Jet-induced inertial instabilities and the growth of mesoscale convective systems

Abstract of dissertation

Many mesoscale convective systems (MCSs) have been observed to form in environments where the isentropic absolute vorticity may have values that approach zero, resulting in regions with weak inertial stability. It has been demonstrated that for a given amount of convective available potential energy (CAPE), deep convective circulations can be modified and enhanced as the inertial stability is reduced. Consequently, there has been speculation that the evolution and organization of convection into MCSs may be related to the presence of an environment in which the inertial stability is weak or unstable.

In some mesoscale environments, particularly in the springtime when CAPE is large and a strong jet stream is still present, the atmosphere is unstable to both upright and slantwise convection. Because the time scales of these two modes are considerably different, upright convection will typically dominate. It is hypothesized that this upright convection can, over longer time scales, exploit the weak restoring force present in the mesoscale inertial stability

To explore the hypothesis that inertial instability plays a role in the development of mesoscale growth and organization, both observational and model data were examined. Environments that supported the growth of MCSs in the PRE-STORM network were sampled with high quality special soundings. Secondary circulations that occurred in the presence of inertial instabilities were analyzed and documented using the high spatial and temporal resolution rawinsonde data from the PRE-STORM field program.

Additional examples of MCS environments were examined using data from the MAPS analysis system. The high resolution of the model, coupled with the ingest of multiple data types, result in the improved analysis of small-scale and short-lived features such as mesoscale inertial instabilities.

To increase the understanding of the basic processes that enhance MCS growth in inertially unstable environments, the RAMS mesoscale model was used. Model results indicate that the strength of the divergent outflow was strongly linked to the degree of inertial stability in the local environment. The results also showed a strong dependence on the magnitude of the Coriolis parameter. Finally, simulations using varying degrees of vertical stability indicated that there was also significant sensitivity to this parameter.

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Introduction

The mesoscale convective complex (MCC), described by Maddox (1980), and the more general mesoscale convective system (MCS) encompass a broad distribution of convective organizations, with squall lines, meso-alpha-scale and meso-beta-scale convective clusters, and other non-squall linear or banded structures (McAnelly and Cotton 1986; Blanchard 1990; Houze et al. 1990). MCCs, in particular, are large thunderstorm conglomerates that produce significant convective season rainfall in the Midwest (Maddox 1983; Fritsch et al. 1986; Kane et al. 1987). They generally reach sizes of 105 km^2, last six to eighteen hours, and travel hundreds of kilometers during their lifetimes (Fritsch and Maddox 1981; McAnelly and Cotton 1989).

The development of nocturnal MCSs has been shown to be a function of large-scale synoptic patterns, terrain-induced features, such as elevated heat sources, and localized mesoscale forcing (Maddox 1980; Cotton et al. 1983; Wetzel et al. 1983; Doswell 1987; Tripoli and Cotton 1989a). Using objective analysis and compositing techniques for ten MCCs, Maddox (1983) identified several distinctive features at the surface and in the lower, middle, and upper troposphere during the formation, maturation, and dissipation stages of MCCs. Classification as an MCC was based on characteristics observable in satellite imagery because of the wide range of atmospheric scales that could be monitored, but did not address internal structural characteristics. More recently, Cotton et al. (1989), using compositing techniques that permit greater temporal resolution, examined 134 MCC events. Their results are similar to those of Maddox, but are more detailed regarding the temporal evolution of the system. Like Maddox, however, Cotton et al. (1989) did not directly address the question of variable structures within the MCCs. They concluded that an MCC is an inertially stable form of an MCS and proposed that a more dynamic definition of an MCC is "an MCS that is nearly geostrophically balanced and whose horizontal scale is comparable to or greater than the (modified) Rossby radius of deformation." Blanchard (1990) has shown there are three basic, recurring mesoscale patterns of convection associated with MCSs, while Houze et al. (1990) have introduced a complex classification system for mesoscale convection associated with springtime rainstorms (i.e., at least 25 mm of rain in 24 h over an area exceeding 12,500 km2). None of these studies, however, have addressed the dynamic and kinematic evolution associated with the upscale development of individual cloud elements into the mesoscale system; instead they focus on the organization of the convection after it has already developed into a mesoscale system and only provide a "snapshot" of the system structure.

Tripoli and Cotton (1989a), using the RAMS mesoscale model, investigated the genesis of an MCS that had its origins in the Colorado mountains. They were able to simulate both the mountain-generated solenoidal circulation and the solenoidal circulation that resides over the High Plains. Their results indicated that both features are important in the genesis of the MCC. The simulation, however, was restricted to two dimensions and could not accurately model the low-level jet, a feature of importance for MCC intensification. Nonetheless, they were able to simulate the upscale growth of convection from the meso-gamma-scale to the larger meso-beta-scale because of the growth of a deep meso-alpha-scale circulation. This result suggests the importance of the secondary circulations generated by the mesoscale convection and supports the findings of previous work (e.g., Zhang and Cho 1992; Zhang and Fritsch 1988).

Nachamkin et al. (1994) examined PRE-STORM (Cunning 1986) data to describe the upscale evolution of an MCC. They noted that mesoscale organization occurred shortly after the upper-level cloud shield reached MCC proportions and the organization manifested itself as a rapid, almost discreet transition. Nachamkin et al. noted that their result agrees with the assertion made in McAnelly and Cotton (1992) that the upscale transition from separate convective clusters to a coherent MCC may occur early in the MCC life cycle, and more abruptly than inferred from previous MCC life cycle research (i.e., Maddox 1983; Cotton et al. 1989; McAnelly and Cotton 1989). Because the earlier studies used composite data, smoothing of both spatial and temporal events was unavoidable and rapid changes were hidden in the composite, or not sampled at all. Substantial effort has been made over many years to address the issues of convective evolution from the meso-gamma-scale to the meso-beta- and meso-alpha-scales associated with MCCs and MCSs. Some of these studies have dealt with kinematic structures observable with satellite, radar, rain gage, rawinsonde, and other data sets and have documented the evolution and structure of these systems. Others have used model simulations to address the evolution of the convective and the dynamic characteristics associated with the convection itself. Still others have attempted to deal with the problem of scale interaction in which the convective scale processes modify the mesoscale environment, resulting in changes that are resolvable with conventional data. Here, we will address issues of synergistic responses between both the convective scale processes and the mesoscale environment.