Organization of Mesoscale Convective Systems

Richard H. Johnson
Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523-1371 USA;
e-mail: johnson@atmos.colostate.edu

Abstract

A recent study of linear, midlatitude mesoscale convective systems (MCSs) over the eastern two-thirds of the United States has revealed three dominant modes of MCS organization: trailing stratiform (TS), leading stratiform (LS), and parallel stratiform (PS) systems. While TS are the most common, LS and PS modes are not negligible and in some cases contribute to flash flooding. A follow-on study of extreme-rain-producing storms over the same region indicates two dominant modes of MCS organization of such storms, one with training convective cells and the other with back-building cells. Study of MCSs during the 1998 GAME/SCSMEX reveals that the shear in the lower and middle troposphere plays a dominant role in determining the orientation of convective lines over the northern South China Sea.

Keywords: mesoscale, convection, MCS, organization, heavy rainfall

1. Introduction

Convection often takes the form of mesoscale cloud systems comprised of individual convective elements at various stages of their life cycles. The cloud elements are often organized into bands, arcs or other contiguous structures. Such systems are often referred to as mesoscale convective systems or MCSs. In this review, we will explore the organization of MCSs, identify specific patterns that are conducive to heavy rainfall and flash floods, and examine the factors that determine the orientation of convective lines during the May-June 1998 South China Sea Monsoon Experiment (SCSMEX).

2. Modes of organization of MCSs

A recent survey has been conducted of the organization of MCSs over the eastern two-thirds of the United States using WSR-88D radar data (Parker and Johnson 2000). The focus has been on *linear* MCSs, defined as MCSs that contain a convective line with a contiguous or nearly contiguous chain of convective echoes sharing a nearly common leading edge and moving approximately in tandem. Nearly all of the 88 cases studied for May and June, 1996 and 1997, were classifiable into three basic modes of organization. These classifications are based on the dominant mode observed throughout the MCS life cycle. The three modes, shown in Fig. 1, are convective lines with trailing (TS), leading (LS), and parallel (PS) stratiform rain. The well-known TS classification (e.g., Houze et al. 1990) accounted for 58% of the cases. However, a new finding is the existence of an important fraction of LS and PS cases, each accounting for 19% of the total population. The existence of the LS mode of organization at midlatitudes has been previously documented, but generally has not received much attention. Both the LS and PS modes move more slowly and are shorter-lived than their TS counterparts, and their environmental flow structures display important differences from those of each other and of TS storms. Wang (2004) found that LS systems frequently occurred during the onset of the summer monsoon over the northern South China Sea during SCSMEX.

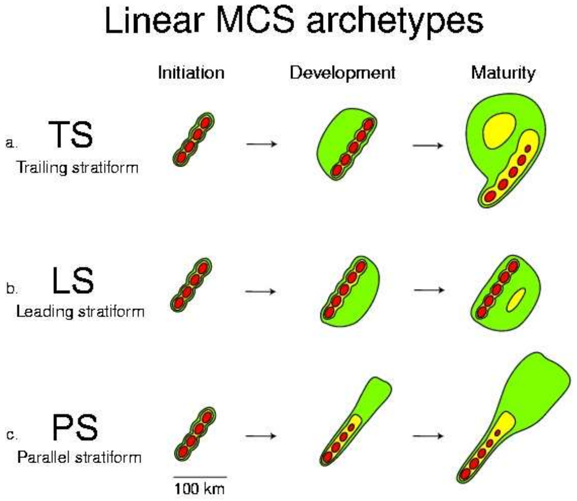

Fig. 1: Schema of idealized life cycles for three linear MCS archetypes: (a) leading line trailing stratiform (TS), (b) convective line with leading stratiform (LS), and (c) convective line with parallel stratiform (PS). Approximate time intervals between phases: for TS 3-4 h; for LS 2-3 h; for PS 2-3 h. Levels of shading roughly correspond to 20, 40, and 50 dBZ.. From Parker and Johnson (2000).

These differences are illustrated in Fig. 2, a depiction of storm-relative wind profiles for LS, PS, and TS systems based on soundings taken in advance of the storms. A major distinction between the LS and TS systems is in the flow aloft, where westerly storm-relative flow occurs in the LS systems. This flow helps to advect hydrometeors ahead of the convective line. PS systems are distinct from the other two types in that there is strong line-parallel, storm-relative flow aloft. This flow explains the preponderance of stratiform precipitation at the northern end of these systems. In all three cases there is strong low-level and weak mid-level line-perpendicular shear, consistent with the observed shear-perpendicular convective line development (LeMone et al. 1998). Presumably, the interaction between the cold pool and the shear plays a role in organizing the convective line (Rotunno et al. 1988).

The easterly low-level, storm-relative flow for the LS cases is based on soundings ahead of the storms. However, there is evidence from more recent studies that in many LS systems, there is a “rear-to-front” low-level, storm-relative flow. These “rear-fed” LS cases often exhibit repeated growth of new convective cells to the west of old ones, or back-building, which can lead to locally heavy rainfall in many instances. An example of the airflow in such a system is shown in Fig. 3 (Pettet and Johnson 2003). This figure is based on a study of two rear-fed LS MCSs using the WSR-88D Doppler radar network. In many respects, the radar re-

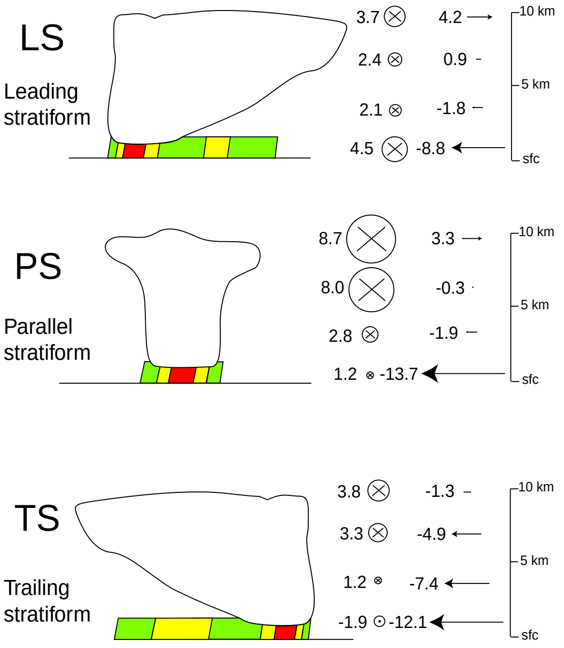

Fig. 2: Vertical profiles of layer-mean storm-relative winds for linear MCS classes. Wind vectors depicted as line-parallel and line-perpendicular components in m s^{-1}. Layers depicted are 0–1 km, 2–4 km, 5–8 km, and 9–10 km. From Parker and Johnson (2000).

flectivity and airflow structure of these systems (Fig. 3) are mirror images of TS systems, including a secondary precipitation maximum (the stratiform region) separated from the convective line by a reflectivity minimum and a midlevel inflow jet (from the front in the case of an LS system and from the rear in a TS system). However, unlike many TS systems, the low-level inflow in the LS systems was elevated, with an associated elevated θ_e maximum.

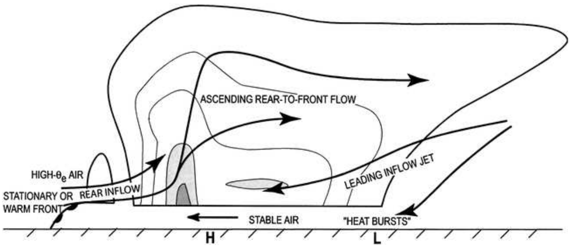

Fig. 3: Conceptual model of a rear-fed LS MCS above a stable surface layer viewed in a vertical cross section oriented perpendicular to the convective line (i.e., parallel to its motion from left to right) during the mature stage of its life cycle. Arrows indicate mean, storm-relative flow. Radar reflectivity is indicated by thin contours. Cloud outline is thicker contour. Areas of enhanced reflectivity are shaded. Surface high and low pressure centers are indicated by H and L, respectively. From Pettet and Johnson (2003).

An important point to be made concerning TS, LS, and PS systems is that their classification was based on the dominant mode of organization over their life cycles. However, these storms frequently transitioned from one mode to another during their lifetimes, as shown in Fig. 4. TS systems typically remained TS throughout their lifetimes, but transitioned from symmetric to asymmetric in structure during the later stages of their life cycles (Hilgendorf and Johnson 1998). The majority of LS systems remained LS, but a number transtitioned to TS at later stages. Parker and Johnson (2004) explained this transition as a result of the LS systems (1) decreasing the line-perpendicular wind shear nearby as they developed, and (2) gradually increasing the system's cold pool strength, leading to more rearward-sloping updrafts. PS systems also often transitioned to TS during their later stages, also likely in response to increasing cold-pool strength with time.

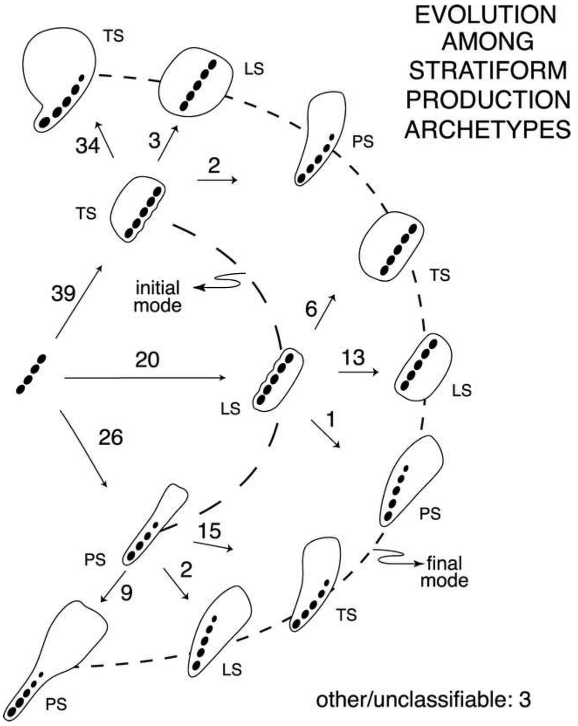

Fig. 4: Illustration of evolutionary pathways for MCSs. Labels along each pathway denote the initial and final modes of stratiform precipitation production. The total number of cases following each step is indicated. Idealized composite positions of convective elements and stratiform precipitation are depicted schematically along each pathway. Note: some pairs of evolutionary pathways (e.g., TS→PS and PS→TS) resulted in generally similar reflectivity patterns. From Parker and Johnson (2000).

3. Extreme-rainfall-producing MCSs

A study has recently been completed of 116 heavy-rainfall cases over the eastern two-thirds of the United States to determine the dominant modes of MCS organization associated with extreme-rain-producing events (Schumacher and Johnson 2004). Storms were studied over a period of three years, from 1999 to 2001, including all seasons. Sixty-five percent of the total number of events were associated with MCSs. Of those, two prominant modes of organization have been found, illustrated in Fig. 5. The first type (Fig. 5a), comprising 32% of the MCSs, is characterized by a typically east-west convective line along a quasi-stationary frontal boundary with west-to-east *training* convective cells on the cool side of the boundary and an area of stratiform precipitation displaced to the north. The second type (Fig. 5b), comprising 20% of the cases, is typically smaller in overall size and features back-building cells along an outflow boundary, with repeated cell formation over the same location and an area of stratiform precipitation typically downstream. It is believed that these two patterns of organization are also present in extreme-rain-producing MCSs in other parts of the world, including the

Asian monsoon region.

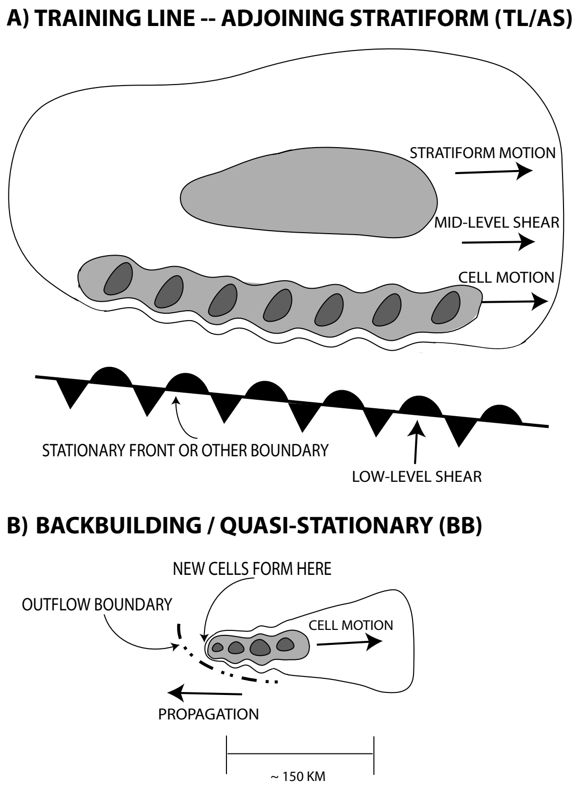

Fig. 5: Two extreme-rain-producing storm mature-stage archetypes. (a) Training-line, adjoining-stratiform (TL/AS) organization, and (b) Back-building (BB) organization, based on a study of 116 such events in the eastern two-thirds of the United States for the period 1999-2001. Distance scale applies to both systems. From Schumacher and Johnson (2004).

4. Organization of monsoon convection during GAME/SCSMEX

It has long been known that the organization of tropical convection is influenced predominantly by the vertical shear and convective available potential energy or CAPE (Moncrieff and Green 1972). Various observational studies in the eastern Atlantic and northern Australia have confirmed the strong influence of environmental winds on the structure, orientation, and propagation of convective bands (e.g., Barnes and Seickman 1984; Alexander and Young 1992; Keenan and Carbone 1992). Recently, LeMone et al. (1998) investigated the organization of convection over the western Pacific warm pool using aircraft data from the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE). In agreement with Alexander and Young (1992) they find that vertical shear in the low-to-midtroposphere is a key factor in determining the orientation of convective bands, while CAPE influences their depth and longevity. Their results have been recently supported by numerical simulations of convection in shear by Robe and Emanuel (2001). We have recently tested these concepts using BMRC C-POL radar data from SCSMEX, and find that, in general, they can be extended to the Asian monsoon region, with some modifications (Johnson et al. 2004).

Four primary modes of organization have emerged from the results of this study, which are summarized in Fig. 6.

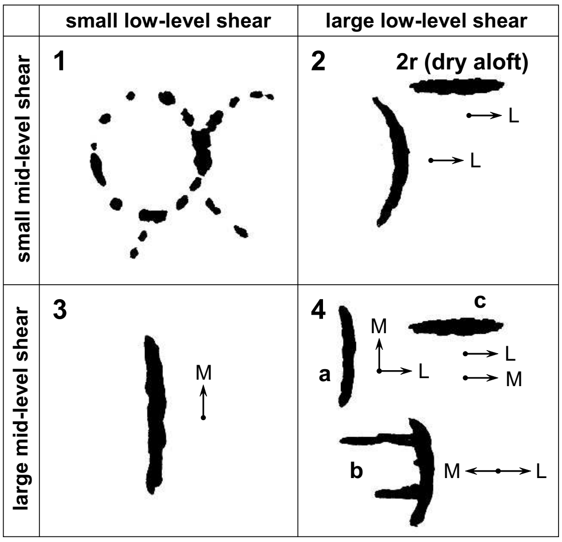

Fig. 6: Schematic depiction from LeMone et al. (1998) of four main categories of convective structures for given vertical shears in the lower troposphere (1000–800 hPa) and at middle levels (800–400 hPa) based on COARE observations, but modified to include results from SCSMEX (modes **2r** and **4c** added). Length of schematic convective bands is ~100–300 km; line segments in upper-left frame are up to 50 km length. Cutoff between “strong” and “weak” shear for lower layer (1000–800 hPa) is 4 m s $^{-1}$ and for middle layer (800–400 hPa) is 5 m s^{-1}. Arrows marked **L** and **M** are shear vectors for lower and middle layers, respectively. See text for descripition of convective modes.

This figure, adapted from LeMone et al. (1998), is a summary of their findings from TOGA COARE, but supplemented by new results from SCSMEX (two new modes **2r**, and **4c**). In general, the organizational modes for SCSMEX were consistent with those determined by LeMone et al. (1998) for the western Pacific warm pool. They found that when the shear in the lowest 200 hPa exceeded 4 m s^{-1} and the shear from 800 to 400 hPa was less than 5 m s^{-1}, the orientation of primary convective band was perpendicular to the low-level shear (Type **2** in Fig. 6). Secondary lines parallel to the low-level shear were found in some cases ahead of the primary band. In the absence of strong low-level shear, lines formed parallel to the 800-400 hPa shear when its magnitude exceeded 5 m s^{-1} (**3** in lower-left frame). When the vertical shear exceeded the thresholds in both layers and the shear vectors were not in the same direction (lower-right frame), the primary band was normal to the low-level shear (**4a** or **4b**). Trailing secondary bands parallel to the midlevel shear occurred if the midlevel shear was opposite the low-level shear (**4b**). When the shear in both layers was weak, convection developed in arcs along outflow boundaries (**1**). Two additional modes of convection have been identified from analysis of SCSMEX C-POL radar data (Fig. 6): shear-parallel bands (**2r**) for strong low-level shear and weak midlevel shear when the air is dry aloft, and shear-parallel bands (**4c**) for strong shears in both layers when the shear vectors are in the same direction. Midlatitude influences likely contributed to these two additional modes by producing strong westerlies (in the case of **4c**) during the passage of a strong upper-level trough and midtropospheric drying (in the case of **2r**) following passage of the trough. Mechanism(s) for **4c** cases are uncertain, but they may be associated with confluence lines connected with the upper-level troughs. In the **2r** cases, the lines are probably a manifestation of horizontal convective *rolls* in the boundary layer (hence the use of **r**). In these cases it is so dry aloft and the instability so weak that the convection cannot penetrate to higher levels and produce strong downdrafts and cold pools, which would otherwise serve to reorient the lines into a shear-perpendicular direction.

4. Summary and Discussion

Recent studies of midlatitude and monsoon convective systems (MCSs) have provided new insight regarding MCS organization, evolution, and structural properties. Investigations using operational radar data over the United States have revealed three dominant modes of organization: trailing stratiform (TS), leading stratiform (LS), and parallel stratiform (PS) systems. While TS are the most common, LS and PS modes are not negligible and, in some cases, are associated with flash floods. Recent study of extreme-rain-producing storms over the eastern two-thirds of the United States indicates two dominant modes of MCS organization of such storms, one with training convective cells and the other with back-building cells. Study of 1998 GAME/SCSMEX MCSs reveals that the shear in the lower and middle troposphere plays a dominant role in determining the orientation of convective lines over the northern South China Sea. Results are similar to findings for the tropics, but two new modes of organization are highlighted, which are argued to be related to midlatitude influences.

ACKNOWLEDGMENTS This research has been supported by the National Science Foundation under Grants ATM-9618684 and ATM-0071371, and by the National Aeronautics and Space Administration under Grant NNG04GA22G. The following individuals are thanked for their help in this research: Matt Parker, Russ Schumacher, Crystal Pettet, Paul Ciesielski, Tom Keenan, Steve Aves, and Rick Taft.

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