, the Rossby radius of deformation.

## 2. Why Study Mesoscale Convective Complexes?

Mesoscale convective complexes are important atmospheric phenomena. “Due to their large size and long duration, important mesoscale/large scale interactions take place, seriously impacting the accuracy of operational numerical models” (Rodgers et al, 1983). All of the papers examined showed that the passage of an MCC changes the surface conditions over a large region, and a few (Rodgers et al, 1983; Fritsch and Maddox, 1981; and Maddox et al, 1981) focused specifically on upper tropospheric changes induced by these systems.

MCCs occur relatively frequently during the warm season (March-September), 192 having been documented over the years 1978 (Maddox, 1980), 1981 (Maddox et al, 1982), 1982 (Augustine and Howard, 1988). Figure 2(a) shows the paths taken by many of them. This number does not include smaller mesoscale convective systems that did not achieve MCC status, but were often significant events in their own right.

Severe weather (such as tornadoes, strong winds, large hail, intense lightning and heavy rains with subsequent flash floods) of some sort occurs with practically every MCC. 53 of the summarized storms caused casualties, supporting Maddox's (1983) estimate of about 1 in 4 that do so. One of the most notorious MCC-induced disasters was the flash flood of July 19-20, 1977 in Johnstown, Pennsylvania, which killed 76 people and caused tremendous damage, an event documented by Bosart and Sanders (1981) and numerically analyzed by Zhang and Fritsch (1986, 1987, 1988b). Also, a particular subclass of MCC, called a derecho (Johns and Hirt, 1985, 1987), is responsible for severe straight-line winds and is known to occur relatively frequently. Hence, it is of great interest to forecasters to be able to predict these events in time to issue warning, especially since the majority of these storms mature during the night. See Figure 2(b).

Pilots can also experience problems with mesoscale convective complexes. As well as creating extended periods of poor flying weather, during the development stage “the agglomeration and expansion of thunderstorm cells may occur so rapidly that the pilot of a slow-moving light aircraft may find himself literally engulfed by thunderstorms” (Maddox and Fritsch, 1984). Due to the anticyclonic air circulation developed in the upper troposphere (Figure 8(a)), a region of increased wind speed is created along the northern periphery of the storm and decreased speed along the southern periphery as compared to the environmental westerly flow. A commercial aircraft flying in the vicinity of the upper-level jet streak to the north of the MCC may have its fuel economy significantly affected (Maddox and Fritsch, 1984).

On the other hand, as will be discussed later, MCCs provide a large percentage of the warm-season rainfall in the American Midwest and are important contributors to the rainfall of the rest of the country east of the Rockies (see figure 5) (Wetzel et al, 1983; Fritsch et al, 1986; Kane et al, 1987; McAnelly and Cotton, 1989). Due to the processing of huge volumes of air, they can provide significant air quality improvement, especially in the heavily urbanized northeastern United States (Lyons et al, 1986). This of course also means that pollutant transport, deposition and acidic rainfall distribution are greatly affected.

Finally, the relatively high density of both upper air and surface weather stations in the areas where the MCCs occur most frequently, satellite photographs and large high-quality databases from the pre-STORM project and others makes the acquisition of data for study relatively easy.

## 3. The Internal Structure and Life Cycle of an MCC

### 3.1 Introduction

The study of a mesoscale convective complex, like that of any other atmospheric phenomenon, involves sifting through large quantities of several varieties of data, from satellite photographs (see Figure 1) to upper air soundings, radar images, surface records and precipitation data. No two MCCs are alike, which means that the researcher must find some way to synthesize the data from several events into a representative composite.

Maddox (1983) was the first to offer such a composite model. He employed a direct approach, taking 10 MCCs and “averaging” them over three time periods: growth, maturity and decay. This method gave a better spatial resolution than the one to follow, but Cotton et al (1989) wished to have better temporal resolution in order to spot transient features. This they did by examining 134 systems divided into two subsets according to when in their lifetimes they had been observed. To reduce the effects of baroclinicity, only cases occurring during June, July and August were selected. Each remaining case was subjectively "graded" on a scale from 0 to 9, based on "how organized it appeared, how typically it evolved, and how isolated it was", and only the 90 rated ≥ 5 were examined in detail. Other papers, however, focused on the life cycle of one particular MCC (e.g. Bosart and Sanders, 1981) or a series of them (Wetzel et al, 1983), detailing their features and evolution.

## 3.2 Genesis

Approximately half of the mesoscale convective complexes studied have roots in orogenic thunderstorms (Maddox, 1980; Maddox et al, 1982; Tripoli and Cotton, 1989) (although Velasco and Fritsch (1987) put the proportion closer to 30%) generated on the eastern slopes of the Rocky Mountains, which first appear on the satellite images around 1400 local time. The storms are advected eastwards with the mean air flow into a region favourable for growth, merge and expand rapidly, reaching MCC size by about 2000, maturing by about 0130 and beginning to dissipate around 0700 (Cotton et al, 1989). This strong nocturnal tendency (see Figure 2(b)) has been linked to the nocturnal maximum of thunderstorms in the American Midwest and also to the presence of the nocturnal low-level jet, as further documented below.

Cotton et al (1983) and Tripoli and Cotton (1989) studied these mountain-generated components. They demonstrated that convection first appears at favoured "hot spots" over certain mountain peaks and is advected eastward as mentioned above. It was found that "nocturnal pooling of stable air in lower lying areas led to a suppression of cumulus deveopment .. until 1200 MDT and the suppression of thunderstorms over the eastern Colorado plains until 1500" (Cotton et al, 1983). In other words, the pre-MCC storms were able to access convectively available potential energy which would otherwise have been lost to normal afternoon convection.

Tripoli and Cotton, using a numerical model, hypothesized that the convection suppression was due to lingering effects of the nocturnal mountain slope drainage wind, confining upslope flow beneath the "deep plains nocturnal inversion", while confining the return flow to above the inversion.

> In effect, the surface warming is transferred to the atmosphere above the inversion without the coincident movement of moisture. This acts to maintain an inversion around 1 km AGL over the plains, capping the moisture-rich air over the plains (Tripoli and Cotton, 1989).

It was noted that an important moisture source for convection is an eastward extension of the "Southwest Monsoon", where warm, moist Pacific air is advected over the mountains and into Colorado. When this moisture was unavailable, the moisture from the east was found to be insufficient to generate deep convection until late afternoon. "Such a delay ... would not place the orogenic system out in the plains until late in the day in an environment of increasing stability" (Tripoli and Cotton, 1989).

Storms that are not orogenic in nature tend to form in the same synoptic environment that promotes further growth and expansion of MCCs. The presence of large quantities of warm, moist, potentially unstable air (see Figure 2(c)) from the surface to nearly 700 mb is a necessity. Weak positive vorticity advection (Maddox, 1980) and warm thermal advection, with the tell-tale anticyclonic wind shear as in Figure 2(d), must be occurring over the region with southerly or southwesterly winds blowing the strongest near the 850 mb level (the "low-level jet"). Large areas of surface convergence are also found in the genesis region. It can be generated either orographically, by an east-west frontal position often found to the north of the genesis region, or by discontinuities in the moisture field near the surface, which may be outflow boundaries from a previous mesoscale convective system (MCS). MCCs also tend to develop on the anticyclonic side of a broad, weak, westerly upper-level jet, with weak diffluence in the flow over the genesis region.

A short-wave trough in the 500-mb flow tends to enhance convection and is very frequently associated with mesoscale convective complexes (e.g. Maddox, 1981; Cotton et al, 1989). Bosart and Sanders (1981) correlated the strength of the storm with the proximity of its centroid to a trough as both moved across the northern United States, and Tripoli and Cotton (1989) stated that although the trough is not necessary, it does enhance development. Cotton et al (1989) concluded that "the MCC is thus driven by combination of interacting cumulus, meso- and larger scale dynamic and thermodynamic processes".

## 3.3 Growth

As the mesoscale convective complex grows, the centre of greatest instability becomes established in the southwest region of the storm (Bosart and Sanders, 1981; Maddox, 1983) and the low-level jet continues to feed moist air into the system. Mesoscale upward motion, at a maximum near 700 mb when the MCC initiates (Maddox, 1983; Cotton et al, 1989), strengthens as the maximum shifts up to the 300 mb level (Wetzel et al, 1983; Cotton et al, 1989). See Figure 3(b). A mid-level convergence and upper-level divergence couplet (Fritsch and Maddox, 1981; Maddox et al, 1981; Fritsch and Brown, 1982; Maddox, 1983; Wetzel et al, 1983; Cotton et al, 1989) (Figure 3(a)) form and help to maintain the "inflow and outflow of mass necessary for long periods of sustained deep convection, while the attendant release of latent heat further enhances the low- to mid-level convergence" (Cotton et al, 1989). Precipitation at this time is mainly convective, with high rates and an efficiency (the amount of available moisture that falls as rain) of about 59%.

Maddox noted that there was little low-level (850-700 mb) temperature change in spite of a long period of pronounced warm advection, which was attributed to mesoscale ascent, evaporation of rain and cool downdrafts (Figure 4(c)). Bosart and Sanders' case was more extreme, with temperatures actually cooling relative to the environment. Cotton et al noticed a major apparent heat sink (see Figure (4a)) centered near 850 mb, which seems to corroborate these observations.

As the storm matures, a thin region of strong divergent anticyclonic outflow, cooler temperature and higher pressure (Fritsch and Maddox, 1981; Maddox et al, 1981; Fritsch and Brown, 1981) develops and remains for the rest of its life, concentrated near the 200 mb level of the troposphere and centred over the coldest cloud tops (Fritsch and Maddox, 1981). See Figures 3(a), 3(c). At 300 mb, however, the MCC has a "warm-core structure" (Fritsch and Maddox, 1981; Cotton et al, 1989), indicating that the transition is quite abrupt. Fritsch and Maddox (1981) suggested that the upper-level mesohigh and cold air perturbations may be caused by several factors. Hydrostatic response to the infusion of additional mass into a column (i.e. introduction of colder, much denser anvil outflow air), creates a "quasi-steady state cold layer". Mesoscale upward vertical circulation, possibly initiated by latent heat released by the convective clouds, and deep convection introduce large quantities of mass into the upper levels of the troposphere. The pressure field must adjust geostrophically to the resultant anticyclonic outflow. "The updraft mass which is infused at high levels typically has weaker horizontal momentum than the environmental winds and in some sense may be considered an "obstacle" to the mean flow" and as a result, as the environmental air is decelerated, its pressure is increased in accordance with the Bernouilli equation (Fritsch and Maddox, 1981).

Fritsch and Brown (1982) proposed that the "mesoscale cold anomaly" may be caused by very deep cumulonimbus clouds that "overshoot" into the lower stratosphere, "detraining" cold air into it and the upper troposphere. They and Cotton et all (1989) suggested that radiative effects also warm the base of the "extensive cirrostratus and altostratus canopy produced by intense convective systems" while cooling its top. The origin of the cool pool from adiabatic cooling due to mesoscale ascent was also suggested by Fritsch and Brown (1982) and Cotton et al (1989).

## 3.4 Maturity and Decay

At the fully mature stage, the above-mentioned stratiform anvil cloud plays a larger role in longwave radiation cooling and also as a precipitation initiator. The area covered by stratiform precipitation increases in size and the volumetric rainrate increases to its maximum value (McAnelly and Cotton, 1989). Precipitation efficiency reached 113% in Cotton et al's composite study as the cloudy atmosphere provided the extra amount from the water that had accumulated during the previous stages. The falling and evaporating precipitation over an extensive area creates cool mesoscale downdrafts, subsequent lower-level divergence and a stromg mesohigh and outflow boundary. Cotton et al noted that the lower-level transition from convergence to divergence occurred near 850 mb due to a precipitation-induced mesohigh. Weak cyclonic vorticity occurs below 750 mb for the storm's life, peaking at about 850 mb and changing little in amplitude from stage to stage (Cotton et al, 1989). Bosart (1986) noted, however, that the Johnstown storm had cyclonic vorticity below 350 mb in both its convective and stratiform regions.

Strong anticyclonic vorticity and outflow occurs near the tropopause (Figures 3(d), 4(d)), however, reaching a sharp maximum near 200 mb. As a result, an anticyclonically curved 200 mb jet streak, present as the storm was generating, strengthens over the northern periphery of the complex (Fritsch and Maddox, 1981; Maddox et al, 1981; Fritsch and Brown, 1982; Maddox, 1983; Cotton et al, 1989). See Figure 7(a). Maddox et al (1981) demonstrated that it was the complex that produced the changes, rather than the changes producing the MCC.

Bosart and Sanders (1981) computed vertical velocities in four sectors of the mature storm. In all sectors except the left front in a cylinder of 166 km diameter surrounding the MCC's centroid, there was a strong ascending motion with a maximum at 500 mb. Strong ascending motion was also found by Maddox (1983), Wetzel et al (1983) and Cotton et al (1989), with Maddox's peak at 500 mb, but the others' peaks close to 300 mb. In the other sector strong descent occurred, driven, so they speculated, by "evaporative cooling beneath a massive anvil". See also Figure 3(c). A deep layer of moist ascent above 600 mb was found by Fritsch and Maddox (1981). Bosart (1986) averaged vertical motions in both the convective and stratiform precipitation regions of the Johnstown storm. The convective region displayed ascent throughout the troposphere, peaking at 500 mb, while the stratiform region had a layer of weak descent below 600 mb capped by a layer of weak ascent.

The mesoscale convective complex begins to decay when it moves into a region where there is reduced low-level support. That is, there is a reduced supply of moisture, surface convergence decreases, cool advection occurs instead of warm, and the air is less unstable. The convective rain area decreases and the stratiform area increases (see Figure 6(b)) as the storm declines, but the precipitation efficiency remains quite high at about 86% (Cotton et al, 1989). Strong anticyclonic outflow and divergence remains at the 200 mb level until the storm has practically disintegrated. Mid-level cyclonic shear appears to strengthen somewhat, Cotton et al (1989) noticed, but the "vertical depth has shrunk and the height of increasing cyclonic shear has risen from being centered near 500 mb at the decay stage to above 400 mb."

Cotton et al's (1989) study indicated that upward motion continues to be strong, especially in the upper levels, but Maddox (1983) has a deep (surface – 500 mb) layer of weak descent, capped by a layer of weak ascent. This apparent inconsistency can be explained by noticing the similarities between the convective and stratiform profiles of Bosart (1986) and Maddox's (1983) "During" and "After" vertical velocity profiles respectively. Since the stratiform region trails the convective region in many MCCs (e.g. Leary and Rappaport, 1987), the similarities hint that Maddox's “After” and “During” profiles correspond to the respective regions.

### 3.5 Heat and Moisture Budgets

Studying the heat budget of their composite MCC, Cotton et al (1989) noted that at all stages of the life cycle, the vertical potential temperature advection increased monotonically with height up to 400 mb, where their level of peak upward motion occurred, and then decreased rapidly. The presence of strong warm horizontal advection below 750 mb during the initial and mature stages was confirmed, and weak cool advection occurred here during dissipation. They also found that “vertical moisture advection dominates the magnitude of the moisture sink [term of the heat budget], but its contribution is partially offset by the non-negligible horizontal moisture advection term (especially at the MCC mature stage)” Maddox (1983) also noted regions of strong upward motion (Figure 3(c)) coupled with significant warm advection at lower levels. Differential thermal advection aloft to the east of the genesis region, with cold advection aloft and warm near the surface, destabilizes the air and primes it for convective activity.

Finally, both Cotton et al (1989) and Bosart and Sanders (1981) concluded that mass convergence in the presence of large quantities of water vapour was the most important contributor to the moisture budget for the duration of the storm, with evaporation a close second. Horizontal moisture advection has a small but non-negligible contribution to the budget as well.

## 4. Precipitation

Fritsch et al (1986) demonstrated that Mesoscale Convective Weather Systems contributed from 30-70% of the average warm-season precipitation in an area from Iowa and Nebraska south to Texas during 1982. Even in the drought year of 1983, “parts of at least 10 states received 25% of their normal warm-season precipitation from MCWS. Moreover, portions of many states received 20% - 40% of their average annual precipitation” from them.

Their claim that series of complexes “may be the most prolific precipitation producing phenomenon” was backed by a comparison between the distribution of rain from Hurricane Alicia and a series of three convective complexes that occurred earlier in the same year. It was found that the MCCs produced twice as much water over 31% more land in 38% less time than the hurricane did, albeit that Alicia was an “average” hurricane, while the series of complexes was one of the most intense that had occurred in the two-year study period. The claim was further promoted by referring to a paper that noted that in 1980 a single large MCC had produced more rainfall than had fallen during Hurricane Allen's first 24 hours on land.

Fritsch et al (1986) make it clear that mesoscale convective complexes and mesoscale convective systems (storms which, for one reason or another, do not meet Maddox's arbitrary criteria) are significant sources of precipitation for a large area of the central United States. They are frequently the cause of floods and may also contribute to the problem of inaccuracy in the warm season Quantitative Precipitation Forecasts. It was concluded that any improvements in the prediction of MCWSs and in the knowledge of their general precipitation structure and distribution would be beneficial.

While examining the geographical distribution of MCWS rainfall, “sharp gradients were apparent in the western and southern edges of the precipitation pattern” in 1982 and, to a lesser extent, 1983, while the amounts tended to taper off gradually to the east. See Figure 5. It was speculated that the gradient alon g the Gulf Coast was due to differential heating over land and water where, with "everything else being equal, the potential buoyant energy over land would be significantly larger" (Fritsch et al, 1986). That is, convection is more likely to be deeper and stronger over land than nearby water. The western boundary coincides with the average location of the "dryline" near 100°W longitude. The precipitation maxima of 1982, located over Oklahoma/northern Texas and northern Missouri/southern Iowa correspond roughly to the "location and seasonal movement of the centroid of the MCC pattern for the MCCs which occurred from 1978 to 1983." No such pattern was visible in 1983, when MCCs provided much less precipitation.

Kane et al (1987) studied the precipitation patterns of individual MCCs that occurred during 1982 and 1983, averaging them together using a complex scheme to create a composite distribution (Figure 6(a)). The average mesoscale convective complex covers an area of about 510,000 km² with at least 1 mm of rain, with an average of 16 mm over the whole area. The size distributions that appear most frequently, however, are 250-350,000 km² and 650-750,000 km². The track of the -32°C cloud centroid correlates poorly with the path of heaviest precipitation, while the track of the -52°C cloud centroid correlated very well with it, adding another reason to to those listed above for eliminating the -32°C cloud cover criterion from the definition of an MCC. This correlation was also found in McAnelly and Cotton's (1989) study.

McAnelly and Cotton's (1989) total precipitation pattern agrees fairly well with Kane et al's (1987) pattern, except that the latter's is larger in magnitude. This was attributed to the use of a denser network by Kane et al, which would be more likely to record intense local convective rainfal, the more conservative space-time domain and the selection process of McAnelly and Cotton, which eliminated "prolonged or atypical" MCCs as well as springtime MCCs.

Most of the heavy precipitation occurs in the first half of the storm's life cycle, with every MCC producing at least 26mm of rain over about 100,000 km². Nearly half of the heavy-rate area is in the right rear quadrant of the storm (with respect to its motion) and most of the rest is in the right front quadrant. See Figure 6(a). These quadrants have been identified as having the greatest instability (Bosart and Sanders, 1981; Maddox, 1983) and hence generally the deepest convection. This finding was also confirmed by McAnelly and Cotton (1989). "MCCs commonly produce a maximum of 75 mm or more" of rain, but "it's rare for the same relative location to receive rain in excess of 75 mm" (Kane et al, 1987).

McAnelly and Cotton (1989) examined 122 mesoscale convective complexes that occurred during the months of June, July and August from 1977 to 1983. Cases occurring earlier or later in the season, as in Cotton et al (1989), were excluded in an attempt to minimize baroclinic influences. Because the emphasis of this paper was the temporal rather than spatial evolution of precipitation generated by the MCCs, the life cycle of each storm was divided into 14 subperiods such that periods 4-11 covered the approximately 10 hour lifetime of the MCC.

It was found that the rainfall area steadily increases to its maximum value at about one hour after the MCC reaches its maximum size, then steadily decreases. The rainfall area was never greater than one-third of the -33°C cloud area and at its maximum was only about 53% of the -54°C cloud area. The volumetric rain rate peaks near the MCC maximum, while the rainfall intensity peaks relatively early in the life cycle and is decreasing when the maximum storm size is reached.

The composite mesoscale convective complex of McAnelly and Cotton (1989) was divided into three regions concentric around its centroid. The smallest central region accounted for 59.2% of the cumulative rain volume (CV) over subperiods 3-12, while the middle region contributed 20.2%. "It is only during the decaying stages of the system ... that the much larger third domain contributes appreciably to the raining area and to the remaining 20.6% of CV." It was noticed that during the steady growth stage of the raining area, there was an apparent shift in the relative contributions of light and heavy intensities, with the heavier intensity contributing less to the rainfall. They hypothesized that "This shift from a relatively small, convectively-dominated system to one characterized by a large extent of more stratiform precipitation, may essentially represent the upscale transformation of the developing system to its long-lived, α-scale, stage." See Figure 6(b).

Both Kane et al (1987) and McAnelly and Cotton (1989) examined subsets of their set of cases, seeking differences for comparison. Both found that all subsets displayed the same trends in rainfall area, volume and rainrate as the compostie storm. Kane et al divided their MCCs into four groups: synoptic, mesohigh, frontal and extreme-right-moving, based on the synoptic environments in which they formed. Little difference was found in the precipitation distribution patterns, but considerable variation existed in the amount and areas covered by rain. "Synoptic events produce almost double the rainfall area of mesohigh events and more than double the volume of water", while frontal events fall between the two. There were too few extreme-right-moving events to draw any statistically valid conclusions.

Mesohigh and extreme-right-moving storms tend to occur later in teh summer, frontal events are fairly evenly distributed and synoptic complexes occur mainly in the spring. Since synoptic MCCs also produce the most rain, it can be concluded with reasonable certainty that springtime MCCs tend to be the rainiest. This conclusion appears to be confirmed by McAnelly and Cotton (1989), who disputed Kane et al's theory that MCC precipitation decreased with latitude. They argued that this was in fact a seasonal effect because the rainier spring complexes, not included in their study, occurred in more southerly latitudes.

McAnelly and Cotton (1989) found that smaller MCCs (areas < 200,000 $km^2$) had magnitudes of rainfall area, hourly volume and cumulative volume that were considerably lower than the large ones. What was most surprising was that thte larger complexes had significantly greater rainrates than the smaller ones for the first two-thirds of the life cycle, suggesting that they were more efficient precipitators. "This suggests that for an MCS to develop into a large MCC, its early meso-β-scale convective clusters need to be more intense than in smaller systems" (McAnelly and Cotton (1989)).

It was found, however, that larger complexes that began in the eastern part of the domain produce more rain than their western counterparts, in spite of a lifetime up to three hours shorter. This supports McAnelly and Cotton (1986), who pointed out that easter mesoscale convective complexes have a larger, more coherent and consolidated core of heavier precipitation because they form in the environment where they can expand rapidly. Western systems form from thunderstorms generated over the lee slopes of the Rockies and are advected into the area of development which then interact with convection already present in the genesis region, and so tend to be less coherent.

Finally, aside from the rainfall areas of the MCCs being about 8-% greater than that of MCSs, no significant differences were found between the two by Kane et al (1987), suggesting that the dynamic and theromdynamic processes involved may be similar. More research needs to be done to verify this hypothesis.

## 5. Mesoscale Warm-Core Vortices

Some features of certain mesoscale convective complexes, especially those with a leading squall line and trailing stratiform precipitation) such as spiral rainbands (Leary and Rappaport, 1987) and cloud patterns (Menard and Fritsch, 1989; Figure 8(b)) as well as cyclonic and anticyclonic air flow perturbations (e.g. Bosart and Sanders, 1981; Figure 8(a)) have indicated the presence of cyclonic circulations within the middle troposphere and anticyclonic perturbations near the tropopause. Secific study of these circluations has revealed the presence of so-called mesoscale convectively generated warm core vortices (MCVs) (Zhang and Fritsch, 1987, 1988c; Menard and Fritsch, 1989; Brandes, 1990; Verlinde and Cotton, 1990) in some MCCs.

"Inertial stability ... provides resistance to radial displacements such that a mesoscale vortex, once formed, will not quickly decay." (Zhang and Fritsch, 1988c). An inertailly stable vortex lasts for 18 to 36 hours (Verlinde and Cotton, 1990; Brandes, 1990) or even several days (Zhang and Fritsch, 1987), producing convective activity after the deimse of tis MCC (Menard and Fritsch, 1989), intensifying stratiform precipitation within an MCC (Zhang and Fritsch, 1987, 1988c) or, given the right environment, intensifying into a tropical storm (Zhang and Fritsch, 1988c) or cyclone (Velasco and Fritsch, 1988c). The vorticity centre is associated with a 500 mb warm core and surface mesohigh and cool pool, and occurs in the region of stratiform precipitation.

The diameter of an MCV is on the order of 100-200 km, making them difficult to detect not only on synoptic scael charts, but also by Doppler radar networks set up to detect thunderstorms. Spinup appears to occur rairly rapidly (Brandes estimated that the vortex he studied became organized within 1.5 hours), and computer models have little difficulty in generating vortices (Zhang and Fritsch, 1988c). Stability of the circulation has been linked to the Rossby radius of deformation $\lambda_R$ which "identifies the scale at which rotational influences or the inertial stability of a system become important. If the scael of the disturbance exceeds $\lambda_R$, the circulation is nearly balanced..." (Verlinde and Cotton, 1990). Tha is, the vortex will be very stable and long-lived. Brandes hypothesized that because of the short spinup time, MCVs should be relatively common features of MCCs, given a few preconditions.

It is still unclear how these vortices are generated. Velasco and Fritsch (1987) speculated that since MCC activity in North and South America is located downwind of north-south mountain ranges, the vortices may be "shed" from the air flow around the peaks. Zhang and Fritsch (1987) proposed a positive feedback process between low- to mid-level heating, low-level mass and moisture convergence and surface pressure falls which is responsible for the spinup of several different mesoscale vortices, including those generated by MCCs. This must occur in a saturated or nearly so environment with a "conditionally unstable" but nearly moist adiabatic lapse rate", one which is produced by deep convection (i.e. Figure 2(c)). Verlinde and Cotton (1990) and Brandes (1990) hypothesized that horizontal vorticity lines generated by temperature gradients and/or the low-level jet could be tilted by convectively induced vertical air currents. All have noted that vertical wind shear plays an important role in the initial stages of the formation of the vortex. Mid-level convergence caused by wind flow and especially by the melting of solid hydrometeors has been hypothesized to enhance vorticity already present (Zhang and Fritsch, 1987, 1988c; Chen and Cotton, 1988; Menard and Fritsch, 1989; Brandes, 1990; Verlinde and Cotton, 1990).

Zhang and Fritsch (1988c) noticed that the area of strong convergence and upward motion occurred ahead of the column of maximum vorticity, and speculated that this may be an important component of the MCV's propagation along a front. Whether this applies to MCCs that do not form near a front remains to be veriried. Menard and Fritsch (1989) noted that the mesovortex in the complex they studied formed in the stratiform region of the storm, which had very little potential for convection, but that deep convection soon developed near the centre of the vortex. This illustrates our current lack of knowledge of the interactions between vorticity and convection and is undoubtedly going to be the subject of further research.

## 6. Air Flow in MCCs

The airflow in a mesoscale convective complex is driven by processes in the convective region and their influences on the surrounding regions. Strong updrafts occur in the convective regions, of course, but strong mesoscale downdrafts, driven by the evaporation of precipitation that falls outside the convective region, are also present.

Three main components of horizontal motion appear to have been identified. First is the warm, moist, southerly low-level jet that feeds the convective region of the MCC. Second, there is the middle level flow converging anticyclonically into the convective zone and the upper-level outflow, where the updraft air encounters the tropopause and diverges anticyclonically (see Figure 7(a), 7(b)). Finally, there is a recently identified rear inflow jet (Johnson et al, 1989; Brandes, 1990) which appears to occur in MCCs characterized by a leading squall line with a trailing stratiform rain region. It is a rear to front flow of drier and potentially cooler environmental air into which precipitation readily evaporates. This loss of rain produces a distinctive notch in the precipitation radar echoes (Stirling and Wakimoto, 1989; Verlinde and Cotton, 1990). If a mesoscale vortex is present, this dry notch will acquire a cyclonic curve and become hook-shaped.

The evaporation of rain chills the air of the jet further, causing the air to sink as it advances to the convective region at the front of the storm (Johnson et al, 1989; Brandes, 1990). Johnson et al also connected the rear inflow jet to the presence of a surface wake mesolow behind the surface mesohigh, a feature noted by several authors (e.g. Menard and Fritsch, 1989). The presence of this rear inflow jet has yet to be confirmed in non-squall line types of MCC.

Verlinde and Cotton (1990) studied the airflow within their MCC by followin the trajectories of imaginary air parcels (see Figure 7(d)). Some of the parcels entering the main updraft region rose to the upper troposphere and entered either the leading or trailing anvil region. Others rose to about the melting level and then descended in the trailing part of the storm. Downdrafts originated in the middle levels of the MCC from the aforementioned low $\theta_e$ air entrained from the coud edges, which may get accelerated at the melting level by falling, melting and/or evaporating precipitation. Verlinde and Cotton (1990) and Menard and Fritsch (1989) speculated that these downdrafts undercut low $\theta_e$ air behind the system and create secondary updrafts which ascend from the melting level to join either ascending air from the main updrafts or the descending front to rear flow.

## 7. Lightning and Effects on Pollution

Noting that about half of the documented mesoscale convective complexes have lightning damage associeated with them, Goodman and MacGorman (1986) examined the cloud-to-ground (CG) lightning strikes produced by 10 MCCs over central Oklahoma. Because the detection network used had only a 70% detection rate, it was concluded that the compiled statistics are conservative estimates of the actual numbers.

Most of the lighning damage occurred between MCC initiation and maturity, coinciding with the time most severe storm reports are made. The number of CG flashes varied widely, with an average of 22,300 occurring, giving a rough overall average of 24.4 per minute. The average peak rate, however, is about 2680 flashes per hour, occurring about 2.6 hours before storm maximum, and on average there are 9 consecutive hours with more than 1000 CG discharges per hour. Finally, about 75% of thelightning flashes occurred by the time the storm had reached maturity, corresponding to the time stratiform precipitation begins to dominate over convective.

Lyons et al (1986) examined the improvement that three mesoscale convective systems, including an MCC, made on the air quality of the Eastern Seaboard of the United States. It was found, for example, tha tthe air near Philadelphia had ozone levels reduced from about 120 ppb to nearly 20 ppb, while a region of northern Virginia had visibilities improved from 3-8 km before the storms to more than 40 km afterwards. Because no rain fell in most of the latter area, it was hypothesized that strong mesoscale downdrafts from the MCSs transported relatively clean air from the mid troposphere to the boundary layer, while updrafts helped move boundary layer air to higher levels.

## 8. MCCs in South America and the Tropics

It is reasonable to assume that mesoscale convective complexes are not unique to North America. The geographical and environmental characteristics of the MCC generating region, such as north-south mountain chains, moist air masses frequently moving poleward from the tropics and frequent middle and upper tropospheric disturbances (short waves) in the westerlies, occur in other locations in the world. Velasco and Fritsch (1987) saw that the region of South America comprising northern Argentina, Paraguay and southern Brazil had these characteristics and found that MCCs occur there too.

It was found that both South and North American MCCs have similar life cycles, being predominantly nocturnal, but the former develop slightly later and last somewhat longer. Close to 30% of both sets of MCCVs used have roots in convective storms generated on the lee slopes of their respective mountain ranges.

South American MCCs, however, tend to be 60% larger than their northern counterparts, which could be caused by the sub-tropical air feeding the convection being moister. The low-level jet that advects this air is stronger in the South, possibly due to the Andes being higher than the Rockies and the sloping terrain to the east of the mountains being steeper. Because the subtropical jet does not migrate poleward with the season, meither does the South Amarican MCC track, whereas the North American polar jet and MCCs do. The “MCC season” in South America is about 8 months long, while in North America it is only about 5 months in duration. Finally, a tentative link between the increase in the number of MCCs and El Niño was made.

Tropical mesoscale convective complexes are more numerous and also distinctly nocturnal, it was found, but their life cycles begin almost 4 hours later, are 1-3 hours shorter than North American complexes, and tend to develop from the remnants of previous convection. There is a high frequency of relatively small systems, though the average size is still colse to that of northern storms. The monthly distribution of MCCs “follows the sun” in both hemispheres. That is, there is a”activity rapidly increasing following the spring equinox and then persisting 1-2 months past the fall equinox”. More research needs to be done on the internal processes of these MCCs to compare them to North American storms.

## 9. Summary

Mesoscale convective complexes form in an environment characterized by high moisture conente and instability from the surface to about 700 mb, warm advection, the presence of a 500 mb short wave, and large amounts of surface convergence. Initial expansion is rapid and most of the severe weather associated with MCCs occurs during this time. By maturity, significant perturbations in air flow can be detected at all levels. The complexes dissipate when they enter regions unfavourable for convection, after a life span of 10-18 hours.

MCCs occupy the middle ground between baroclinic midlatitude squall lines and barotropic tropical convective systems like cloud clusters. They form in essentially barotropic environments and are basically so in nature, buth they require baroclinic influences like low-level jets and mid-level short waves to initiate and sustain them. Vertical profiles of divergence, vertical velocity and vorticity have been compared to those of tropical systems (e.g. Maddox, 1983; Wetzel, 1983) and found to be similar only in some respects.

Although MCCs originate from the interaction of convective elements, a stratiform precipitation component rapidly appears and assumes an increasingly important role (see Figure 6(b)). Unquestionably, MCCs are significant producers of precipitation, especially for large areas of the American Midwest. An average maximum rainfall is on the order of 100 mm (Kane et al, 1987), but the storms that produce flash floods, such as the Johnstown disaster, produce two or more times that amount.

Probably the most important, and one of the most difficult to detect, dynamic feature of many (and perhaps most) mesoscale convective complexes, is the inertially stable vortex. Occurring in the stratiform region of the storm, the vortex may be responsible for enhancement of stratiform precipitation, the shape and longevity of the storm and generating post-storm convection.

In conclusion, this report has attempted to summarize the results of research that has been done so far, but the topic of midlatitude mesoscale convection retains a good deal of mystery. As scientists attempt to probe the inner workings of these vast, complex sometimes violent, but also beneficial storms, more questions arise and others remain unanswered. The following section outlines where more research can and should be addressed in the future to expand our knowledge of the dynamics of the atmosphere.

## 10. Suggestions for Further Research

- Numerical weather prediction models, perhaps due to the parameterizations used to deal with convection, are unable to predict the occurrence of MCCs. It has been amply demonstrated that these storms produce significant perturbations in the atmosphere that in turn affect the accuracy of future forecasts. It is therefore important for this reason and others mentioned previously to develop procedures that will forecast their development.
- Inertially stable vortices generated by meoscale convective systems need to be studied further. Attempts should be made to generate a dataset of storms that have these vortices, with the object being to create a composite similar to what Maddox (1983) and Cotton (1989) did.
- Although some studies have been made (Cotton et al, 1983; Tripoli and Cotton (1989) of the interactions of the pre-MCC storms, a more detailed examination of the dynamics is required. It remains unclear exactly why and how clusters of thunderstorms interact to produce the MCC.
- Although one attempt has been made to mathematically model an MCC (Xu, 1987) using conditional convective instability theory and solitary wave solutions, more efforts should be made to use the tools of theoretical dynamic meteorology to obtain a physical understanding of the processes involved.
- Several mesoscale convective complexes have passed over the Great Lakes region of North America. The influences that these large bodies of water have on the storms as heat and moisture sources could be studied.
- Velasco and Fritsch (1987) examined MCCs that occur outside of midlatitude North America, but only in the New World. Studying MCCs wherever in the world they occur should reveal common processes involved in their life cycles as well as an idea of their importance in such things as

global heat, mass and moisture transfer. Economic and political problems in many of the areas will hinder this research, unfortunately.

- Cotton et al (1989) restricted their dataset for their composite MCC to events occurring in June, July and August, in order to minimize baroclinic influences. MCCs that occur outside of these times could thus be studied in order to study baroclinic influences on them.
- An effort should be made to compile all MCC and perhaps MCS events since satellites were first launched to expand the North American dataset.
- Attempts to study precipitation particle size distribution in MCCs (Yeh et al, 1988; Fan et al, 1988; Willis and Heymsfield, 1988) have been made, with preiliminary results showing that raindrops basically follow the Marshall-Palmer distribution and that ice crystals don't. Chen and Cotton (1988) demonstrated the effects of ice-phase microphysical processes and long-wave radiation on a model of an MCC, and Zhang and Fritsch (1988a) experimented with other processes on their model of the Johnstown MCC. These papers have made it clear that any model of a mesoscale convective system that is desired to be accurate must include some form of melting/freezing parameterization for precipitation. More work should be done on this subject.
- Series of convective complexes and comparisons of MCCs in drought and non-drought years have been discussed by Fritsch et al (1986). A more complete examination, especially with the aid of a larger database, may shed more light upon precipitation characteristics of MCCs.
- Menard and Fritsch (1989) noticed that the MCC they studied moved in the direction of the wind shear vector. It was stated that this is a characteristic of MCCs and suggested that the storms “may be strongly influenced by cloud scale properties”. This property needs further investigation.

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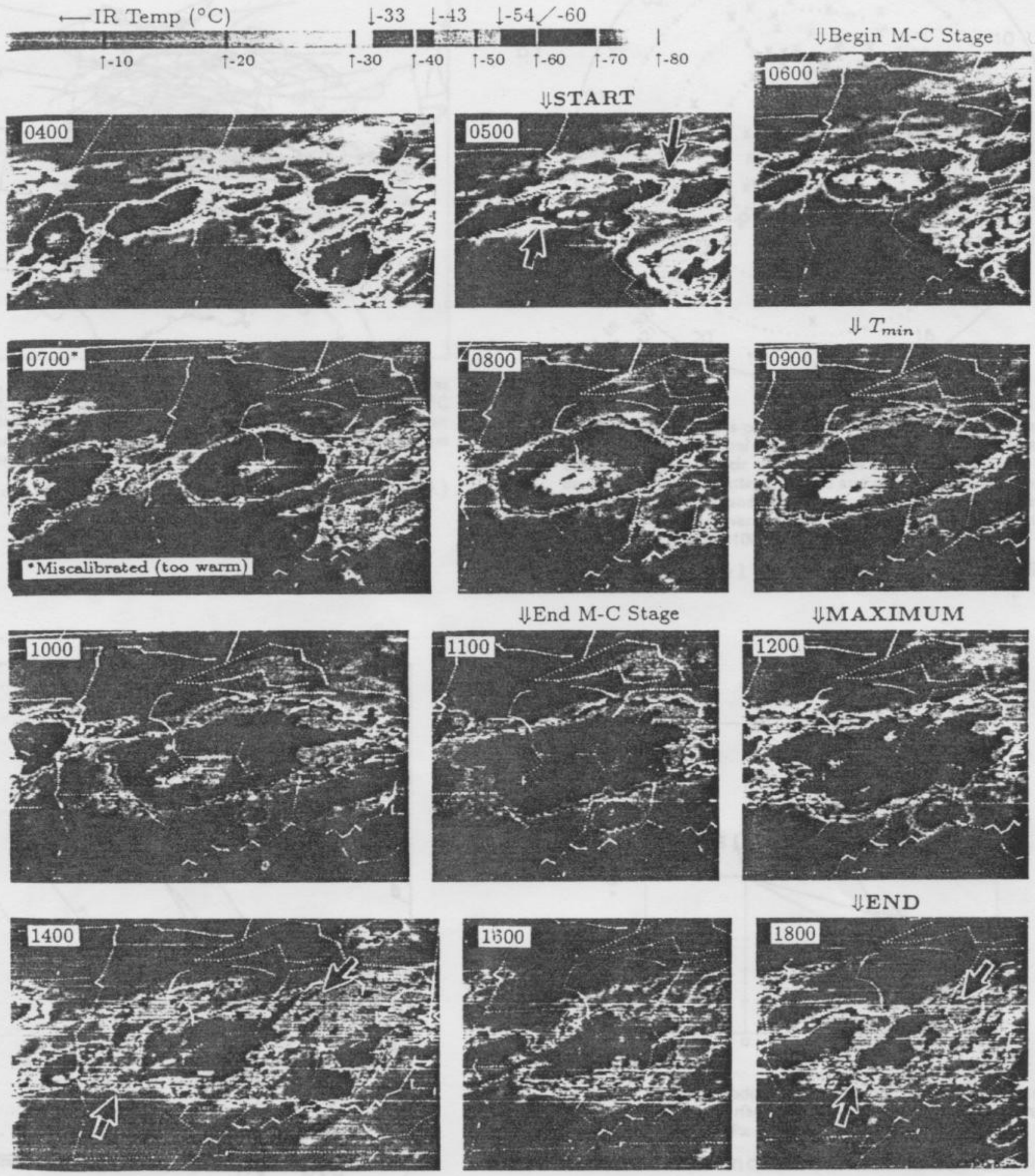


FIG. 6. The MB-enhanced, IR satellite sequence showing the evolution of a relatively high-rated MCC (rating = 7; see text) on 8 Aug 1977. Indicated times are UTC. *Start, maximum* and *end* times are indicated, as are the beginning and ending of the *mesoconvective (M-C) stage* and the *mesoscale thermal minimum* ($T_{min}$). Each pair of arrows (at selected times) indicates the long-axis ends of the −54°C (dark-contoured) cloud-shield area considered to be the MCC. The temperature scaling for the MB enhancement is indicated (°C) below the gray-scale bar; the values above the bar indicate IR thresholds (°C, with 0.2 decimal omitted) for the contours associated with discrete gray-scale steps.

Figure 1: The Life Cycle of a Mesoscale Convective Complex
(From McAnelly and Cotton, 1989)

a)


FIG. 1. Satellite-defined tracks of the 122 MCCs in the analysis sample, based on centroids of the cloud-shield area colder than −54°C at 3-h intervals. Each MCC track extends from 3.75 h before its *start* position ($S$) to 3.75 h after its *end* position ($E$), with the *maximum* position given by the system number.

(From McAnelly and Cotton, 1989)

b)

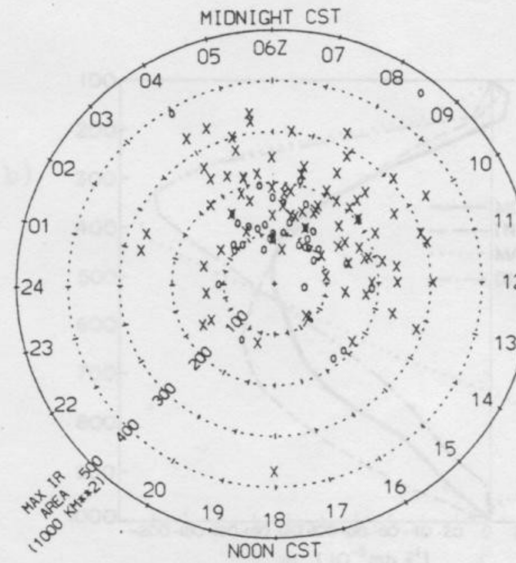


FIG. 2. Distributions of diurnal timing (UTC clock coordinate; 0600 UTC = 0000 central standard time) and size (radial coordinate) of the 122 MCCs at their maximum −54°C areal extent. Large X's denote the relatively better organized and more 'ideal' systems with ratings 5–9 (see text), and small O's denote the lower-rated systems (ratings 1–4). Time averages in text are based on maximum-size times from −0300 to 2100 UTC.

(From McAnelly and Cotton, 1989)

c)

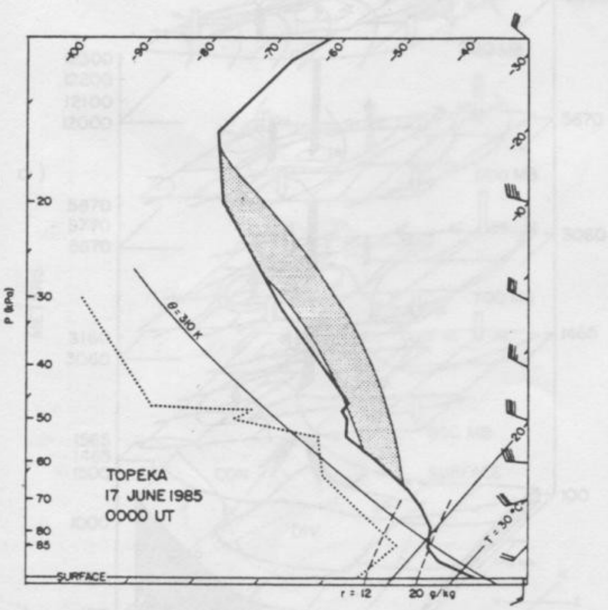


FIG. 2. Pre-MCC sounding taken at Topeka, Kansas, 0000 UTC 17 June 1985. The shaded area shows the extreme ranges for convective available potential energy based on observed surface temperatures and mixing ratios in the prestorm environment. Full wind barbs represent 5 m s$^{-1}$.

(From Verlinde and Cotton, 1990)

d)

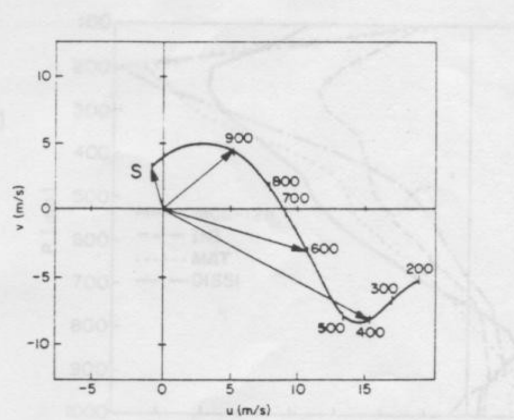


FIG. 3. Composite hodograph of pre-MCC soundings, 17 June 1985 0000 UTC. The surface wind vector is indicated by S: all other levels are indicated in hPa.

(From Verlinde and Cotton, 1990)

Figure 2: Paths, Times and Typical Initial Conditions of MCCs

a)

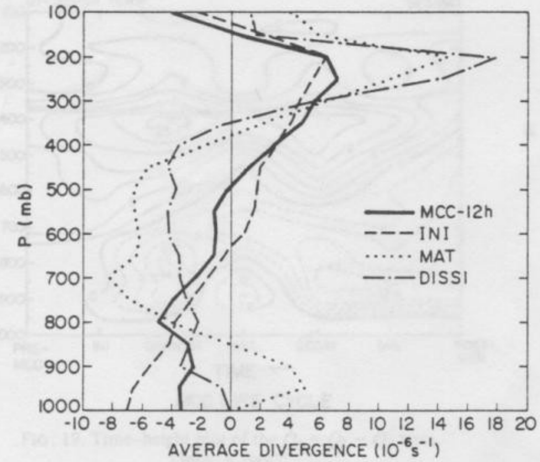


FIG. 12. Vertical profiles of horizontal divergence (horizontally averaged over the 3 × 3 central grid points at 50-mb intervals) at the MCC-12 h, initial, mature, and dissipation stages. Units: $10^{-6}$ s$^{-1}$.

(From Cotton et al, 1989)

b)

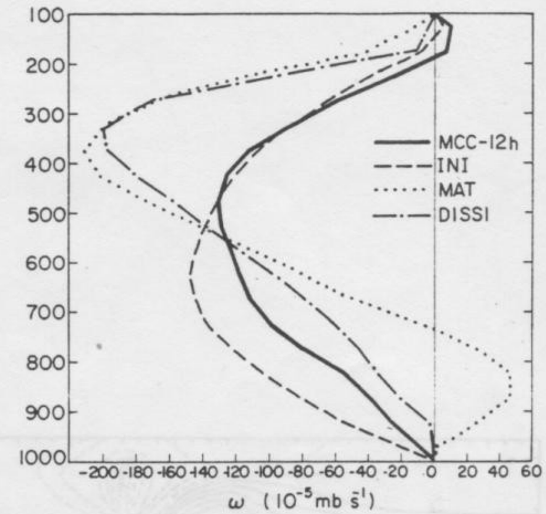


FIG. 13. Vertical profiles of vertical velocity (ω) at the MCC-12 h, initial, mature, and dissipation stages, calculated by integrating the corresponding divergence profiles in Fig. 12. They represent average ω over the 3 × 3 central grid-point region (4.4 × $10^5$ km$^2$). Units: $10^{-5}$ mb s$^{-1}$.

(From Cotton et al, 1989)

c)

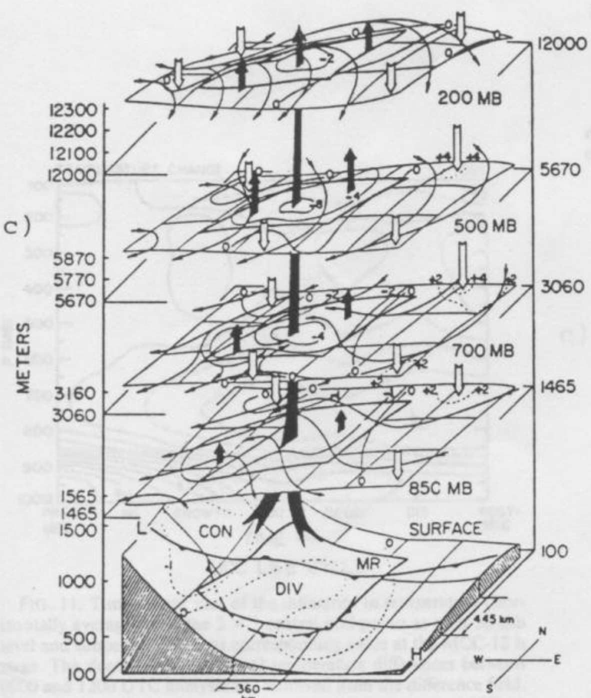


FIG. 6. Composited mature MCC and its near environment (adapted from figure 50 of Maddox, 1981). Dark arrows illustrate regions of upward motion; light arrows indicate regions of downward motion. Selected contours of vertical velocity (omega in μb s$^{-1}$) are shown.

(From Xu, 1987)

d)

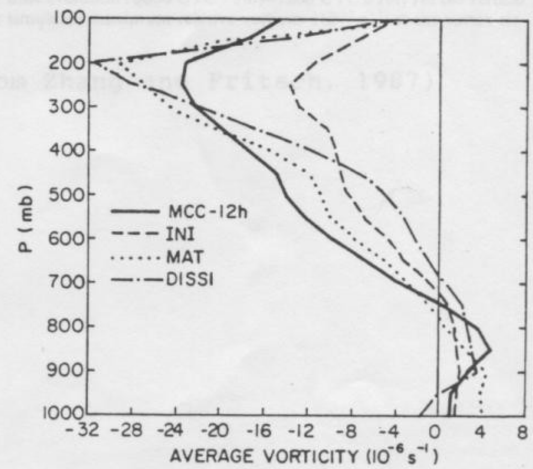


FIG. 15. Vertical profiles of relative vorticity (horizontally averaged over the 3 × 3 central grid points at 50-mb intervals) at the MCC-12 h, initial, mature, and dissipation stages. Units: $10^{-6}$ s$^{-1}$.

(From Cotton et al, 1989)

Figure 3: Typical Vertical Profiles and Structure of MCCs

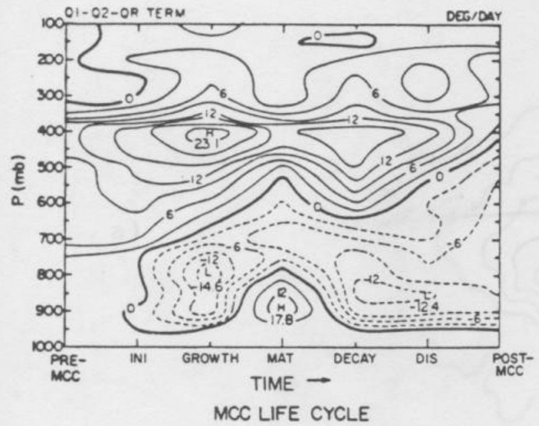


FIG. 19. Time–height plot of the $Q_1 - Q_2 - Q_R$ term. Units: K day$^{-1}$.

Solid Line = Heat Source
Dashed Line = Heat Sink
(From Cotton et al, 1989)

a)

b)

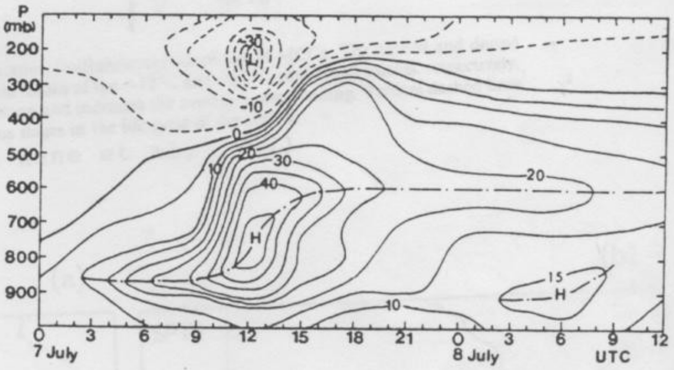


FIG. 14. (a) The time evolution (0000 UTC 7 July–1200 UTC 8 July) of the vertical distribution of the simulated maximum relative vorticity ($10^{-5}$ s$^{-1}$) at the vortex circulation center

(From Zhang and Fritsch, 1987)

c)

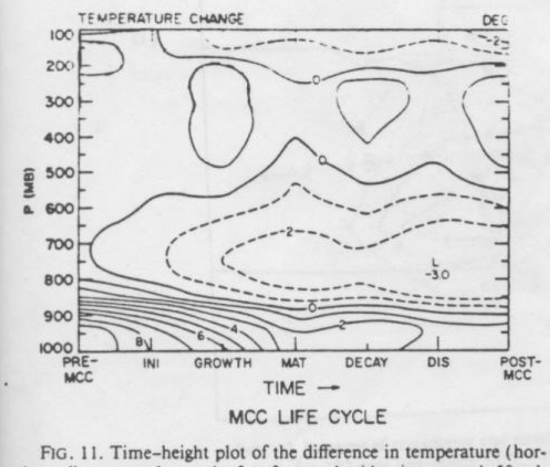


FIG. 11. Time–height plot of the difference in temperature (horizontally averaged over the 3 × 3 central grid points at each 50-mb level and subperiod) from its corresponding value at the MCC-12 h stage. The domain-mean, diurnal temperature differences between 0000 and 1200 UTC analyses are removed from the difference field. Positive values indicate warmer temperatures than at the MCC-12 h stage. Units: K.

(From Cotton et al, 1989)

Figure 4: Time Evolution of Heat Sources, Relative Vorticity and Temperature of MCCs

a)

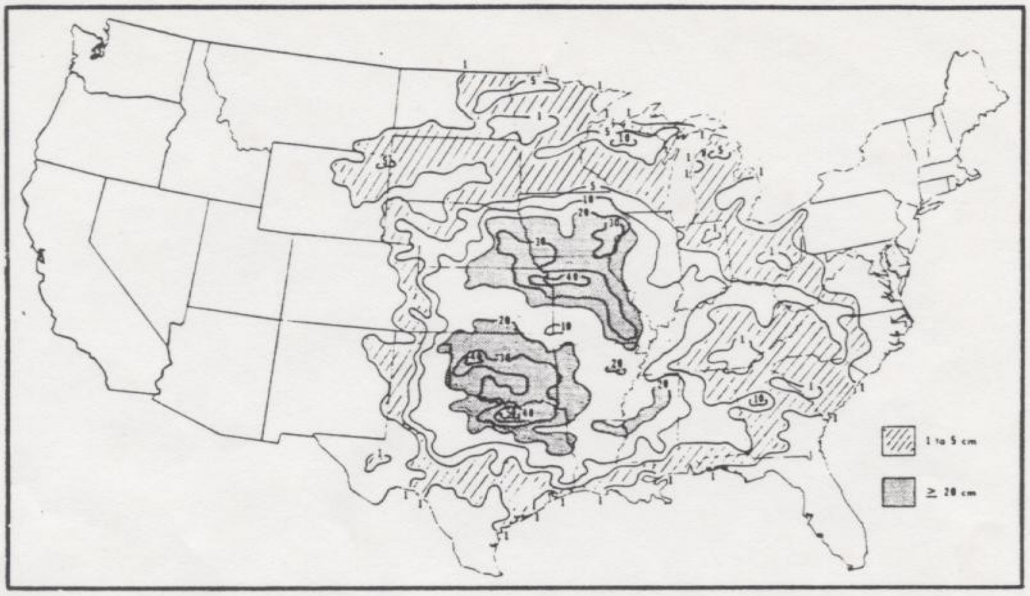

FIG. 1. Accumulated precipitation (cm) from 44 MCC's from the 1982 warm season. Hatched and shaded regions indicate precipitation accumulations of 1 to 5 cm and ≥20 cm, respectively. Note that the outer isohyet is the 1-cm line and that lighter accumulations, especially from the debris of dying MCC's, extend beyond this isohyet.

(Normal Year)

b)

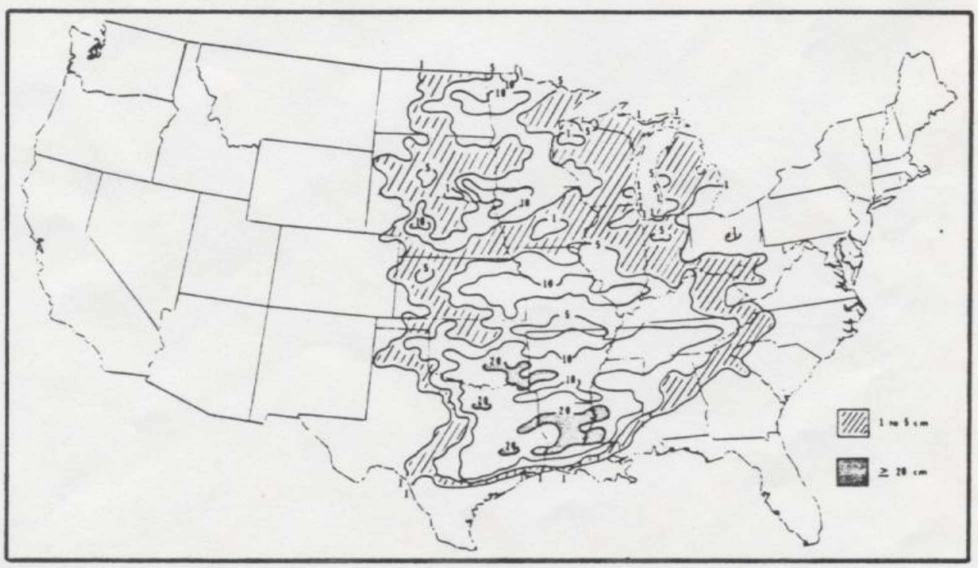

FIG. 4. As in Fig. 1 except for 30 MCC's from the 1983 warm season.

(Drought Year)

Figure 5: Comparison of Yearly Accumulated MCC Precipitation
(From Fritsch et al, 1986)

a)

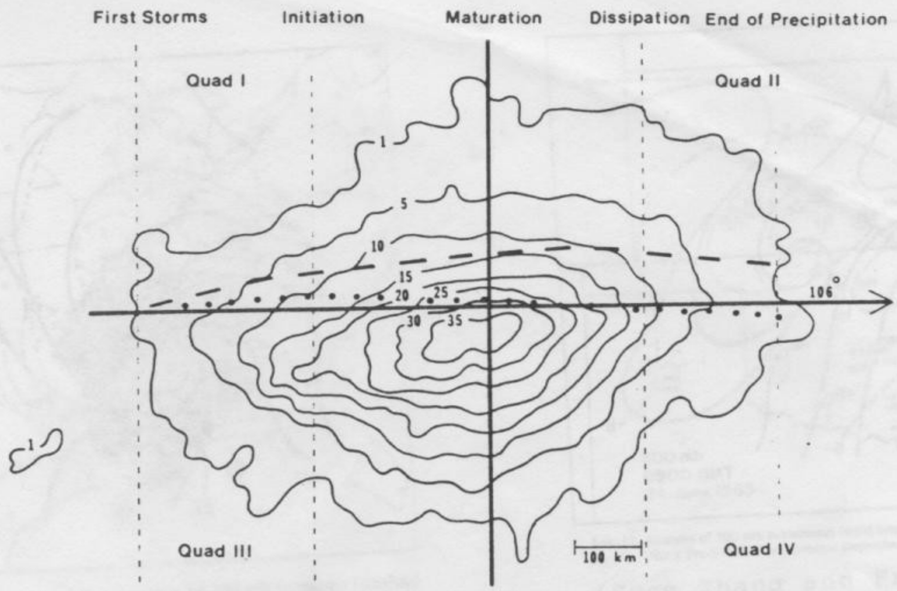


FIG. 2. Normalized composite precipitation (millimeters) pattern for 74 MCCs. The dashed and dotted lines are the approximate average centroid tracks of the −32°C and −52°C cold-cloud shields, respectively. The horizontal axis is the axis of propagation and indicates the average storm heading. Vertical dashed lines indicate approximate locations of various stages in the life cycle of the MCCs.

(From Kane et al, 1987)

b)

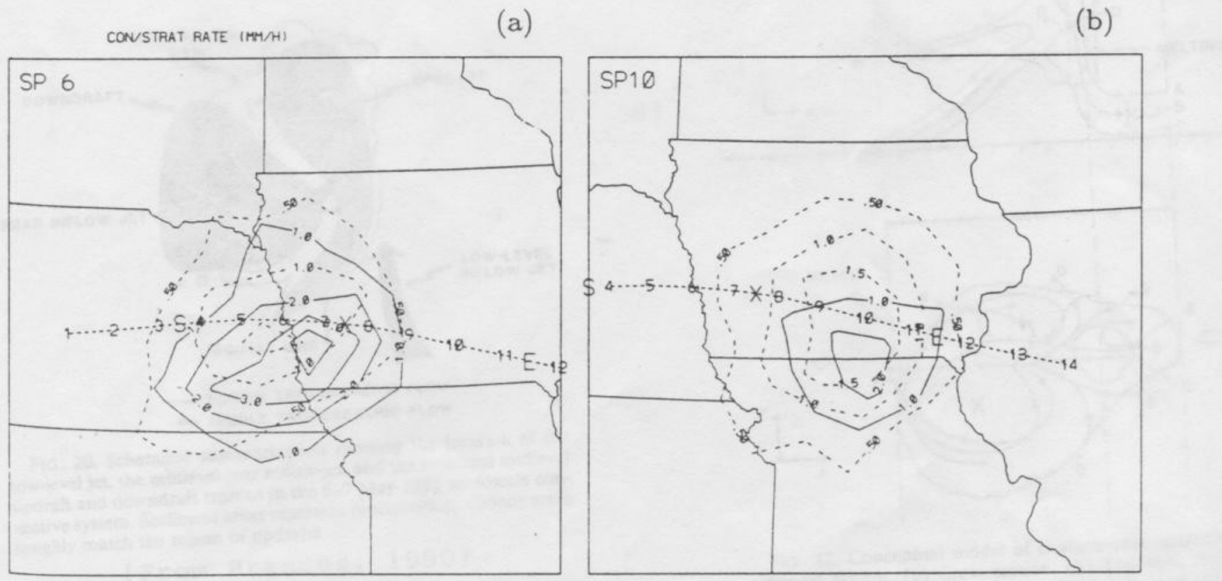


FIG. 13. Patterns of convective and stratiform precipitation rate for (a) subperiod 6 and (b) subperiod 10, based on threshold rate of 10.2 mm h$^{-1}$, for 122-case composite MCC. The grid-cell values are the composite volumetric rate due to convective/stratiform intensities, divided by the grid-cell area. Convective contours are solid and in intervals of 1 mm h$^{-1}$, and the stratiform contours are dashed and in 0.5 mm h$^{-1}$ intervals.

(From McAnelly and Cotton, 1989)

Figure 6: Precipitation Distribution of MCCs

a)

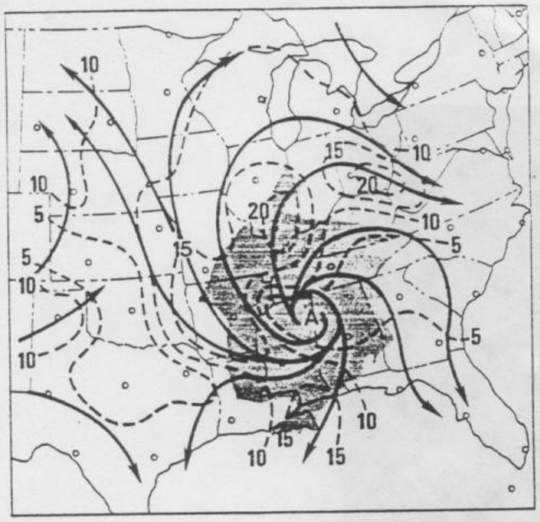

FIG. 19. 1500 km bandpass analysis of 200 mb isotachs (dashed lines, m s$^{-1}$) and streamlines (solid lines) for 1200 GMT 7 May 1978. Shaded area as in Fig. 18.

(From Fritsch and Maddox, 1981)

b)

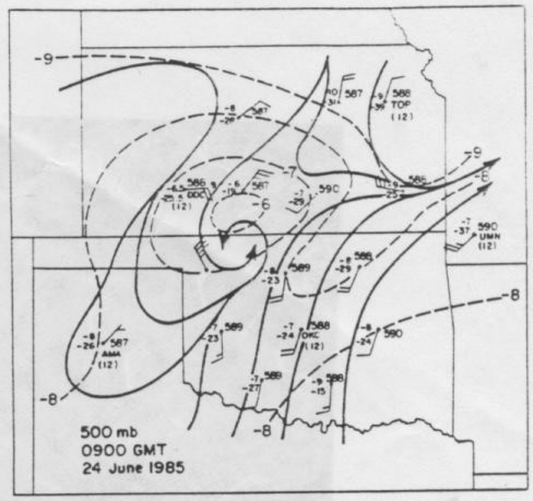


FIG. 12. Analysis of 500 mb streamlines (solid lines) and isotherms (dashed lines, °C) for a Pre-STORM mesovortex (reproduced from Johnson, 1986).

(From Zhang and Fritsch, 1987)

c)

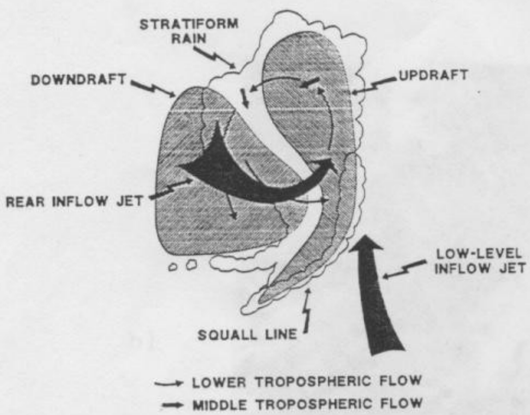


FIG. 20. Schematic summarization showing the location of the low-level jet, the midlevel rear inflow-jet, and the principal midlevel updraft and downdraft regions in the 6–7 May 1985 mesoscale convective system. Scalloped areas represent precipitation. Cloudy areas roughly match the region of updrafts.

(From Brandes, 1990)

d)

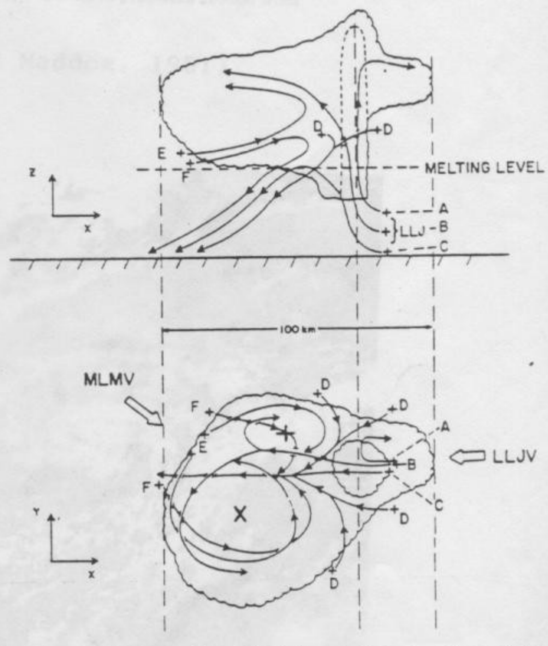


FIG. 12. Conceptual model of characteristic streamlines of the observed system. (a) Cross section. (b) Top view. The different streamlines are discussed in the text. The low level jet (LLJ) and the middle level momentum vector (MLMV) are indicated on the figure. The heavy plus indicates the middle level anticyclonic circulation while the heavy X indicates the middle level cyclonic circulation.

(From Verlinde and Cotton, 1990)

Figure 7: Air Flow Patterns of MCCs

a)

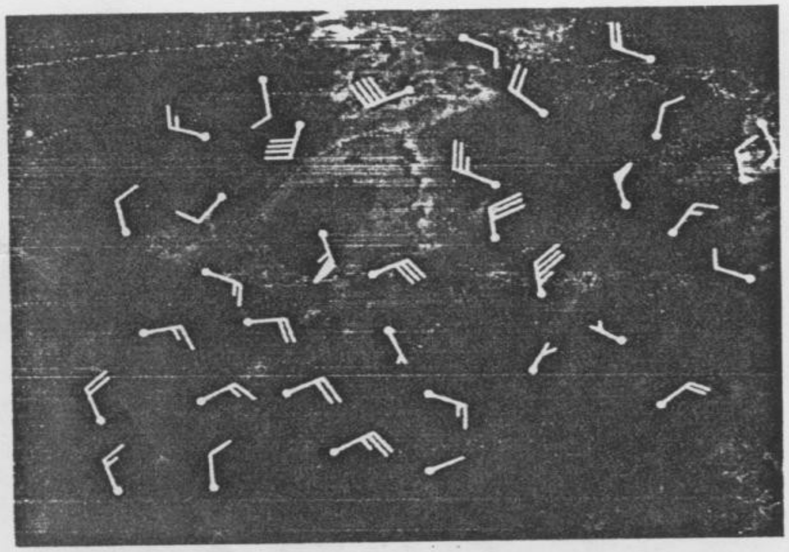

FIG. 2. Infrared satellite imagery of mesoscale convective complex at 1200 GMT 28 June 1979. Wind barbs are vector errors of the 12 h LFM predicted 200 mb wind field. Full wind barb = 5 m $s^{-1}$: flag = 25 m $s^{-1}$.

(From Fritsch and Maddox, 1981)

b)

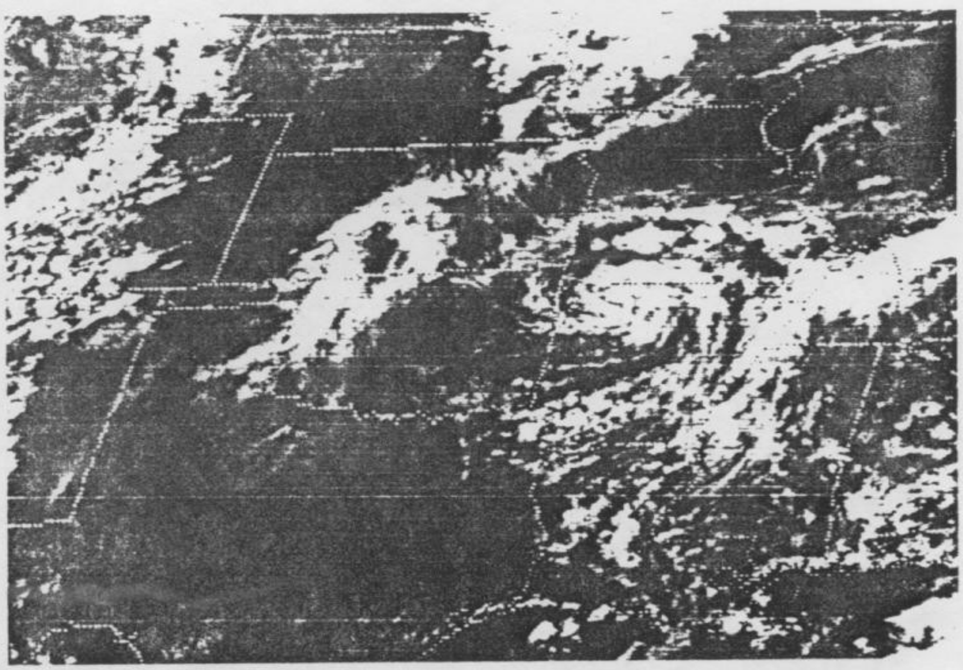

FIG. 28. Visible satellite image for 1830 UTC 8 July 1982.

(From Menard And Fritsch, 1989)

Figure 8: a) Perturbations Induced by an MCC
b) An Inertially Stable Vortex