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OCEANIC MESOSCALE CONVECTIVE SYSTEMS OF THE AUSTRALIAN MONSOON

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1. INTRODUCTION

Ten mesoscale convective systems (MCS's) within various wind regimes in the Australian summer monsoon have been studied, with airborne Doppler radar and multiple aircraft data obtained over the ocean near Darwin, Australia (Fig. 1) during the 1987 Equatorial Mesoscale Experiment (EMEX). For a summary of the project, see Webster and Houze (1991).

Thermodynamic environmental conditions differed relatively little among the ten cases; mesoscale structure instead depended systematically upon the synoptic wind environments within which they were embedded. These environments can be put roughly into three categories: weak depression, hurricane, and straight flow. Satellite observations suggest that these categories represent distinct, climatologically important populations of MCS's (for details, see Mapes and Houze 1991).

In every case, the mesoscale structure consisted of an ensemble of convective lines and stratiform regions, much like the tropical oceanic MCS's of GATE¹ (Houze and Betts 1981) and MONEX² (Johnson and Houze 1987). As in those studies, lines of convection in EMEX were often generated along the edges of boundary-layer cold pools, and evolved into stratiform precipitation. This paper summarizes our observations of the strong dependence of the particular 4-dimensional patterns assumed by the convective and stratiform parts of these MCS's upon the prevailing large-scale wind fields within which the MCS's occurred.

2. MONSOON WIND ENVIRONMENTS

The Australian summer monsoon season (reviewed by McBride 1987) is characterized by an intensification of off-equatorial deep convective activity in the Australian longitudes, particularly over the warm ocean near the Australian coast (Fig. 2). The 1987 Australian monsoon season in particular has been described by Mapes and Houze (1991).

The time progression of the 1987 Australian monsoon may be characterized as a repeating pattern with three stages, as illustrated in the three panels of Fig. 3. In the first stage, there is a burst of MCS activity around the north Australian coast, mostly over the ocean. Cyclonic circulation in the lower troposphere begins to spin up, over a period of days (Fig. 3a). The first such incident in the season is often termed the monsoon onset. In 1987, these (two) bursts were apparently triggered by planetary-scale events at higher latitudes, in both the northern and southern hemispheres.

The second stage occurs after a few days of MCS-synoptic interaction have spun up strong circulation(s); in the case of Fig. 3b, tropical cyclone Connie is over the Indian Ocean, while tropical depression Irma is over the Gulf of Carpentaria. Near the center of the depression(s), hurricane precipitation features such as eyewalls, spiral rainbands, and large areas of stratiform precipitation are observed. At larger radii, beyond the area of highly curved flow and large thermodynamic perturbations, MCS's can be found in an environment of strong, relatively straight lower-tropospheric winds (generally, the synoptic cyclone is vertically coherent, so there is little directional shear of the deep lower-tropospheric monsoon flow). Coastal influences appear to be important in initiating these MCS's.

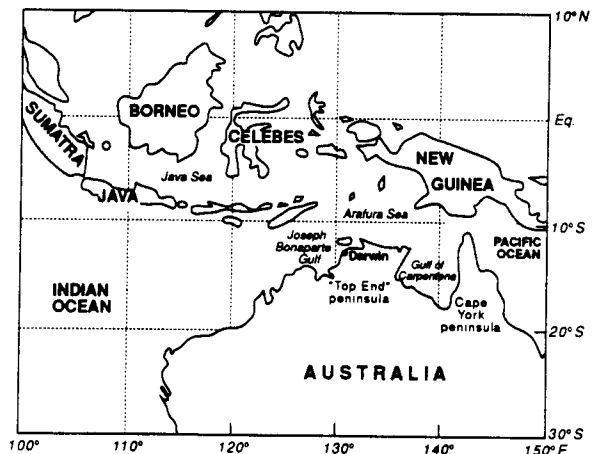


Figure 1: Base map of north Australia / Indonesia region.

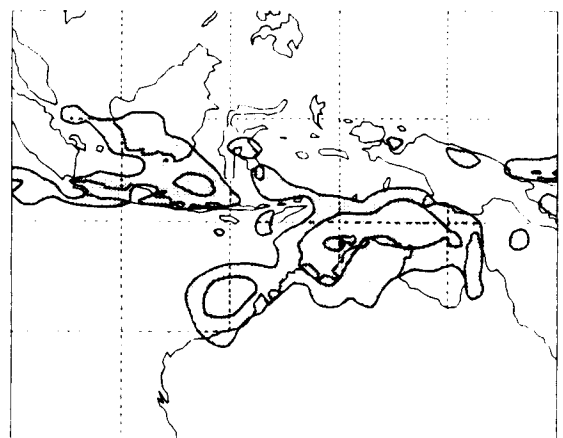


Figure 2: Percentage high cloudiness (PHC), defined as the fractional coverage of satellite-observed infrared cloud tops colder than -55°C , during the period 14 January to 3 February 1987. Contour interval 10%.

¹ The Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment, held over the eastern tropical Atlantic in 1974.

² The GARP Monsoon Experiment, held over the South China Sea in 1978-79 and over the Arabian Sea and Bay of Bengal in 1979.

In the third stage of the process, the outer MCS activity decreases and most of the remaining cold cloud top seen in satellite imagery is that associated with tropical cyclones. After cyclone landfall (Fig. 3c), there is little MCS activity left, and a "break" period persists until something triggers the first stage again and the cycle restarts.

3. MCS TYPES

3.1 Categories based on wind environment

Within the framework of the above description, there are essentially three classes of wind environments within which monsoon MCS's occurred:

1. Weak cyclonic depression, weak wind (EMEX 6,7)*.
2. Strong depression/hurricane (EMEX 4, 5).
3. Strong, straighter winds outside the depression area (EMEX 1, 3, 8, 9, 10).

As indicated, the EMEX aircraft program sampled examples of MCS's in all three types of environments. Within each category, the MCS's exhibited similar mesoscale organization; we suggest that this was not coincidental, but rather an indication of the importance of the wind environment in determining the mesoscale organization.

The MCS's were generally in the mature to decaying stages of their life cycles during the aircraft sampling. Each MCS was composed of elongated or linear areas of convective precipitation, and areas of stratiform precipitation. Convection was typically found along boundary-layer cold pool edges, with the possible exceptions of the hurricane rainband of EMEX 4 and the weak convective arc in the EMEX 1 MCS (discussed below). The stratiform precipitation evolved from earlier convective precipitation, in cases with weak or along-line deep-tropospheric vertical wind shear. Cross-line shear produced overhanging anvils, from which stratiform precipitation also fell.

The actual spatial configuration of precipitation at any given time was a product of the above processes. The location of the leading edges of (convection-produced) cold pools, and hence of new convective areas, depended on the low-level wind environment. The configuration of stratiform precipitation reflected the time history of previous convection, as well as the wind shear across and above the melting level, which created overhanging anvil stratiform areas. The well-studied squall line form of MCS organization is a particularly simple special case, in which a nearly 2-dimensional cold pool edge moves nearly steadily in one direction.

3.2 Schematic view of the EMEX MCS's

To aid in the subsequent discussion, we have devised a schematic illustration of the mesoscale precipitation patterns, observed with airborne radar, under the different large-scale flow conditions (Fig. 4). Dark shading shows convective areas, while light shading shows stratiform areas, and the numbers indicate the EMEX flight mission numbers. The streamlines represent the direction of lower-tropospheric flow, which tended to be similar on 850, 700, and 500 mb charts. Fig. 4a corresponds roughly to the weak depression flow as seen in Fig. 3a, while Fig. 4b is more akin to the strong flow depicted in Fig. 3b. Features of the individual cases are described below.

* The number indicates the sequential flight number, from one to ten, of the radar-equipped NOAA P3 aircraft used in EMEX.

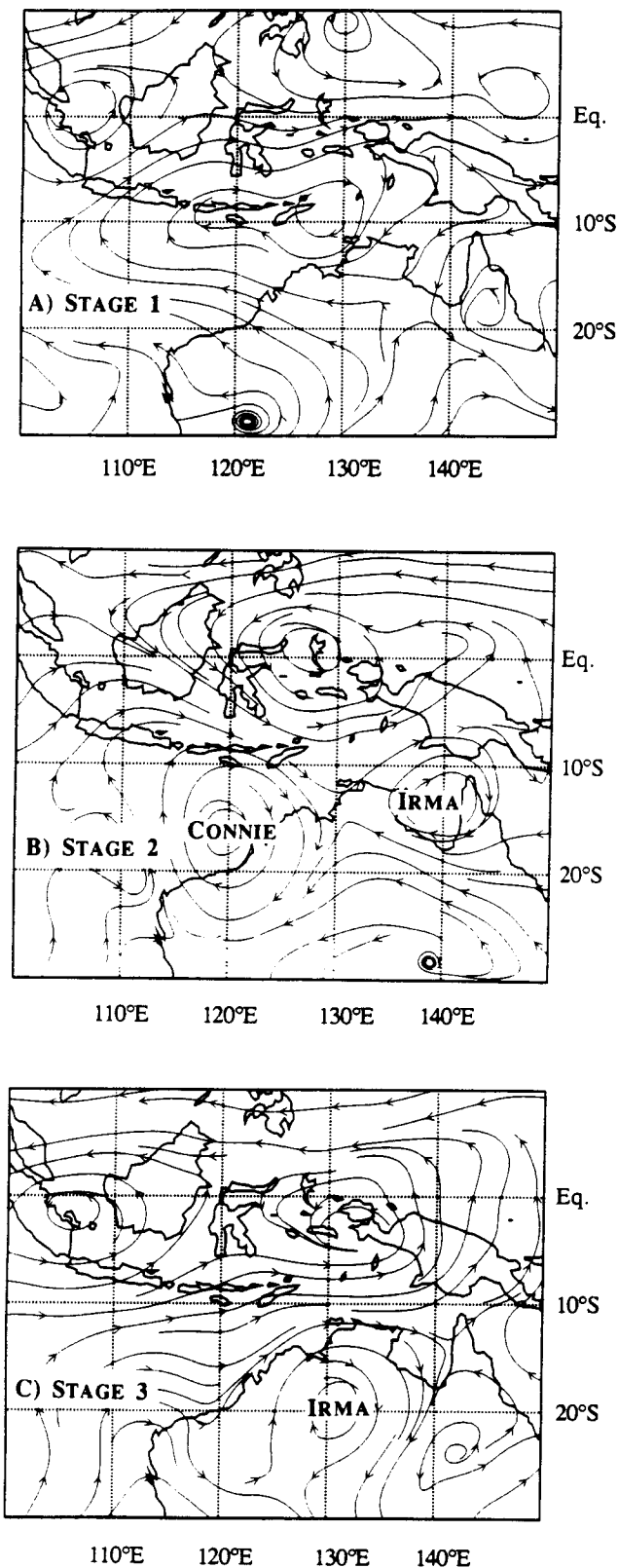


Figure 3: Streamlines of 700 mb flow illustrating the three stages of the monsoon spinup cycle, from 12 GMT European Center analyses. a) 13 January, b) 18 January, c) 23 January 1987.

3.3 Weak depression cases

This category is exemplified by the MCS's sampled in EMEX flights 6 and 7 (27 and 29 January 1987). In each case, very broad, deep convective lines in various orientations were observed in the early stages of the MCS life cycle. Vertical incidence airborne Doppler radar data indicated that the level of maximum vertical velocity in this convection was in the upper troposphere. Echo tops within these systems were very high, and deep, long-lived stratiform precipitation areas were observed to evolve from the initial intense convection, in the same geographical area, since winds were relatively light. In the EMEX 7 stratiform area, a balanced cyclonic vortex was observed, confined to the middle troposphere, above the melting level.

3.4 Strong depression/hurricane convection

While hurricane precipitation systems sampling was not a major objective of EMEX, the fourth and fifth flights both included initial survey flights through the central area of cyclone Irma, followed by intensive sampling of nearby MCS's. The EMEX 4 MCS can be called a hurricane rainband; at 250 km radius, it spanned a 45° sector of Irma and bore many resemblances to the hurricane rainbands at similar radii described by Powell (1990). It consisted of a wide zone undergoing convection, in a strong cross-band vertical wind shear through the lower troposphere; the result was extremely turbulent winds and shredded reflectivity patterns, with the crisper, more cellular reflectivity edge on the inner side of the band.

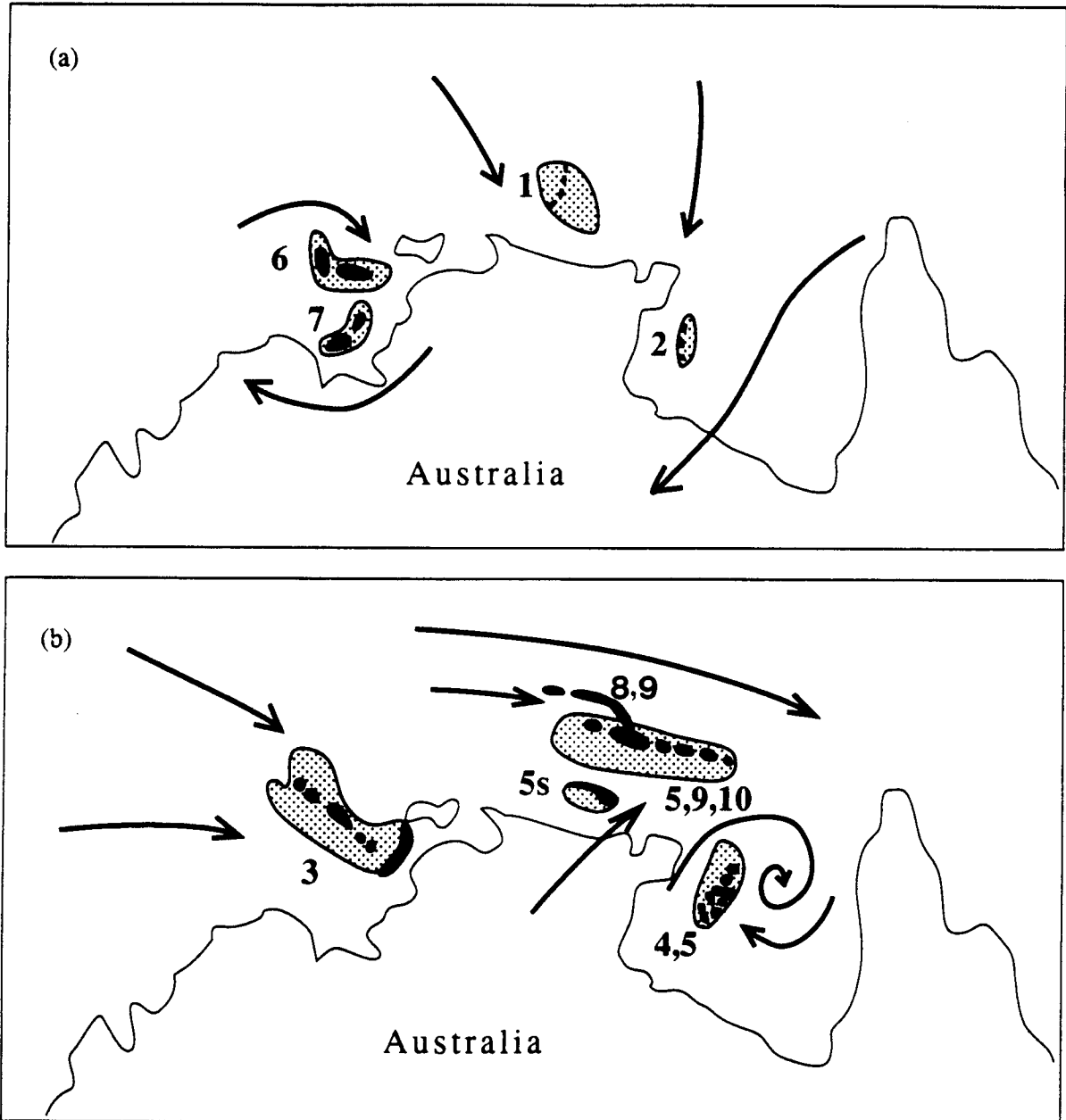


Figure 4: Schematic guide to the EMEX MCS's (numbers) relative to streamlines of lower-tropospheric flow and north Australian coast. Dark shading indicates areas of convective precipitation, while lighter shading indicates stratiform precipitation. Two cycles of the synoptic evolution illustrated in Fig. 3 have been composited together here. a) Weak-flow cases depicted with weak depression flow, similar to Fig. 3a. b) Strong-flow cases depicted with mature cyclone flow, similar to Fig. 3b.

The EMEX 5 flight, after a pass through the eye of hurricane Irma, sampled an MCS at ~450 km radius; it lay in the confluence zone between curved streamlines around the cyclone and straighter winds beyond. Morphologically, it appeared to be a hybrid between the EMEX 4 and EMEX 9-10 cases, so we have indicated it in both places on Fig. 4b. It was wide, with multiple convective areas, like the EMEX 4 rainband, and it occurred in an environment of cross-band lower-tropospheric vertical shear and a substantial mean cyclone-associated pressure perturbation field. However, the convection in this band exhibited more linear organization than the EMEX 4 rainband convective areas. A second small squall-arc structure, more akin to the straight-flow MCS squall arcs, was also observed in the vicinity (denoted 5s on Fig. 4b).

3.5 Straight monsoon flow MCS's

This class of MCS's was best exemplified by EMEX flights 3, 8, 9, and 10. Within these MCS's, two very distinct types of linear convective organization were observed: along-wind lines, and cross-wind squalls. In EMEX 3, aircraft sampling focused on the along-wind line, while the associated squall indicated on Fig. 4b moved over Darwin, as seen by radar and observers there. EMEX 3 exhibited leading anvil precipitation (north of the along-wind line, Fig. 4b) as well as trailing stratiform precipitation, to the southwest.

In the EMEX 8 and 9 MCS's, cross-wind (north-south) squalls participated in the discrete propagation of the longer along-wind (east-west) lines, in the following manner. A squall arc, which intersected the along-wind line in an area of enhanced convection, moved rapidly downwind (eastward), leaving a wake of cold boundary-layer air immediately north of the old along-wind line. A new convective line developed along the north boundary of this new cold pool, such that the old convective line lay well behind the new line (Fig. 4b). The old line, now trailing the new line, evolved into stratiform precipitation.

The EMEX 1 MCS was basically a straight-flow case, but it lay out at the fringe of the monsoonal cloudy area, in relatively weak flow (Fig. 4a). A stratiform precipitation area was already present when the aircraft arrived, and the only convection observed was an embedded arc of weak, short cells (<10 km top height) at the front edge of a westerly wind surge, centered above the boundary layer, at ~2 km. Sharp-edged (but weak) updrafts, measured by the NCAR Electra, confirmed that free moist convection was taking place, but its base may have been above the boundary layer, and the inertia of the converging jet, rather than a cold pool boundary, may have been the agent of lifting which triggered the convection.

3.6 EMEX 2

The EMEX 2 MCS was a small, isolated, nearly stationary line of sporadic convective cells, in the easterlies beyond the active monsoon area. It eventually developed a small stratiform area, within which a remarkably strong perturbation pressure field was observed.

4. CONCLUSIONS

The EMEX MCS's formed over the ocean and resembled MCS's seen in GATE and MONEX, in that each was composed of an ensemble of convective and stratiform precipitation areas. The convective areas were generally lines formed at cold pool boundaries, while the stratiform areas evolved from convective areas, as the latter weakened. Some of the stratiform precipitation, however, fell from sheared-over anvils.

The particular patterns in which the convective and stratiform areas in a given MCS manifested themselves appeared to be closely associated with the prevailing synoptic-scale wind regime. During EMEX, the monsoon flow went through a repeating sequence in which over-water depressions formed and intensified over the Bonaparte Gulf (in the west) and the Gulf of Carpentaria (in the east). The structure of the MCS's depended on whether they were located in a weak depression, a fully developed cyclone, or in the straighter, over-water flow leading into a cyclone.

The weak-depression MCS's had variously oriented lines of broad, deep convection intermingled with stratiform precipitation; cyclone MCS's exhibited typical hurricane rainband structure; and the straight-flow MCS's had both along-wind lines of convection and cross-wind squalls. The squalls acted to propagate discretely the along-wind lines, by moving past rapidly, ahead of the line, and leaving a boundary-layer cold air wake, along which new convection formed, as the old convective line decayed into stratiform precipitation.

5. ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation Grant ATM9008406 and NOAA Grant 50-WCNR-8-06088.

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