Meso-$\beta$- Scale
and
Meso-$\alpha$-Scale
Convective Systems
Mesoscale Convective System

• Grouping of deep cumulonimbus clouds merged at the anvil forming a meso-β–scale or larger cluster.

• Defining the term “MCS” implies that there are one or more dynamics mechanisms maintaining and growing the system.

• What are some of these mechanisms?
Organization of MCSs

• Linear
  – Mesoscale forced
    • Convergence line
    • Sea breeze
    • etc
  – Middle Latitude Squall lines
    • Frontal
    • Prefrontal
    • Derecho
      – Progressive
      – Serial (prefrontal)
    • Supercell
  – Tropical Squall Lines

• Circular
  – MCS
  – MCC
Linear Meso-β-scale MCS’s

• Linear organizations can appear for wide range of reasons including:
  – Wave-CISK
  – CSI
  – C-SI
  – Barotropic converging flows
  – Baroclinic forcing (density current)
Circular MCSs

• Develop with high horizontal eccentricity (minor axis/major axis) anvil shapes for several reasons:
  – Low shear
    • Multiple cell regeneration along a gust front
    • Synoptic forcing
    • Anvil spreads radially leaving circular appearance
  – System rotation
    • Gradual geostrophic adjustment to heating in low shear environment
      – Deep cumulus latent heating...very inefficient because Rossby radius too large
      – Shallow melting zone cooling in anvil - small Rossby Radius (shallow) more efficient adjustment
      – Balling up of line (shear ) vortex in squall line
        » Line vortex forms more efficiently from momentum transport at small scales since mass adjusts to wind!
        » Large line vortex can ball up into circular vortex forming a circular system
Organization Mechanisms

1. Independent Mesoscale Circulation
   a) sea breeze circulation
   b) slope flow circulation
   c) land use forced thermal circulation

2. Independent Synoptic Circulation
   a) frontal circulation
   b) ageostrophic Jet-Streak circulation
3. **Mesoscale basis of self-organization**

   - **Conditional Instability of the First Kind (CIFK):** Traditional conditional instability occurring on meso-β- and meso-α-scale.
   - **Conditional Instability of the Second Kind (CISK):** Growth and maintenance of a meso-β- and meso-α-scale disturbance through assumed interaction with meso-γ-scale convection.
   - **Conditional symmetric instability (CSI):** Traditional linear conditional instability applied to a rotating fluid.
   - **Convective Inertial Instability (CII):** Combined CIFK and inertial Instability.
   - **Thermodynamic Process (engine):** A cyclic thermodynamic process used to describe organization.
CISK

- Unstable growth of a wave on the scale of several cumulus (meso-β-scale and larger) in response to latent heating
- Originally applied to the growth of a hurricane depression by Charney and Elliasen
- Later applied to the growth of any wave using linear theory (wave-CISK)
Frictional CISK
(Charney and Elliasen, 1962)

• Once believed to be the basis of organization for a tropical cyclone
• An “ensemble” of cumuli is supported by mesoscale ascent driven by Ekman pumping of cyclone vortex.
• Cumulus feed back to vortex strength by heating on scale of vortex (through a cumulus parameterization). In the linear formulation, this major assumption is a feedback that makes linear instability in the system appear that is used to account for the hurricane growth.
• Flaw:
  – The cumulus parameterization assumes the scale interaction that it is trying to find.
  – Many hurricanes don’t have cumulus!
• 20 years later, they realized that explaining the growth of a hurricane this way was a circular argument.
Wave-CISK

- Upward mesoscale vertical motion driven by the propagation of linear wave (gravity wave, rotational wave, any wave) drives cumulus heating that amplifies the wave.
- Cumulus parameterization used to represent cumulus feedback on wave.
- Flaw: cumulus parameterization assumes the scale interaction it is trying to predict.
Density Current Organization

• Mesoscale density current formed by combined effect of a group of cumulus over time acts to organize lifting along the gust front (density current boundary).

• Density current moves relatively slowly and has a long lifetime when compared to time scale of individual cumulus. Hence the density current is the basis of the system organization.

• But:
  – Density currents are a nonlinear packet of shallow trapped internal waves…a solitary wave.
  – Not treated by linear theory
Air-Sea Interaction Instability

- Thermodynamic instability allowing tropical cyclone circulation to couple directly with water surface.
- New paradigm for explaining the dynamics of a weather system.
- Break from traditional CISK description of tropical cyclone.
Geostrophic Adjustment

• Recall winds adjust to mass for scales larger than $L_R$ and mass adjust to wind for scales smaller than $L_R$.
• In mid-latitude squall line momentum transport by the rear inflow jet converging with the front updraft inflow produce a mid-level line vortex through momentum transport and the mass field adjusts to the vorticity, ie the pressure lowers along the line vortex.
• This regionally decreases $L_R$.
• The melting layer heating function projects on to a small $L_R$ because the layer is shallow, further enhancing the line vortex.
• Hence the squall line grows a quasi-geostrophic component through *scale interactions*.
• Eventually the line vortex can ball up creating a circular vortex and a circular convective system of meso-alpha scale proportions.
Dynamic Flywheel

- The formation of a quasi-geostrophic component to an MCS is significant because:
  - Quasi-geostrophic flows have long time scales compared to transient gravity wave components, with e-folding times of $\frac{1}{2}$ pendulum day.
  - The quasi-geostrophic component effectively stores the available energy of the storm’s convective latent heating in its mass balanced circulation.
  - Essentially, the quasi-geostrophic system works in reverse to what synoptic-small scale flow interaction: The small scale vertical motion, driven by conditionally unstable latent heating, creates a geostrophic flow that would have created the vertical motion had the process run in the forward direction. Hence the tail wags the dog using energy coming from the tail.

- The mid level line vortex of the middle latitude squall line is such a component that provides a lasting organization of the system. In essence the quasi-geostrophic component of the system, built from cumulus and slant wise processes, stores the energy released in the latent heating into a long time scale balanced quasi-geostrophic circulation. That is why that circulation can be called a *dynamic flywheel*.
Middle Latitude Squall Line
Conceptual Model
Middle Latitude Squall Line
(Serial Derecho)
Prefrontal Middle Latitude Squall Line

- In its formative stage the line organizes along a preexisting convergence line and is three-dimensional in character, i.e. it is composed of a linear arrangement of individual convective cells.
- The mature line becomes essentially two-dimensional in construction and follows the equilibrium model of sheared convection presented earlier.
- It is the mature stage of squall line MCS that begins with a line of cumulus initiated along a preexisting boundary such as a cold front or local thermal circulation. After several hours of down shear tilting short lived cumulus a deep density current is built that becomes the basis of maintenance of the steady state quasi-two-dimensional line structure.
- Persistence of the quasi-steady structure can evolve to build a strong positive vortex sheet along a shear line at middle levels. Associated mass adjustment to the vorticity results in low pressure and mesoscale circulations that support the line.
Middle Latitude Squall Line
(continued)

- Eventual shearing instability can lead to “balling up” of the vortex sheet into a circular warm core vortex aloft
- Mid-level vorticity maximum can drive mesoscale ascent in support of convection. Role of slantwise convection in trailing stratiform anvil.
- Slantwise mesoscale subsidence driven by melting and evaporation in anvil.
- Compensating upward slantwise motion are forced helped by new condensation and ice growth along upward motion.
- Vertical circulation may build jet streak feature at upper levels
Super Cell Squall Lines

- Another form of the middle latitude squall line is a super cell line
- Formed by a line of right moving super cells oriented so that left movers move back over density current and right movers move with squall line.
- Very dangerous squall line because of the increased potential for tornadoes
Serial Derecho
(Prefrontal Squall Line)
Super Cell Squall Line

Fig. 17. Top: a three-dimensional perspective view of the $\theta_v = 335$ K surface for a portion ($56 \leq x \leq 116$ km, $14 \leq y \leq 82$ km) of a line containing two supercells. Below there is the $z = 4$ km horizontal plane exhibiting line-relative flow vectors at every other grid point (a length of two grid intervals $= 20$ m s$^{-1}$); the shaded regions encompass places where rainwater exceeds 0.1 g kg$^{-1}$; the circular contour encompasses updraft greater than 10 m s$^{-1}$. The flow in the horizontal plane at the surface is denoted similarly except, the updraft contour (at $z = 350$ m) encompasses values greater than 1 m s$^{-1}$ and the barbed line denotes the cold-air boundary defined by the $-1$ K perturbation.
Progressive Derecho
(Bow Echo)

- This is similar to middle latitude squall line except for an increased role of the up-downdraft and the interaction with a stable layer.
- Occurs pole ward of stationary front with extremely unstable capped air equator ward.
- Pole ward advection of unstable air over front feeds updraft of strong elevated deep convective line.
Progressive Derecho  
(continued)

- Dynamic lifting of vigorous convection entrains stable frontal air lifting it and cooling it until it is released in a strong up-downdraft.
- Up-downdraft crashes downward, assisted by evaporatively cooled air from middle levels (rear inflow jet or from front of storm) hitting surface and spreading as a strong wind storm.
- Spreading wind pushes up more post frontal air into convection.
Progressive Derecho (continued)

- By definition, the derecho is long lived (6 hours or more) and contains severe winds.
- Most common over upper mid-west United States just north of an east-west oriented stationary front.
- Associated with conditionally unstable air located equator ward of the front and capped by an elevated mixed layer usually advected from the Rockies.
Derecho Climatology

Fig. 1. Area affected by convective windstorm of 5 July 1980 (dashed line). Three-hourly squall line positions are indicated in UTC (from 0300 5 July to 2100 5 July). Officially measured convective gusts are indicated by wind bars [full barb signifies 5 m s⁻¹ (10 kt), flag signifies 25 m s⁻¹ (50 kt)]. Personal injuries (67) are indicated by dots, and deaths (6) are shown by an "x". As is typical in such cases, a majority of the casualties involved persons engaged in outdoor activities, particularly of a recreational nature, and persons residing in mobile homes.

Fig. 2. Total number of derechos occurring in 2° lat by 2° long squares during the months of May through August for the period 1980–1993.

---

**TABLE 2. Number of cases and percentage of total cases beginning during 6-h time periods.**

<table>
<thead>
<tr>
<th>Time period UTC</th>
<th>No. cases</th>
<th>Percentage of all cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>0400–1000</td>
<td>6</td>
<td>8%</td>
</tr>
<tr>
<td>1000–1600</td>
<td>9</td>
<td>13%</td>
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<tr>
<td>1600–2200</td>
<td>28</td>
<td>40%</td>
</tr>
<tr>
<td>2200–0400</td>
<td>27</td>
<td>39%</td>
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</table>
Usually North of an E-W Front
Progressive Derecho
Satellite and Radar

FIG. 4. Examples of radar echo patterns and cloud features associated with progressive derechos as depicted by Radar Summary Charts and corresponding 3.2 km (2-mile) equivalent resolution infrared (mb curve) satellite images: a) 1335 UTC 5 July 1980; b) 1135 UTC 7 June 1982; c) 1535 UTC 8 June 1982; and d) 2235 UTC 10 June 1982.
Australian Squall Line
(Similar to Progressive Derecho)
### Classification of Squall-Line Development

<table>
<thead>
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<th>t=0</th>
<th>t=Δt</th>
<th>t=2Δt</th>
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<tr>
<td>(8 Cases)</td>
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</tr>
<tr>
<td>(5 Cases)</td>
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</table>

Fig. 10.23. Idealized depiction of squall-line formation. [From Bluestein and Jain (1985).]
Tropical Squall Line
Fig. 10.1. Radar reflectivity contours (dBZ) at low levels (0.5–1.5 km) deduced from the Korhogo radar scan. Rectangular mesh south of Korhogo (K) represents the region of dual-Doppler radar observations. [From Chauzy et al. (1985). Copyright by the American Geophysical Union.]

Fig. 10.2. Advance of the squall-line disturbance on 4 and 5 September 1974 from its origins to the Atlantic. Asterisks mark the points of origin of squall-line elements A–Q, with hour of origin indicated. Alternating scalloped and thin lines are the leading edge of the anvil cloud at 2-h intervals. Thick solid curves mark the position of the arc front on the visible pictures. Dashed lines outline the anvil every 6 h. The series of arcs emanating to the west of point K is the principal squall line. Line b–b’ is a long-lived but dormant arc of middle cloud. [From Fortune (1980).]
Tropical Squall Lines

Fig. 10.3. Convective-scale updraft (heavy lines) and downdraft (light lines) contours superimposed on the horizontal flows at the altitudes of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4 km, observed at 0418 UTC, 22 June 1981. Contours correspond to 3, 6, and 9 m s⁻¹ for updrafts and to −0.5 and −2 m s⁻¹ for downdrafts. [From Chong et al. (1987).] (Figure continues.)
Tropical Squall Lines

Fig. 10.4. Vertical section of radar reflectivity contours along the propagation axis. [From Chauzy et al. (1985). Copyright by the American Geophysical Union.]
Tropical Squall Line

- Updraft and downdraft approach from the front (western side) of the eastward propagating storm.
- Moves faster than the wind at any height, i.e. there is no steering level!
- Dynamical analysis suggest that the tropical squall line may have a dynamics basis that is true wave-CISK organized around a deep tropospheric internal gravity wave.
- Density current plays a major role. As with middle latitude squall line, convection slopes over density current.
Tropical Squall Line (continued)

- Theory requires that the density current move at the same speed as the convective wave to remain steady and coupled. The difference is that the deep convection moves as a gravity wave whereas in the middle latitude squall line the convection moves with the steering level of the mean westerly flow.
Tropical Squall Line (continued)

• As with middle latitude squall line about 50-60 % of the rain falls in the deep cumulonimbus towers at the leading edge of the line and 40-50 % falls from the stratiform region containing the remnants of old towers overlying the density current.

• Strong role of gravity wave is consistent with a tropical atmosphere where Rossby radius is large.
Comparison of Tropical Squall Line and Mid-Latitude Squall Line

• Mid-Latitude
  – Fundamentally two-dimensional in structure
  – Line moves eastward with the velocity of the wind at the steering level.
  – Line organized around a growing coupled quasi-geostrophic/ density current structure
  – Environmental wind shear westerly to tropopause.
  – Updraft slopes up shear over density current.
  – Updraft transports momentum up shear and down gradient, and effectively acts to weaken vertical environmental shear.

• Tropical
  – Fundamentally three-dimensional in structure, ie downdraft cross updraft in 2D plane diagram
  – Line propagates westward with a speed exceeding the environmental wind at any level.
  – Line organized around a growing coupled internal gravity wave/ density current structure
  – Environmental wind shear easterly below 700 mb and westerly above 700 mb to tropopause
  – Updraft slopes up- shear (below 700 mb) over density current.
  – Updraft transports momentum down shear and up gradient above 700 mb, and effectively acts to strengthen vertical environmental shear.
Tropical Non-Squall Cluster
Type 1

Fig. 10.14. Active cloud tops (outlined by contours) in the height interval 2.5 to >13 km, during the first box circuit by the aircraft, 1300-1445 GMT. Numbers are heights (kilometers) above the sea and times of measurement. The corners D₁ to D₄ define the box circuit between latitudes 8°34' and 9°56'N, and longitudes 21°2' and 22°23'W. Clouds are aligned parallel to the mean wind shear vector. [From Warner et al. (1980).]
Tropical Non-Squall Cluster
Type 2

Fig. 10.15. Radar and satellite depiction of cluster A. The scalloped outline indicates the approximate boundary of the cloud shield. The contours indicate precipitation at 1, 20, 25, 30, and 40 dBZ detected by the P3's lower fuselage radar at 0908 GMT. The flight track of the P3 is annotated with time (GMT) to indicate the aircraft position. The two convective cells penetrated by the P3 are labeled I and II. The flight level was 7.8 km. [From Churchill and Houze (1984a).]
Tropical Non-Squall Cluster
Type 3

Fig. 10.16. Radar composite, 990-mbar streamlines superimposed, for 1400 GMT, 15 July 1974. Three levels of reflectivity are indicated, determined subjectively. The northwest portion of the echo is not enclosed, as it is believed to extend beyond the limits shown. [From Zipser and Gautier (1978).]
TCC Organization

• Long-Lived signature
• Mean vorticity
Systematic Buildup of the following in a TCC:

- Vertical Vorticity
- Horizontal Divergence
- Vertical Velocity

Fig. 10.19. Vertical component $\zeta$ of relative vorticity at the center of the composite nonsquall cluster for three life-cycle stages. [From Tollerud and Esbensen (1985).]

Fig. 10.20. As in Fig. 10.19, except for horizontal divergence $\delta$. [From Tollerud and Esbensen (1985).]

Fig. 10.21. Vertical velocity $\omega$ at the center of individual clusters during their mature stage. Dates and times (in GMT) for each profile are given. [From Tollerud and Esbensen (1985).]
Meso-α-Scale Circular Convective Systems

- Significant projection of heating onto balanced scales above the Rossby radius of deformation.
- Growth of Vortex from cumulus latent heating
  - Geostrophic adjustment
    - Deep cumulus heating => Large Rossby Radius => slow and inefficient adjustment
    - Shallow melting zone => more efficient adjustment => rotation => smaller Rossby Radius => more efficient adjustment to deep heating of cumulus updrafts
  - Mass to wind => line vortex => balls up into circular vortex => shrink rossby radius => efficient geostrophic adjustment to latent heating
- Role of slantwise convection
  - Latent heating, ie theta redistribution
    - More efficient than cumulus heating because spread over a larger horizontal scale
    - Driven by melting
  - Momentum redistribution
    - Form line vortex as with vertical cumulus
Tropical Non-Squall Clusters

• Grouping of tropical convection:
  – Along ITCZ
  – Associated with easterly wave (just ahead of trough)
  – Associated with upper level trough (cold low)
  – Associated with land-water contrast

• Typical Size and Lifetime
  – 100,000 km²
  – 1-2 days
Tropical Non-Squall Clusters (continued)

- **Structure**
  - **Formative stage**
    - Isolated cells
    - Randomly clustered lines
  - **Intensifying Stage**
    - Individual cells grow and merge
    - Density currents grow and merge
  - **Mature Stage**
    - Stratiform area develops
    - System scale density current
    - New growth upwind
  - **Dissipating Stage**
    - Large region of mostly stratiform precipitation
Tropical Non-Squall Clusters (continued)

• Movement
  – Direction of lower tropospheric flow
  – Slightly less than speed of easterly (Rossby) wave (accounts for decay)

• Typical Size and Lifetime
  – 100,000 km$^2$
  – 1-2 days
Tropical Non-Squall Clusters (continued)

• Developing

• Typical Size and Lifetime
  – 100,000 km²
  – 1-2 days
Non-Squall Clusters (continued)

- **Developing**
  - Divergent anticyclone aloft
  - Weak inertial stability at outflow level
  - Mid-level convergence
  - Mesoscale ascent
  - Positive vorticity at middle levels
  - Low pressure at the surface

- **Non-developing**
  - Non-divergent anticyclone aloft
  - Strong inertial stability at outflow level
  - Little or no mid-level convergence
  - Weak or no mesoscale ascent
  - No positive vorticity maximum
  - No surface low
Mesoscale Convective Complex (MCC)

- Circular type meso-\(\alpha\)-scale organization.
- Similar to middle-latitude squall line except circular vortex in anvil region.
- Classic MCC structure:
  - Warm core vortex at middle levels
  - Density current and meso-anticyclone at the surface.
  - Anticyclones outflow aloft feeding into jet streak.
  - Vertical circulation upward in MCC, outflow aloft into jet streak poleward creates *dynamic flywheel* that stores energy and persists the system even after the energy-supplying convection stops.
FIG. 1. Enhanced infrared satellite image showing an MCC over the central United States at 0630 GMT 13 August 1982.
Fig. 4. Enhanced infrared GOES satellite images of the central United States showing the evolution of MCC number 2 on 5 August 1977: (a) 0014 GMT; (b) 0400 GMT; (c) 0645 GMT; (d) 0900 GMT; (e) 1200 GMT. All are GOES-East images except (c), which is from GOES-West. The stepped shades of medium gray, light gray, dark gray and black are thresholds for areas with apparent blackbody temperatures colder than −32°, −42°, −53 and −59°C, respectively. Temperatures progressively colder than −63°C appear as a gradual black-to-white range.
Table 10.1
Mesoscale Convective Complex Definition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
</table>
| Size:           | (A) Cloud shield with IR temperature $\leq -32^\circ$C, must have an area $\geq 100,000$ km$^2$  
                 | (B) Interior cold cloud region with temperature $\leq -52^\circ$C, must have an area $\geq 50,000$ km$^2$  |
| Initiate:       | Size definitions A and B are first satisfied                               |
| Duration:       | Size definitions A and B must be met for a period $\geq 6$ h               |
| Maximum extent: | Continuous cold cloud shield (IR temperature $\leq -32^\circ$C) reaches maximum size |
| Shape:          | Eccentricity (minor axis/major axis) $\geq 0.7$ at time of maximum extent  |
| Terminate:      | Size definitions A and B no longer satisfied                               |

$^a$ From Maddox (1980).
Climatology of MCC’s

Figure 17.2. Continued. (b) MCCs, 1–15 May; (c) MCCs, 16–31 May; (d) MCCs, 1–15 June; (e) MCCs, 16–30 June; (f) MCCs, 1–15 July; (g) MCCs, 16–31 July.
Climatology of MCC’s

Fig. 1. Satellite-defined tracks of the 122 MCCs in the analysis sample, based on centroids of the cloud-shield area colder than $-54^\circ$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.
Climatology of MCC's

Fig. 17. Geographic and monthly distribution of MCCs in and around the Americas. Locations are for the MCC cold-cloud shields at the time of maximum extent. See Figure 14 caption for sample periods. Hurricane symbols indicate an MCC that developed into a tropical storm. Systems that were first a tropical storm and then an MCC are not shown.
Climatology of MCC’s

Fig. 1. Geographical and seasonal distribution of MCCs in Africa in 1986 and 1987. Locations are for the MCC at the time of maximum extent of the cold cloud shield. The dates along the sides indicate the time of minimum solar zenith angle: northward migration cycle on the left, southward cycle on the right. Shading indicates the tropical rain forest areas (Terbohrgh 1992).

Fig. 2. Tracks of African MCCs for (a) January–March 1986, (b) August 1986, (c) January–March 1987, and (d) August 1987. Dots indicate the genesis (first shown) stage; solid line indicates MCC path between genesis and dissipation, dashes indicate the dissipation or retrograde stage. Centers numbered correspond to the MCC state number and the MCC removed positions at the time of maximum areal extent. Pluses (—) indicate where an MCC transformed into a tropical depression, and the cyclone symbol indicates tropical storm stage. Shading indicates sea surface temperature greater than or equal to 20°C (RBT). Data from Hendricks (1991). Light shading highlights areas with elevation greater than or equal to 1,000 ft.
Climatology of MCC’s

Fig. 8. Geographical and monthly distributions of MCCs in the western Pacific region. Locations are for the MCC at the time of maximum extent of the cold-cloud shield. Hurricane symbols indicate MCCs that developed into tropical storms.

Fig. 9. Tracks of MCCs. Dots indicate pregenesis (first storms) stage; solid line indicates MCC path between genesis and dissipation; dashes indicate dissipating-remnants stage. Circled numbers correspond to the number of the system listed in Miller (1990) and also indicate the point of maximum cold-cloud shield extent during the lifetime of the system. Hurricane symbols indicate when an MCC transformed into a tropical storm; plus (+) signs indicate the presence of a preexisting low-level cyclonic circulation, possibly a residual circulation from a tropical cyclone or depression. (a) 1983-1985 northern systems; (b) 1983-1985 southern systems. Shading in (a) indicates average location of >28°C sea surface temperature in June. Shading in (b) as in (a) except for January.
MCC
Evolution

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 ($T_{\text{mn}}$). Each pair of arrows (at selected times) indicates the long-axis ends of the $-54^\circ$C (dark-contoured) cloud-shield area considered to be the MCC. The temperature scaling for the MB enhancement is indicated ($^\circ$C) below the gray-scale bar; the values above the bar indicate IR thresholds ($^\circ$C, with 0.2 decimal omitted) for the contours associated with discrete gray-scale steps.
Composite Structure for Pre-MCC Stage

Fig. 57a. West to east cross-section of mesoscale height (solid lines, in m) and u-component (dashed lines, in m s⁻¹) perturbations 12 h prior to the MCC.

Fig. 57b. West to east cross-section of mesoscale temperature (dashed lines in °C) and moisture (solid lines, in g/kg) perturbations 12 h prior to the MCC.
Composite Structure for Mature MCC Stage

Fig. 58a. West to east cross-section of mesoscale height and u-component perturbation at the time of the MCC. Details similar to Fig. 57.

Fig. 58b. West to east cross-section of mesoscale temperature and moisture perturbations at the time of the MCC. Details similar to Fig. 57.
Composite Structure for Mature MCC Stage

Fig. 59a. South to north cross-section of mesoscale height u-component perturbations at the time of the MCC. Details similar to Fig. 57.

Fig. 59b. South to north cross-section of mesoscale temperature and moisture perturbations at the time of the MCC. Details similar to Fig. 57.
Composite Structure for Post MCC Stage

Fig. 60a. West to east cross-section of mesoscale height and u-component perturbations 12 h after the MCC. Details similar to Fig. 57.

Fig. 60b. West to east cross-section of mesoscale temperature and moisture perturbations 12 h after the MCC. Details similar to Fig. 57.
Composite MCC Structure
Cotton and Lin

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.

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}. 
Composite MCC Structure
Cotton and Lin

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

Fig. 14. Time-height plot of vertical motion. Each subperiod $\omega$ profile was obtained as in Fig. 13. Units: $10^{-5}$ mb s$^{-1}$.
Composite MCC Structure
Cotton and Lin

Fig. 15. Vertical profiles of relative vorticity (horizontally averaged over the 3 x 3 central grid points at 50-mb intervals) at the MCC-12 h, initial, mature, and dissipation stages. Units: 10^{-5} s^{-1}.

Fig. 16. Time-height plot of the difference in relative vorticity (horizontally averaged over the 3 x 3 central grid points at each 50-mb level and subperiod) from its corresponding value at the MCC-12 h stage. Positive values indicate a more cyclonic (or less anticyclonic) vorticity than at the MCC-12 h stage. Units 10^{-5} s^{-1}. 
Idealized MCC Structure
Idealized Tropical Cyclone Structure
Tropical Cyclone

- Extension of the Warm Core middle–level vortex to the surface.
- Inducement of Ekman pumping
- Non-linear growth due to increased heating efficiency as vortex strengthens
- Creation of new instability by increased energy through lowering of pressure
- Carnot Cycle of heating
HURRICANE ANDREW
NWS MIAMI RADAR
August 24, 1992
08:35 UTC
04:35 EDT

Hurricane
Research
Division
NOAA/AOML
Miami, FL

Domain: 100 x 100 km

dbZ

>48
45
42
39
36
33
30
27
24
21
18
15
<15