4.4 AN OVERVIEW OF THE BOW ECHO AND MCV EXPERIMENT (BAMEX)

Planned Field Phase: May 20 – July 6, 2003

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1. Introduction

The study of long-lived (e.g., 6-24 hr.) mesoscale convective systems (MCSs) continues to be a prominent topic in meteorology, mainly because of the profound effect such systems can have on local weather. The spectrum of significant MCSs is approximately bracketed by bow-echoes at small scales, which can be responsible for generating large swaths of damaging surface winds, and mesoscale convective complexes with mesoscale convective vortices (MCVs) at larger scales, which can produce widespread heavy rainfall and flash flooding. Both are examples of convective systems that develop appreciable vertical components of vorticity and often are seen to evolve into comma shaped precipitation regions. According to Frisch et al. (1986), at least half of the warm-season rainfall in the central United States is produced by long-lived mesoscale convective systems (MCSs) In addition, Fritsch et al. state that "...series of convective weather systems are very likely the most prolific precipitation producer in the United States, rivaling and even exceeding that of hurricanes." Understanding how MCSs organize, propagate and regenerate has important implications for understanding the transport and cycling of water on regional (1000 km) scales.

The U.S. Weather Research Program seeks to (a) increase the skill of Day 1 model quantitative precipitation forecast (QPF) skill by 50% and (b) make Day 2 prediction as accurate as current Day 1 prediction. In addition, the skill of warm season QPFs is only about half of its cool season counterpart. Because of the prominence of MCSs in determining warm season precipitation, improving prediction of these systems will likely contribute substantially to the goals of the USWRP. Long-lived MCSs often produce flooding rains and widespread damaging winds in swaths roughly 100 km wide that can extend for 1000 km over time scales of 12-48 h. Therefore, understanding the processes producing severe weather within MCSs, combined with improved prediction of mesoscale characteristics of MCSs, can increase dramatically the lead time for the prediction of widespread episodes of severe weather.

Much of what is unknown about long-lived MCSs involves how coherent horizontal circulations form and how predictable such circulations might be. Observations to date have been made mainly by ground-based radar, rawinsondes and wind profilers and satellites. Except for a few isolated examples, the coverage of radar has been insufficient to document horizontal and vertical circulations on scales of 30-300 km. To date, there has not been an observational program that has collected sufficient data to document the life cycle of MCSs and test hypotheses regarding their maturation, decay and subsequent regeneration. With the recent nation-wide deployment of WSR-88D radars and other semi-permanent infrastructure, we believe the time is right for a targeted field effort that builds on the existing operational capability to achieve datasets that are unprecedented in their spatial and temporal resolution. Additional motivation for a field effort at this time results from the wealth of recent numerical simulations, generally devoid of confirmatory observations, that exist from which numerous dynamical hypotheses concerning the evolution of long-lived convective systems have been advanced.

In general, the frequency of bow echoes and larger, MCV-producing systems is high enough that an experiment of 6-8 weeks duration in the early warm season should experience several cases of each. Recent and ongoing efforts, many funded by the USWRP, have allowed new estimates of the climatological frequency of MCSs featuring damaging straight-line winds (derechoes) and systems that produce MCVs. The climatology of derechoes, a subset of bow echo disturbances, suggests about 6-7 events per year during the months of May, June and July. The frequency of bow echoes, though not known exactly, is perhaps a factor of two greater. The frequency of tornadoes produced within bow-echoes is currently being investigated and should be available soon enough to assist in planning of the experiment. Recent work on MCVs suggests roughly 20 events per year (with an event lasting at least 3 hours after the demise of the parent convective system) may be found during this period.

Considering the mutual interests of bow echo and MCV studies, the period mid May to mid July is considered optimum for a field project to investigate both phenomena. The spatial distribution of these events (sec. 2) is clearly centered in the Midwest with some extension into the Ohio Valley (especially for bow echoes). Given the fact that these systems are long lived, affect extensive geographical areas and can occur anywhere within a broad latitudinal band during the early warm season, BAMEX is designed to be a highly mobile experiment. The goal is a mapping of the life cycle of long-lived convective systems with emphasis on the developing and mature phases of bow echoes and on the mature and decaying phases of MCV-producing systems. Furthermore, especially with MCV-producing systems, the MCV often becomes the focus of new convection during the next day and possibly a new MCS. BAMEX is designed not only to examine individual MCSs, but also to address the causal link between successive convective systems.

The merging of the study of bow echoes and MCVs into a single field campaign results from a goal to combine a nearly identical set of required observational resources and thereby maximize the scientific return on our investment. Direct conflict between objectives of bow echo and MCV studies is not anticipated to occur frequently owing to the different environments in which each is believed to form. Furthermore, by focusing on the large and small ends of the organized-convection spectrum, we hope to reduce the enormity of the overall problem of organized convection to a tractable subset. What we learn about these systems will likely be representative of the larger class of MCSs, broadly defined.

Numerous scientific objectives are discussed in section 2. However, the primary goals of the project may be succinctly summarized as follows:

1. Improve predictability of bow-echo disturbances, especially those producing severe weather.
2. Improve predictability of secondary convection generated by mesoscale vortices.
3. Document and understand factors contributing to the development of horizontal circulations within long-lived convective systems.

4. Improve 6-24 hour QPF.

2. Science Review

2.1. BOW ECHOES

2.1.1 Observations

On the early morning of 15 July 1995, a convective system spawned over Ontario moved across much of upper New York State and central New England, producing surface winds of 30 to over 45 ms^{-1} (60 to over 90 kts), killing 8 people, and producing one of the largest tree blowdowns ever observed in the Adirondack Mountains (Cannon et al. 1998, McCarthy 1996, Bosart et al. 1998). On 5 May 1996, a convective system moved rapidly across the Lower Ohio Valley, producing wind gusts up to 41 ms^{-1} and widespread wind damage over much of eastern Missouri, southern Illinois and northern Kentucky (Spoden et al. 1998). On the night of 16 May and early on the morning of 17 May 1996, a convective system raced across South Dakota, producing straight-line winds in excess of 50 ms^{-1} (100 kts), toppling nearly 600 power poles and producing widespread damage to buildings (Rasch and Ess, 1998).

Convectively produced windstorms, such as those mentioned above, pose a significant hazard to life and property over much of the US during the spring and summer months. According to Storm Data, from January 1995 to July 2000 over $1.4 billion in property damage, 72 deaths and 1008 injuries were reported to the National Weather Service (NWS) as having been caused by such events. The longer-lived, larger-scale events have been given the generic name of ``Derecho'' (Johns and Hirt 1987), a term that originated in the late 1800's to refer to convective systems producing wide and long swaths of straight-line wind damage (Hinrichs 1888). More detailed studies of these systems, however, have shown that a vast majority is associated with a particular type of organized convective system, which is more popularly referred to as a ``bow echo'' (so named due to its characteristic bow shape on radar displays). First described in detail by Fujita (1978), bow echoes now represent one of the best-known modes of convective organization associated with severe weather events, especially for high winds.

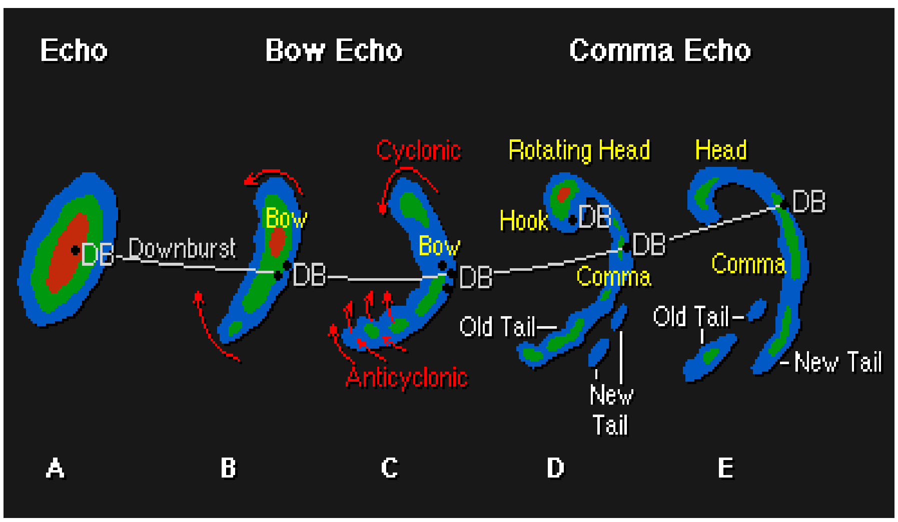


Figure 2.1. A typical morphology of radar echoes associated with bow echoes that produce strong and extensive downbursts, labeled DB on the figure (from Fujita 1978).

The typical morphology of radar echoes associated with a bow echo is presented in Fig. 2.1 (Fujita, 1978), depicting the evolution of a single large or small group of strong convective cells to a bow-shaped line segment, and finally to a comma-shaped echo in its declining phase. Bow-shaped convective systems are observed over a range of scales, from single cells to squall line systems several 100s of kms in horizontal extent (Klimowski et al. 2000). The systems of primary interest for the present study, however, are the especially severe, well-organized bow echoes, which generally range between 40 and 140 km in horizontal scale and have a longevity of greater than three hours.

A recent example is shown in Fig. 2.2 from 5 May 1996 near Paducah Kentucky, which depicts a

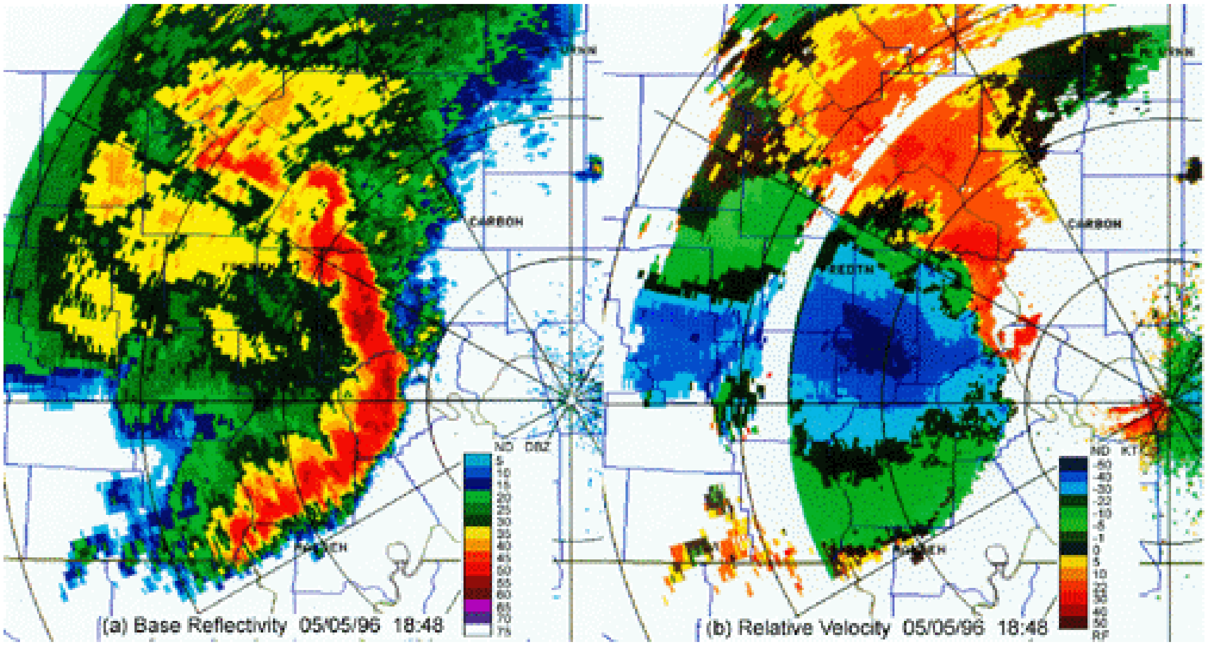


Figure 2.2. (a) Base reflectivity and (b) relative velocity from the Paducah WSR-88D radar at 18:48 GMT for 5 May 1996. Velocities are presented relative to a storm motion of 33 kts from 280 deg.

large bow-shaped convective system, with two smaller-scale bows embedded with the larger circulation. This case illustrates the range of scales of bowed convective segments that can occur, often within a single MCS. The Doppler winds clearly depict some of the well known kinematic features of bow echoes, including a rear-inflow jet (Smull and Houze 1987; Jorgensen and Smull 1993) and associated rear-inflow notch (Burgess and Smull 1990;Przybylinski 1995) behind the core of the system. Also evident is weak anticyclonic shear to the south of the bow and stronger cyclonic shear behind the northern end of the bow. Additionally, the smaller embedded bows each have their own localized rear-inflow jets with associated rotational features on the ends. Upon reaching the surface, strong system-scale rear-inflow is hypothesized to be responsible for much of the resulting wind damage from these systems. However, damaging winds can also occur in conjunction with individual rotating cells. It is not currently known how important these cells are relative to the mesoscale rear-inflow and to what extent mesoscale and cell-scale wind features superpose to create the greatest damage.

Besides their association with strong, straight-line surface winds, there is also a strong association between bow echoes and tornadoes (e.g., Fujita 1978, Przybylinski et al. 1996, Funk et al. 1996a, Wakimoto 1983, Smith and Partacz 1985, Przybylinski 1988, Funk et al. 1996b, Prost and Gerard 1997, Pence et al. 1998). A recent study by Tessendoff and Trapp (2000) suggests that squall-line/bow echo tornadoes account for up to 20 per cent of all tornadic events nationwide. Also, contrary to popular belief, such tornadoes can be quite strong and long-lived. A particularly intriguing property of bow-echo tornadoes is their tendency to be located from the apex of the bow northward. To date, there has been very little study or research-quality observations of such events.

Climatological studies of environments associated with severe bow echoes depict a wide range of conditions in which such events occur (e.g., Johns and Hirt 1987, Bentley and Mote 1998, Evans and Doswell 2000). The especially severe, long-lived events during the warm season (May-August) tend to occur in environments with very large CAPE (e.g., 2000-5000 j/kg) and moderate-to-strong low-to-mid level vertical wind shears (e.g., at least 15-20 ms^{-1} of shear over the lowest 2-5 km AGL). The most common synoptic pattern that supports the development of such systems is that described by Johns (1982, 1984) for severe weather outbreaks in northwesterly flow. Over 80% of the 70 events studied by Johns and Hirt (1987) began along or to the north of a weak east-to-west oriented quasi-stationary frontal boundary and then moved along the boundary. In a recent study of 110 bow echo events, Klimowski et al. (2000) also found that roughly half formed within 50 km of a mesoscale outflow or preexisting thermal boundary. Some examples of the synoptic-scale flow associated with cases in weak and moderate large-scale influence, respectively, are shown in Fig. 2.3 (from Evans and Doswell, 2000).

The specific frequency of bow-echo occurrence has never been directly established, but we can estimate it from the frequencies for the most significant and long-lived bow echo events through recent climatological studies of derechoes. During the period of May through August for the years 1980-1983, Johns and Hirt identified 70 such cases in the US, most of which occurred in the upper Midwest. More

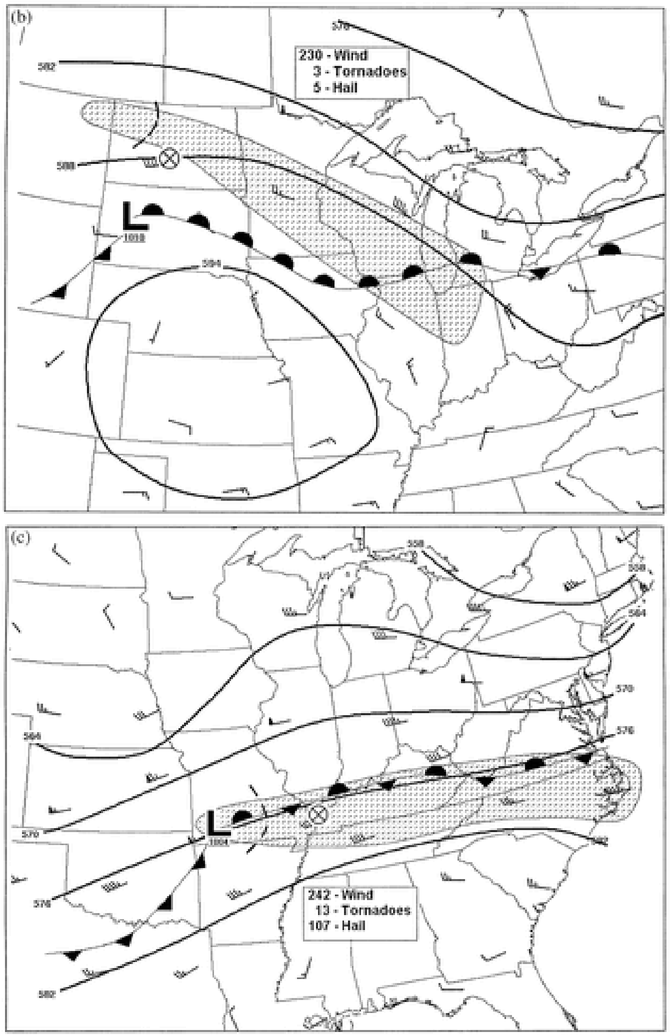


Figure 2.3. Geopotential height and radiosonde winds at 500 hPa along with surface cyclone center position and frontal analysis at 1200 UTC of two severe bow echoes episodes: (a) weakly forced case of July 19, 1983 (left or top), and (b)moderately forced case of June 4, 1993 (right or bottom). Stippled region outlines area of damaging winds during each case. Curved dashed line denotes position of primary convective line at 1200 UTC. The number and type of severe weather reports are listed on each figure (from Evans and Doswell, 2001).

recent climatological studies by Bentley and Mote (1998) and Evans and Doswell (2000) identify a similar corridor of derecho development in the upper Midwest, as well as additional corridors along an axis from Kansas through Oklahoma and Texas, and also in the southeast (Fig. 2.4).

2.1.2 Modeling

Idealized numerical modeling studies to date have been able to reproduce much of the observed spectrum of bow-echo type phenomenon, ranging from strong, bow-shaped lines of cells, forced by a strong surface cold pool and deep lifting along the cold pool's edge (e.g., Weisman and Klemp 1986,

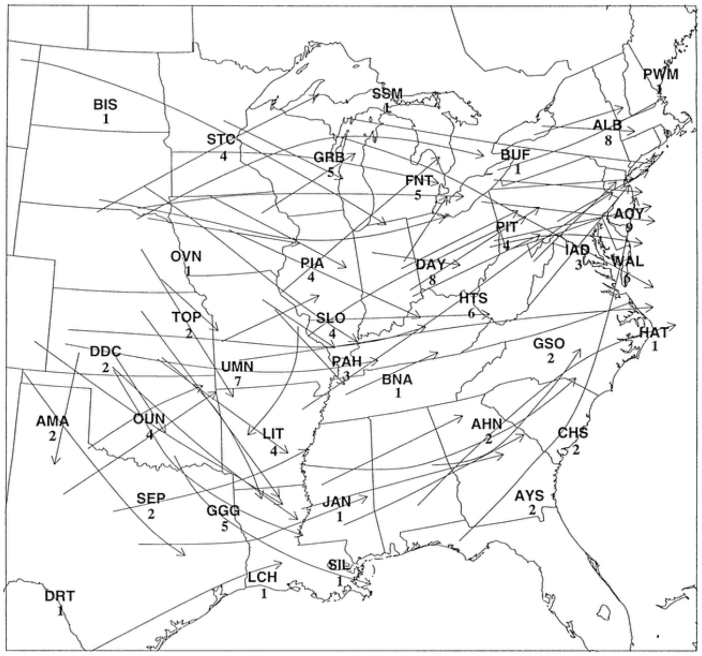


Figure 2.4 Graphical plot of each derecho centroid, along with the number and location of proximity soundings used in this study. (from Evans and Doswell, 2001).

Rotunno et al. 1988, Weisman et al. 1988, Skamarock et al. 1994, Coniglio and Stensrud 2000), to highly organized systems with strong ``book-end'' vortices and elevated rear-inflow jets (e.g., Weisman 1992, 1993, Weisman and Davis 1998) . Similar to the observational studies, the environments for simulated long-lived severe-wind-producing systems generally include large CAPEs and moderate low-to-mid level shear of at least 10-15 ms-1 over the lowest 2-5 km AGL. However, the more organized bow echoes require stronger shear values of at least 15-20 ms^{-1} over the lowest 2-5 km AGL. Coniglio and Bosart (2000) also suggested an importance of environmental vertical shear above 5 km as a factor affecting the severity of bow echoes.

The idealized modeling results for the more strongly-sheared systems are summarized in Fig 2.5, which depicts the evolution of a finite line of convective cells over a 6 h period in an environment of 20 ms-1 of vertical wind shear in the lowest 2.5 km AGL and 2200 jkg-1 of CAPE (Weisman and Davis 1998). When Coriolis forcing is included, a northern cyclonic vortex dominates over time (e.g., Skamarock et al., 1994), as is also often observed (e.g., Figs 2.1 and 2.2). In larger bow echoes, these mid-level cyclonic vortices are observed to develop into balanced mesoscale convective vortices (MCVs, e.g., Davis and Weisman 1994). These cases represent a phenomenological overlap with the larger MCSs, which produce long-lived MCVs, although long-lived MCVs that emerge from dissipating bow echoes are believed to be rare. Additionally, smaller-

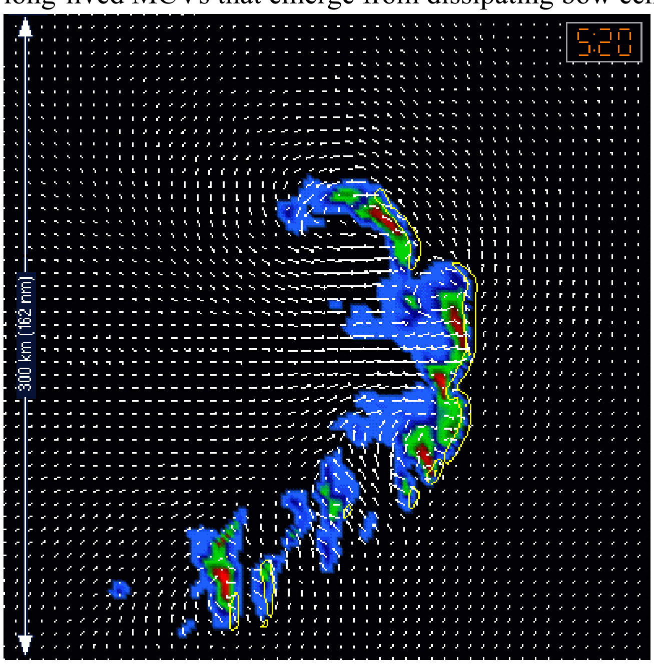


Figure 2.5. Horizontal cross sections of system-relative flow, rainwater mixing ratio and vertical velocity at 2 km AGL for the U_S = 20ms^{-1} 2.5 km-shear simulation 4.5 h after initialization with a north-south line of warm bubbles. The Coriolis force is included. Vectors are presented every 4 grid points (8 km), with a vector length of 8 km equal to a wind magnitude of 20 ms^{-1}. The rainwater is contoured for magnitudes greater than 1 g kg^{-1} (lightly shaded) and magnitudes greater than 3 g kg^{-1} (darkly shaded). The vertical velocity is contoured at 5 ms^{-1} intervals, with the zero contours omitted. A domain speed of u_m = 18.5 ms^{-1} has been subtracted from the flow field. Tick marks are spaced 20 km apart (adapted from Weisman and Davis 1998).

scale bow-shaped segments with dominant cyclonic line-end vortices are observed to develop along the line, as similarly shown by the observational example presented in Fig.2.2.

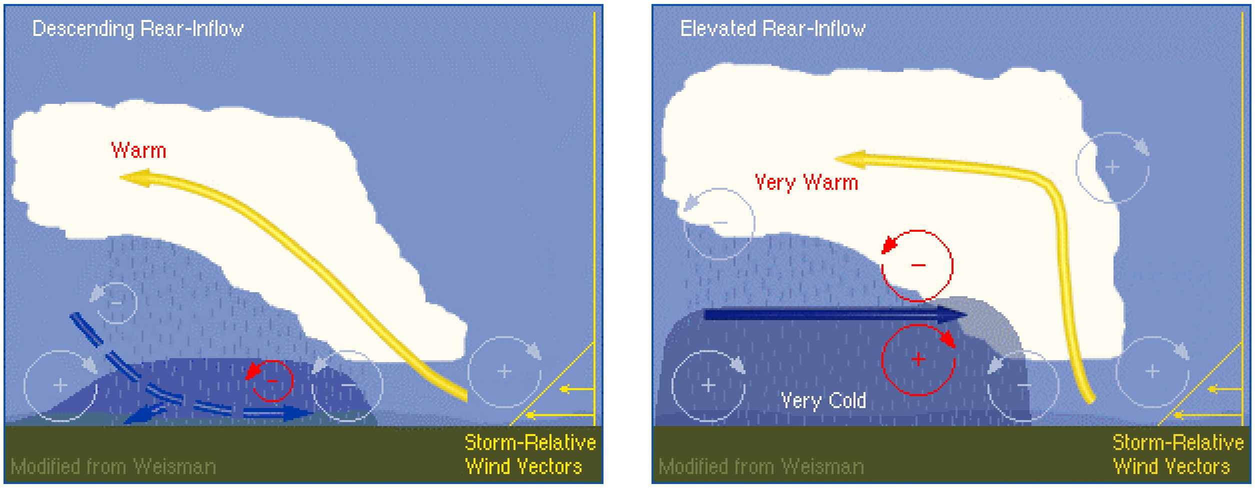


Figure 2.6. Schematic vertical cross section of a mature convective system with (a) descending rear-inflow jet and (b) an elevated rear-inflow jet. The updraft curre
the rear-inflow current in denoted by the blue vectors. The shad
thin, circular arrows depict the most significant sources of h
associated with the ambient shear or which are generated w
the text. Regions of lighter or heavier rainfall are indicated
vertical lines, respectively. The scalloped line denotes the o

From a two-dimensional perspective, these simulated convective systems tend to evolve from an initially downshear-tilted, to upright and then upshear-tilted configuration as the convectively-generated cold pool strengthens and deepens over time (e.g., Weisman 1993). Once the system begins to tilt upshear, a rear-inflow jet is generated in response to the buoyant front-to-rear ascending current aloft and rearward spreading cold pool at the surface (e.g., Lafore and Moncrieff 1989; Weisman 1992). This rear-inflow jet may descend and spread along the surface, contributing to stronger surface outflow but weaker leading-line convection (Fig. 2.6a), or may remain elevated, enhancing the lifting at the leading edge of the system, and promoting stronger leading line convection (Fig. 2.6b). Mid-level line-end vortices contribute further to bow echo severity by focusing and strengthening the mid-level rear inflow jet, thereby enhancing the resultant convective downdrafts and surface outflow (Fig. 2.6).

2.1.3 Unresolved Issues

Although there has clearly been much research to date on the morphology, dynamics, and severe weather potential of bow echoes, and although many hypotheses have been put forth to explain the properties of such systems, there has never been an observational program that has collected sufficient kinematic and thermodynamic data over time and space to truly document the lifecycle of these events and to test such hypotheses. It is hoped that for the first time, BAMEX will supply forecasters and researchers alike with sufficient observations to address the critical outstanding issues. A particular interest of BAMEX will be to document the processes by which more isolated convection evolves upscale into the larger, more coherent bow-shaped segments. The ability to anticipate this morphosis represents a critical gap in our ability to forecast and warn for such events.

Most of the arguments that propose to explain the development of severe winds within bow echoes depend on the development of a strong, deep cold pool and associated mesohigh, which accelerates the surface flow. The strength of the cold pool also depends on the structure and strength of the rear-inflow jet, which can entrain drier mid-level air into the mesoscale downdraft, enhancing evaporative effects, and additionally transport higher momentum air down to the surface. The microphysical make-up of the stratiform precipitation region has also been hypothesized to be important in this regard. The relative magnitudes and importance of these various contributions to surface outflow strength have never been clearly established, making it quite difficult to anticipate the development of severe winds in any given event. The conditions that lead to the development of descending, rather than elevated, rear-inflow jets especially need to be clarified.

In order to address these issues, we need to document the evolution of the buoyancy fields throughout the convective system, both within the cold pool at the surface and within the stratiform regions aloft. There is also a need to clarify the relative roles of convective versus mesoscale effects in the production of the severest winds. One of the more intriguing mysteries is how severe bow echoes can occur at night in the presence of a stable nocturnal boundary layer that does not as readily support the generation of the strong surface cold pool. Interactions between the convection and the stable boundary layer and the subsequent production of internal gravity waves has been offered as one possible explanation (e.g., Bernardet and Cotton 1998), but also has yet not been clearly established.

Issuing appropriate severe weather warnings for bow-echo tornadoes is especially problematic. More often than not, there is no readily identifiable supercell signatures or mid-level mesocyclone preceding such tornadoes. Instead, the rotation usually appears first near the ground, with very little lead time before tornado formation (e.g., Trapp et al., 1999). The relationship between tornadoes and the mid-level line-end vortices that are located behind the active leading-line convection and above the surface cold pool, in general, needs to be clarified (e.g., Funk et al. 1996). On some occasions, low-level circulations that develop along the leading edge of a bow echo are observed to grow in scale and eventually merge with the cyclonic line-end vortices. Little is known about the processes by which such vortices merge or how this process affects system evolution and the production of severe weather. The fact that non-supercell tornadoes develop primarily northward of the apex of the bow (Forbes and Wakimoto, 1983) has not yet been explained.

Recent observational studies also suggest the importance of pre-existing, line-normal thermal boundaries to the formation, propagation, and severe weather associated with bow echoes. Such boundaries can provide a focused region of enhanced low-level convergence that could lead to stronger localized convection and stronger surface winds, Additionally, such boundaries could be associated with enhanced horizontal vorticity that could feed into the system in a streamwise sense and enhance the potential for tornadogenesis (e.g., Przybylinski et al. 2000, Schmocker et al. 2000). Most numerical studies of bow echoes to date, however, have only considered highly idealized environments, characterized by horizontally homogeneous initial states. Hence, it is necessary to understand how bow echoes evolve in complicated mesoscale environments, and specifically how the interactions between bow echoes and preexisting boundaries and/or convective cells impacts the development of severe weather.

The identification of Doppler radar precursors to help forecasters warn for severe wind events has been only marginally successful to date. Schmocker et al. (1996) found that near the forward flank (downwind flank) of the convective line a mid-level radial convergence (MARC) signature often preceded the bowing of the reflectivity field and subsequent severe straight-line outflow at the surface. This signature was incorporated into the Damaging Downburst Prediction and Detection Algorithm (DDPDA; Eilts et al. 1996) and evaluated for several bow echo storm systems by Karl et al. (1999). However, they found that the DDPDA experienced unacceptably high false alarm rates and low probability of detection. More research is clearly needed to understand how signatures such as MARC are related to system dynamics and the production of severe weather.

Another unresolved issue is the factors that control the scale of such systems. Both observations and idealized numerical simulations show that bow-shaped systems can exist over a range of scales sometimes all within the same mesoscale convective system (e.g., Figs 2.2 and 2.5). However, a subjective survey of the most severe, long-lived bow echoes suggests a preferred horizontal scale of between 40 and 120 km.

A similar scaling preference could be inferred from the idealized modeling studies as well. A better understanding is needed of how system scale is related to severe weather production.

2.1.4 Summary of Scientific Objectives

The fundamental objective of the bow-echo component of BAMEX is to document the life cycle of bow echoes, emphasizing mechanisms of severe weather production and predictability. The questions included below summarize the major unresolved issues that underlie each numbered objective:

1. Relate bow echo behavior to synoptic scale or mesoscale environment.
    - Determine which convective environments are conducive to bow echo genesis.
    - Quantify the characteristics and roles of pre-existing mesoscale and synoptic scale features in initiating and maintaining bow echoes.
    - Determine factors that distinguish the genesis and maintenance of daytime and nocturnal (stable boundary layer) bow echoes.
2. Characterize system morphology and evolution.
    - Determine the relationship between the system-scale buoyancy field and the system's kinematic structure and strength. Reconcile inferences derived from idealized modeling studies.
    - Quantify the relative importance of lower-tropospheric versus middle-to-upper-tropospheric vertical wind shear for system structure and maintenance.
    - Document the process of upscale-growth from individual cells to coherent bow-shaped segments.
    - Understand the mechanisms producing convective-scale and mesoscale vortices and their interrelationship. Document upscale growth of convective-scale vortices and the development of bowed segments within longer lines convective lines.
3. Document conditions leading to occurrence of severe weather.
    - Document the mechanisms producing strong straight-line surface winds within bow echoes and how they differ for daytime versus nocturnal scenarios.
    - Understand the factors governing whether rear-inflow jets will descend to the surface.
    - Reconcile the role of individual cells versus mesoscale features in the production of the most damaging winds.
    - Determine the role of pre-existing surface boundaries in enhancing bow echo severity and longevity.
    - Understand the process of tornadogenesis within bow echoes and how does it differ from classical supercell mechanisms.
    - Determine why tornadogenesis appears favored north of the apex of the bow.
4. Assess bow echo predictability.
    - Determine what severe weather precursors associated with bow echoes can be identified with radar, and with what lead time.
    - Assess what is required to forecast such events with operational numerical models.

2.2. MESOSCALE CONVECTIVE VORTICES (MCVS)

2.2.1 Background

Composite studies (Maddox 1983; Cotton et al. 1989) have revealed that midtropospheric mesoscale convective vortices (MCVs) of 50-300 km radial extent may be a common structural component of many large mesoscale convective systems (MCSs) forming in relatively weakly sheared environments. The mesoscale vertical motion within the stratiform region of MCSs is believed to provide the necessary vortex stretching to induce MCS-scale cyclonic rotation. Both simulations (Davis and Weisman 1994; Olsson and Cotton 1997) and observations (Bartels et al. 1997) have indicated that MCVs are balanced vortices and capable of persisting well beyond the cessation of the MCS from which they were spawned (Menard and Fritsch 1989; Fritsch et al. 1994; Bartels et al. 1997). These long-lived MCVs have been observed to initiate and focus subsequent heavy rainfall with attendant flooding (Bartels and Maddox 1991, Bosart and Sanders 1981, Fritsch et al. 1994, Trier et al. 2000a). An example of a long-lived MCV event that occurred from 20-22 August 1998 is shown in Fig. 2.7. The swirling cloud pattern evident in visible satellite imagery several hours after sunrise (Fig. 2.7a) is the signature of an MCV spawned by an MCS that occurred the previous night. By late afternoon, convection formed near the MCV center (Figs. 2.7b,c), moved eastward, and evolved into an MCS before dissipating the following evening. Mesoscale convection redeveloped overnight in the vicinity of the remnant vortex (not shown). This subsequent mesoscale convection left an MCV in its wake the following day (Fig. 2.7d), as in the previous diurnal cycle. Convection over eastern Nebraska during the early morning hours of 21 August was associated reports of widespread flash flooding (*Storm Data*, National Oceanic and Atmospheric Administration 1998).

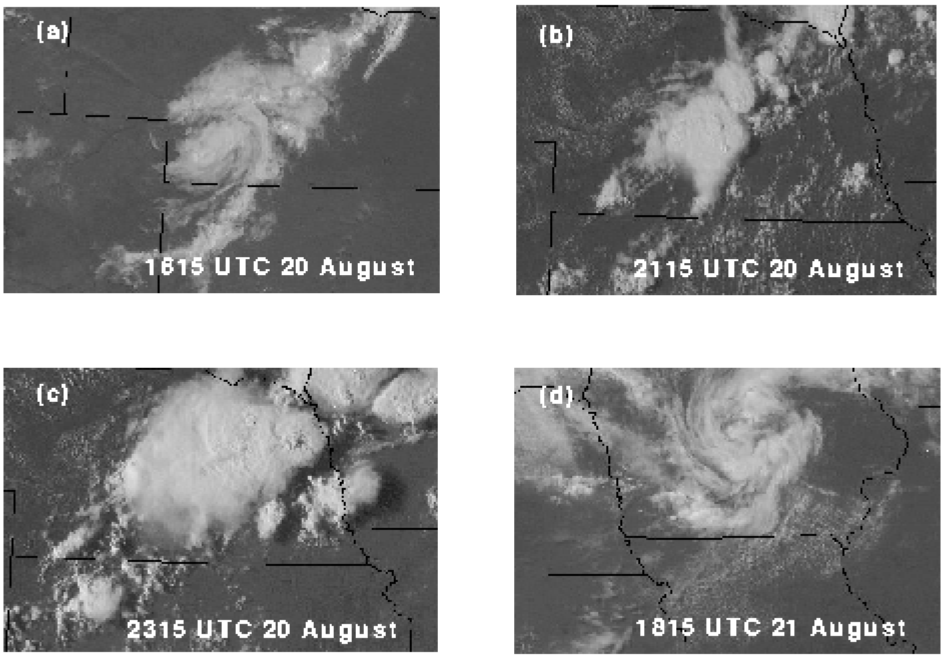
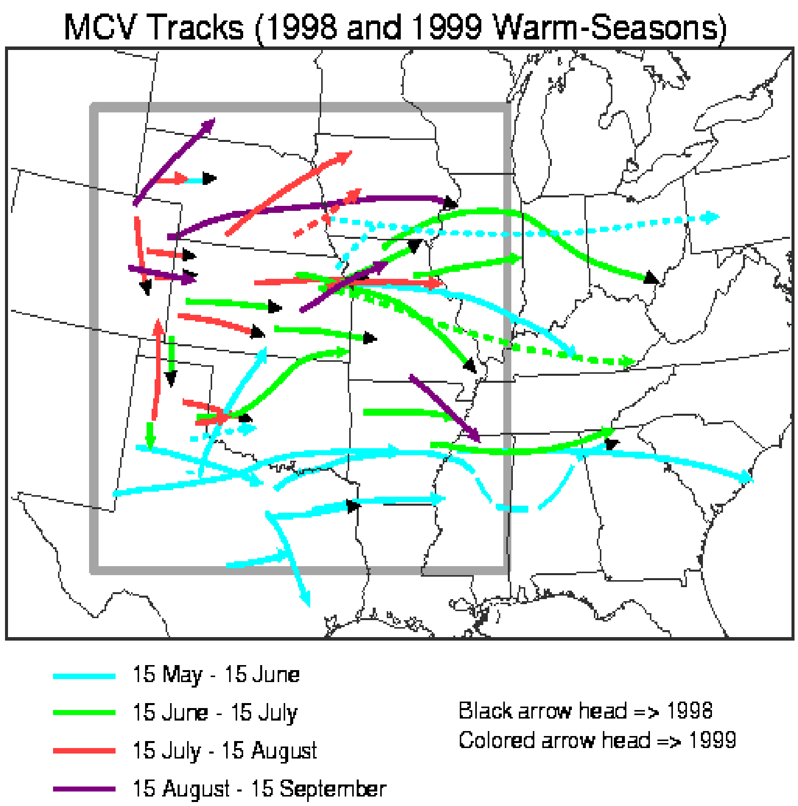


Figure 2.7. GOES-8 visible satellite imagery depicting a long-lived MCV at (a) 1615 UTC 20 August, (b) 2115 UTC 20 August, (c) 2315 UTC 20 August, and (d) 1815 UTC 21 August 1998. Adapted from Trier et al. (2000a).

Recent studies have taken advantage of the greater density and variety of data sources in the modernized National Weather Service of the United States (Trier et al. 2000a) and data assimilation systems such as the National Centers for Environmental Prediction (NCEP) Rapid Update Cycle (RUC) (Davis et. al. 2001) to better establish the frequency and geographic occurrence of MCVs (Fig. 2.8). Much of the operational and research interest in MCVs stems from the likelihood that they play a central role in initiating or modulating subsequent development of organized convection. Climatological studies of MCVs (Johnston 1981; Bartels and Maddox 1991; Trier et al. 2000a; Davis et al. 2001) have consistently established that retriggering of convection occurs in the vicinity of MCVs in about 1/2 of MCV cases. Long-lived MCVs, which can persist for several days or more, with multiple cycles of MCSs (Bosart and Sanders 1981; Fritsch et al. 1994; Trier et al. 2000a), have been responsible for excessive rainfall (local amounts in excess of 200 mm) and flooding over discontinuous swaths of 1000 km or more. In these cases, the redevelopment of organized MCSs in the vicinity of the MCV is likely crucial to extending the lifetime of the balanced vortex regime by either strengthening a single MCV through diabatic heating (vortex stretching) or by initiating a new MCV center. Such cases are excellent examples of how successive episodes of mesoscale convection can be dynamically linked, with the linkage in this case being the balanced vortex regime that occurs between outbreaks of convection.



rowheads denote 1999 cases.

The primary link between MCVs and subsequent convection may arise from mesoscale vertical motion produced by their interaction with background vertical wind shear. Raymond and Jiang (1990) presented a conceptual model of a steady, balanced vortex embedded in ambient vertical shear. Here, the vertical motion pattern consists of ascent (descent) downshear (upshear) associated with isentropic motion of the basic-state flow along isentropes deformed by the vortex (Fig. 2.9a), and additional ascent (descent) downshear (upshear) associated with the vortex flow along the isentropes of the basic-state baroclinic zone (Fig. 2.9b), provided the environmental vertical shear is thermally balanced. Raymond and Jiang further argued that the ensuing vertical parcel displacements may be sufficient to initiate convection downshear of the MCV, while suppressing convection upshear. Hence, given a broad (e.g., synoptic-scale) region that is susceptible to convection, the MCV could act to imprint a dipole structure of organized convection on an otherwise statistically uniform environment.

In reality, such vortices are not steady and often undergo significant weakening due to differential advection by the ambient vertical shear during portions of their life cycle. Thus, an important aspect of the vortex/ambient shear interaction concerns whether this mechanism is sufficient to support convection prior to the time at which the MCV circulation significantly weakens. Consistent with the Raymond and Jiang hypothesis, MCVs across the central United States in 1998 showed a distinct downshear preference for convective redevelopment (Trier et al. 2000a). Moreover, idealized adiabatic simulations based on these observations demonstrated that quasi-balanced lifting alone was sufficient to saturate a 1--2-km-deep layer of conditionally unstable air located immediately above the boundary layer, given both vortices of sufficient initial strength and sufficiently moist environmental conditions.

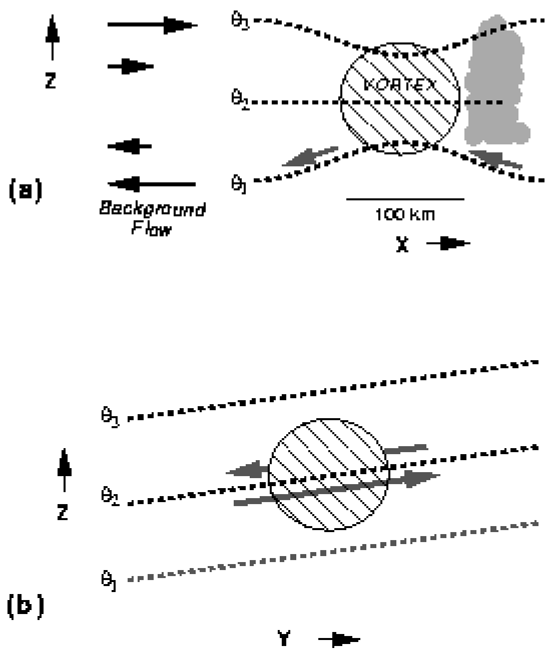


Figure 2.9. Schematic illustrating quasi-balanced lifting in the vicinity of a positive PV anomaly (hatched region) in ambient vertical shear. (a) Upglide associated with the background vertical shear along isentropic surfaces deformed by the vortex, and (b)

In their study of 1999 MCVs, Davis et al. (2001) found that longevity of an MCV is strongly correlated with its maximum intensity. MCVs with maximum relative vorticity less than the planetary vorticity (*f*) had little chance to persist beyond a single diurnal cycle. From separating the populations of MCV cases that were and were not associated with convective redevelopment, they concluded that the longer-lived cases resulted from retriggering of convection, which presumably helped prolong the life of the MCV through renewed generation of vertical vorticity. Note that the association among MCV intensity, longevity, and convective retriggering is consistent with the simple idea that for a given ambient shear, greater vortex intensity results in stronger balanced lifting. However, Davis et al. found that by far the most important factor in determining whether convective retriggering would occur was environmental moisture. This result combined with those of Trier et al. (2000a,b) suggest that, given a relatively uniform conditionally unstable environment, knowledge of an MCV circulation may be more helpful in determining where subsequent convection might occur rather than if it will occur.

2.2.2 Unresolved MCV Issues

Research activity in the past two decades has yielded dramatic increases in the understanding of MCVs. In addition there has been a recently heightened awareness among field forecasters of the strong relevance of MCVs to the 6--12-h QPF problem (Davis et al. 2001). Despite such advances, there are several important aspects of MCVs that remain poorly understood.

For instance, the process of MCV formation has yet to be well observed. Idealized convection-resolving numerical simulations (e.g., Skamarock et al. 1994; Davis and Weisman 1994; Weisman and Davis 1998) have shown that systematic tilting of horizontal vorticity associated with MCS-generated buoyancy gradients is responsible for the development of vertical vorticity that is subsequently enhanced by midtropospheric convergence of planetary vorticity. Here the simulated convection resembles the frequently observed asymmetric squall-type MCS (e.g., Houze et al. 1989, 1990; Blanchard 1990; Loehrer and Johnson 1995), which consists of a leading convective zone followed by an expansive region of stratiform precipitation on its poleward end, wherein the developing MCV resides. However, while this type of convective organization is common, the few published observations of MCVs spawned from this type of MCS (e.g., Brandes 1990; Scott and Rutledge 1995) have lacked the spatial and temporal data coverage to confirm the basic vorticity generation mechanisms deduced from the simulations. Moreover, both detailed case studies (Bartels et al. 1997) and MCV climatologies (Davis et al. 2001) have indicated that MCVs can, and often do, form within mesoscale areas of convection that are not characterized by this type of organization.

Once formed, the longevity of MCVs appears highly variable from case to case. While strong vertical wind shear through the mid-troposphere appears to inhibit MCV formation (Trier et al. 2000), there is little evidence that shear determines MCV longevity (Davis et al. 2001). Davis et al. present strong evidence that MCVs lasting longer than about 12 h depend on regeneration of vorticity by new convection. MCVs that are stronger initially appear more likely to regenerate. This gives a well-defined relationship between MCV strength and longevity for the longest-lived subset of MCVs. However, we have little information about what allows MCVs to persist beyond the decay of the convection which gives rise to them. Numerical simulations suggest that practically all systems with appreciable stratiform regions produce system-scale rotation, but there are many fewer observed MCVs than MCSs. It is important to probe the decaying stages of MCSs to resolve this discrepancy. Unfortunately, the decaying stages of MCSs have been scantily observed previously, so we have almost no adequate data sets that can be examined.

Also at issue are the details by which organized convection is retriggered in the vicinity of long-lived MCVs. While it is clear from previous work that MCVs tend to enhance convection downshear and suppress convection upshear of their center, it is not clear to what extent the mechanism of balanced lifting acts independently from planetary boundary layer forcing mechanisms to initiate convection. For instance, afternoon convection in the vicinity of MCVs has been observed to form along convective outflow boundaries and at the edge of the MCV cloud shield, where thermally direct solenoidal circulations are likely to occur (Trier et al. 2000a). Long-lived (multiple-day) MCV episodes that produce flooding rains are often characterized by successive MCSs that are most intense and well organized at night (e.g., Fritsch et al. 1994; Trier et al. 2000a). In these cases, moisture transport by the nocturnal LLJ, which itself may develop independently from the vortex, is likely crucial in sustaining convection.

The mechanism(s) by which convection is retriggered within MCVs may also relate to whether they will intensify or weaken the vortex. Trier et al. (2000a) noted that the longest-lived MCV episodes during the 1998 season were each associated with successive MCS activity, however there were numerous other cases where secondary convection coincided with the cessation of the MCV. Mechanisms that focus convection near the center of the preexisting vortex or enable MCS organization that is likely to spawn a new vortex are anticipated to best promote multi-day MCV episodes.

2.2.3 Summary of Scientific Objectives

1. Document the development of MCVs within organized mesoscale convective systems
   - Determine the factors responsible for the strength of MCVs.
   - Relate environmental vertical shear and thermodynamic stability to MCV evolution.
   - Relate MCS internal structure (e.g., cold-pool strength, warm plume aloft, mesoscale horizontal and vertical motion fields) to MCV evolution.
   - Determine the conditions under which MCVs persist beyond the decay of the parent convective system.

2. Document the redevelopment of convection or the lack thereof within MCV cases.
   - Determine mesoscale (vortex-induced) vertical motion and its relationship to the evolution of thermodynamic structure in the vicinity of MCV and convective redevelopment.
   - Determine influences of the diurnal cycle on the evolution of the thermodynamic and kinematic structure within the MCV environment and how such influences pertain to redevelopment of convection within MCVs.
   - Identify and measure PBL forcings and their relationship to convective redevelopment.
3. Determine the feedback of convective redevelopment on the lifecycle of MCVs.
   - Determine the sensitivity of the location of convective retriggering to MCV evolution.
   - Determine the extent to which long-lived MCV episodes consist of single vortex or vortex redevelopments associated with successive MCSs.
   - Document the evolution of an MCV in the absence of secondary convection.
4. Assess predictability of MCV formation, maintenance and attendant precipitation.

3. Observations to Address Science Objectives

3.1 INSTRUMENTATION AND OBJECTIVES

Because of the scale of the convective systems under study in BAMEX (~50-300 km diameter) relative to the spacing of operational WSR-88D radars, and our desire to map the 3- dimensional kinematic and thermodynamic structures of bow-echoes and (MCVs), nearly all experiment-specific data must be gathered by aircraft (in particular airborne Doppler and dropsonde equipped aircraft) and ground-based mobile facilities. The novelty of BAMEX is its system-following strategy by which we will be able to sample individual convective systems at different times in their lifecycle and therefore gain a better perspective of many stages of convective organization. The NWS routine observations (with more frequent rawinsonde launches) will provide the larger scale and background observations to provide the context in which the mobile facility observations will be placed. Table 1 lists the special observational facilities, both airborne and ground- based, that could be available for BAMEX.

Together the ground-based facilities are termed the Ground-Based Observational Facilities (GBOS). The NRL P-3 and jet aircraft will be requested from the NSF deployment pool, the NOAA P-3 through the NOAA flight hour allocation process. During BAMEX all three aircraft will fly simultaneously to sample maturing MCSs, with both the P-3 and NRL P-3 having dual-Doppler capability (Jorgensen et al. 1983) and the dropsonde aircraft flying at higher altitudes, generally to the rear of the leading convection. As demonstrated in Lee and Wakimoto (1997), wherein high-resolution observations of a bow echo by ELDORA are presented, these aircraft can map both mesoscale and convective scale structures within mature convective systems. The platform that will serve as a dropsonde jet has not been formally selected at the time of the writing of this document. However, the leading candidate is a Lear Jet leased by the National Science Foundation.

The SMART-Rs will be most useful for augmenting the aircraft observations in the lower and middle troposphere and for providing boundary-layer data in clear air ahead of MCSs. One radar has already been tested in the Convection and Moisture Experiment (CAMEX). The other is being rebuilt and will be by later in 2002. The observations provided by the mobile sounding systems, a “mobile mesonet” (Rasmussen et al. 1994, Straka et al. 1996), and dropsondes will characterize the thermodynamic environment and assist thermodynamic retrievals that might be computed from radar data.

Facility	PI	Requested s
NOAA P-3 Aircraft	Jorgensen (NSSL)	148
Microphysical probes on P-3	McFarquhar (UIUC)	N/A
MTP on P-3	Heymsfield (NCAR) Mahoney (JPL)	N/A
NRL P-3 Aircraft (ELDORA)	Wakimoto (UCLA) Lee (NCAR)	180
High-Level Jet	Davis (NCAR)	140 hrs/600 dropsondes
Ground-Based Mobile Radar (SMART-Radars – 2)	Biggerstaff (OU)	N/A
University of Alabama/Huntsville Mobile Integrated Profiling System (MIPS)	Knupp (UAH)	N/A
Ground-Based Mobile Sounding System (1-2)	Weisman (NCAR)	150 sondes
Additional Mobile Sounding Systems (4)	Pasken (SLU)	385 sondes
NSSL Mobile Mesonet (4)	Dowell (NCAR)	N/A
ISFF stations	Gallus (Iowa State) et al.	9

Table 3.1 Primary Facilities to be used in BAMEX

The system-following, mobile-platform emphasis of BAMEX maximizes the chances for successfully documenting numerous convective systems. We have proposed to double-crew the P-3 and jet which, when combined with the GBOS, will allow BAMEX to observe the next-day remnant MCV and convective regeneration downstream from the parent convective system. This is a unique opportunity to examine the link between successive convective systems and also sample a variety of convective environments.

As can be seen from Table 3.2, the facilities needed to address the bow echo and MCV scientific objectives are nearly the same, hence the advantage of a combined experiment. We briefly summarize the strategies of the airborne and ground-based observing facilities below. It is highly desirable to coordinate the airborne with the ground-based platforms, but given the rapid motion of the MCSs relative to the ground-based facilities deployment speed, it will not always be practical to make substantial modifications to the aircraft flight tracks or the ground-based facilities deployment depending on the relative positions of each. Therefore a fundamental property of the operations plan will be the stand-alone nature of the aircraft flight and ground-based facility deployment plans.

Objective	Requested Facilities	Existing Facilities
BE-1: Environment	(1) Jet, dropsondes: mesoscale structure (2) NRL P-3, in situ: low-level inflow to system (3) MIPS: shear profile PBL structure	(1) NWS sondes (3-hourly): convective destabilization (2) Rapid Update Cycle: synoptic-scale structure

	(4) Mobile sondes: augment dropsondes (5) Mobile Mesonet: boundary locations	(3) WSR-88D VAD wind profiles: environmental shear
BE-2: Evolution	(1) Jet, dropsondes: thermodynamics in stratiform region (2) P-3, dual-Doppler: system-scale vortices (3) NRL P-3, ELDORA: convective-scale vortices (4) SMART-Rs: convective-scale vortices	WSR-88D, single Doppler: early convection
BE-3a: Severe weather: wind	(1) P-3, dual-Doppler: system-scale vortices and rear inflow (2) SMART-Rs: mid-to-low-level wind mapping (3) MIPS: PBL top inversion, nocturnal PBL stability (4) Mobile mesonet: winds and cold pool strength	(1) WSR-88D, single Doppler: convergence signals (2) Surface Mesonets (OK, IA, KS, MN, AL): wind and temperature data
BE-3b: Severe weather: tornadoes	(1) SMART-Rs: mid-to-low-level wind mapping (2) NRL P-3, ELDORA: low-level winds (3) Mobile mesonet: boundary locations	WSR-88D, single Doppler: mesocyclone signatures
MCV-1: Evolution and strength	(1) Jet, dropsondes: thermodynamics in stratiform region (2) P-3, dual-Doppler: system-scale vortices (3) NRL P-3, ELDORA: mesoscale updraft, convection intensity (4) SMART-Rs: 3-D wind mapping (5) Mobile Mesonet: cold pool strength, surface pressure	(1) WSR-88D, single Doppler: reflectivity rotation signals (2) NPN 404 MHz Profilers: mesoscale rotation (3) Rapid Update Cycle: synoptic-scale structure
MCV-2: Induced destabilization	(1) Jet, dropsondes: mesoscale structure	(1) NWS sondes (3-hourly): convective destabilization (2) NPN 404 MHz Profilers: vertical wind shear (3) Rapid Update Cycle: synoptic-scale structure (4) WSR-88D: Early convective evolution
MCV-3: MCV redevelopment	(1) Jet, dropsondes, mesoscale structure (2) NRL P-3, in situ, ELDORA: inflow characteristics, leading-line evolution (3) P-3, dual-Doppler: mesoscale vorticity, convective evolution (4) MIPS: shear profile, low-level jet, nocturnal PBL evolution (5) Mobile sondes: augment dropsondes (6) SMART-Rs: 3-D wind mapping	(1) WSR-88D, single Doppler: reflectivity evolution and rotation signals (2) NPN 404 MHz Profilers: low-level jet structure (3) Rapid Update Cycle: low-level jet structure

Table 3.2. Objectives (left), requested platforms and observations to address objectives (center) and observations from existing observational infrastructure (right).

The BAMEX experimental design is particularly well suited for observing system-scale features (scales of tens of km to 100 km). For convective systems 100-200 km in length, we can achieve a temporal resolution of about 15-30 minutes with the aircraft. While inadequate for convective motions, this time resolution is acceptable to resolve the evolution of mesoscale vortices (time scales of the inverse Coriolis parameter, or about 3 hours) and rear-inflow jets (time scales of 1-2 h). The SMART-Rs will augment the Doppler aircraft coverage in the lower and middle troposphere, increasing the temporal resolution relative to the airborne radars due to rapid scanning and enhancing the ability to derive thermodynamic fields from the winds. Dropsondes from the jet, spaced roughly 50 km apart, will offer an unprecedented sampling of the mesoscale thermodynamic structure and be valuable for constraining the thermodynamic retrievals from the radar data. The total data set will combine the longer time-scale, mesoscale information derived from the aircraft with shorter duration, high frequency measurements derived from MIPS and the SMART-Rs. This combination is important for resolving motions on a range of scales needed to fully address objectives BE-2, BE-3a, MCV1 and MCV3 (see table).

Thermodynamic information is critical for addressing objectives related to the development and descent of rear-inflow jets in bow echoes, quantifying the importance of surface boundaries in the formation of severe convective cells in bow echoes, documenting the structure of mature MCVs, and for interpreting mesoscale lifting mechanisms near MCVs. The mobile mesonet will measure pressure and thermodynamic fields at the surface ahead and behind the convective line. Dropsondes and in situ aircraft measurements will broadly document the vertical extent of the cold pool. The acoustic sounder in MIPS will provide high temporal resolution of the PBL structure at a given point as the MCS passes. These measurements, perhaps aided by modeling studies (Sec. 4) will help us recover the structure of the buoyancy field in the lower troposphere on scales of tens of kilometers. The dropsonde and in situ aircraft thermodynamic measurements will document the structure of MCVs in the lower and middle troposphere on scales of several tens of kilometers as well.

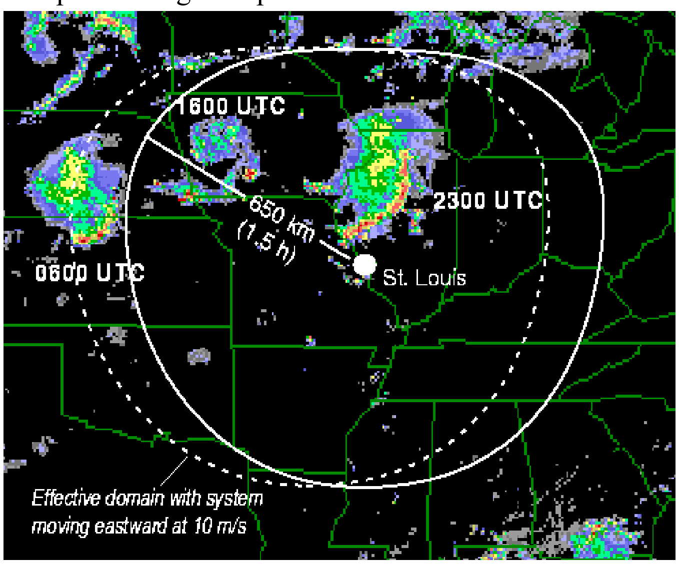


Fig. 3.1 Snapshots of radar reflectivity at three times, composited onto a single map, during the lifecycle of an MCS observed on 23 June, 2000. The times shown, 0600 UTC, 1600 UTC and 2300 UTC, indicate the structure during the first nocturnal mature stage, the remnant vortex stage and the regenerative stage, respectively. The area enclosed by the solid white line is the area that can be sampled by BAMEX aircraft assuming a maximum of a 1.5 h ferry. The region enclosed by the dashed line represents the effective BAMEX area for a system moving eastward at 10 m s^{-1}, the speed of the 23 June case.

With ELDORA scanning the leading convection, and a well-placed GBOS, there is the potential to observe smaller scale aspects of the convective systems, including the dynamics of individual cells. In the latter category would be the merger of cells, often observed before the occurrence of severe surface winds, development of supercell storms along the line and tornado formation. However, because these latter phenomena have intrinsic spatial scales of 10 km or less and evolve on time scales of minutes to tens of minutes, there is a significantly smaller probability of capturing the evolution in sufficient detail to address the science objectives pertaining to cellular evolution. However, because so little is known about the dynamics of cells in this kind of system, even opportunistic success in one or two cases could lead to a major advance for anticipating severe weather from such systems.

We recognize the possibility that the GBOS and aircraft will not always be able to observe the same MCS, primarily due to the smaller effective radius of operations of the GBOS compared to the aircraft. In these cases the GBOS may still sample an MCS, though not the one sampled by aircraft. The GBOS alone will still be able to address a subset of the overall BAMEX objectives, including documenting the PBL structure in severe wind cases, examining the relationship of surface boundaries to the genesis of severe cells and documenting the full 3-D kinematic structure of the system over a period of a few hours. There will also be cases when the aircraft along are observing an MCS. In these cases, mesoscale kinematic and thermodynamic information will still be obtained, addressing objectives BE-1, MCV-2 and aspects of BE-2a, MCV-1 and MCV-3. Thus, while not optimal, a significant subset of BAMEX objectives can still be addressed when the aircraft and GBOS do not sample the same MCS.

3.2 EXPERIMENTAL DESIGN

All weather forecasting and facilities directions will be conducted from the BAMEX Operations Center (BOC) based at the NWS Forecast Office in St. Louis, MO. The choice of St. Louis is motivated by existing climatologies of the combined set of bow echo and MCV occurrences (Figs. 2.4 and 2.8, respectively). Given the airspeed of the various aircraft involved, (roughly 110-120 m s^{-1}) and the desire to have at least 3-4 hours on-station, any convective system within about 600-800 km of St. Louis can be sampled by air. This enables BAMEX aircraft to reach central Kansas and Nebraska to the west, Wisconsin to the north, Ohio to the east and Arkansas and northern Mississippi to the south (Fig. 3.1).

While the coordinator for the ground-based facilities will likely be based at the BOC in St. Louis, MO, the mobile systems will be continuously deployed throughout the intensive operational period. This is a key element to the design of the ground-based component of BAMEX. Since the platforms will not be required to return to a fixed base, they can be repositioned to take advantage of the prevalent weather patterns. This will maximize the opportunity to observe bow echo events without causing undue crew fatigue.

It should be noted that this strategy is designed to allow a somewhat gradual shift in the overall operations area or to move into a favorable regime associated with a large-scale weather pattern. The strategy is not meant to imply that the ground-based observing systems will be able to travel several hundreds of miles each day. Instead, the platforms will focus in an area of approximately 250-mile radius from the previous operations site.

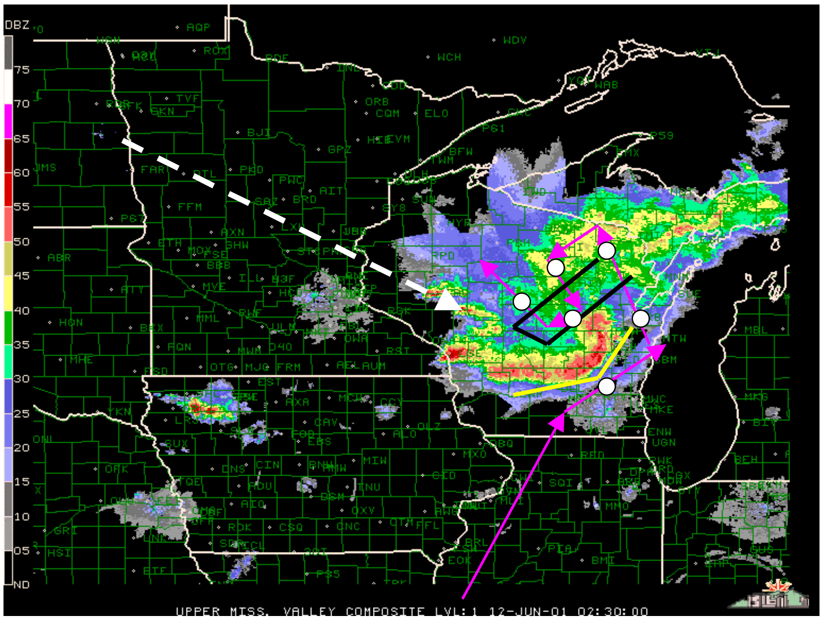
3.2.1 Aircraft

There are 3 basic goals that need to be satisfied by the aircraft in order to address the BAMEX objectives of understanding the development of circulation features (rear-inflow jets, mesocyclones and mesoscale vortices) within mature bow echoes and larger MCSs:

1. Map out flow in stratiform region
    - document the evolution of rotational features
    - document evolution of rear inflow
    - measure buoyancy gradients
    - document vertical structure of system-scale features
2. Document evolution of leading-line convection
    - capture significant cells and rotational features.
    - document convection ahead of MCVs (within 200-300 km).
3. Sample inflow thermodynamics

The primary means of achieving these objectives is the Doppler radars mounted on the NOAA P-3 and NRL P-3 and the dropsondes deployed by the jet. Given the 9-hour endurance of the Doppler aircraft, there should be enough on-station time to complete 3 or 4 of the basic flight patterns over a time period of 5-6 hours. Aircraft will be deployed when it is reasonably certain that incipient convection will organize into an MCS. The emphasis of BAMEX is therefore on the organizing, mature and decaying stages of MCSs, with a de-emphasis on convective initiation. To maximize the fraction of the MCS lifecycle sampled, we will typically stagger the deployment of the P-3s to observe deep convection as it organizes (see below).

MCV-producing MCSs typically reach maturity in the Midwest U.S around midnight. Therefore, a typical aircraft operation would involve a takeoff in the early evening (~9 pm local time) and returning near daybreak (~6 am). Bow echoes tend to mature in the late afternoon and evening, implying a somewhat earlier takeoff and return. For both types of MCSs, it is desirable to have the NRL P-3, equipped with ELDORA, observe the convective storms comprising the organizing MCS due to its enhanced data spacing over the Doppler radar mounted on the P-3. In the mature stage when convection as well as circulations within the trailing stratiform regions are developing both aircraft should be employed due to the extensive attenuation of X-band radar that occurs when looking through the leading convective line. During the dissipation stage when convective is weakening extensive mesoscale observations are still required in the stratiform region to document the development of vortices. These requirements justify the temporal staggering of Doppler-equipped aircraft takeoffs and the possible double-crewing of the dropsonde jet in order to achieve the goal of MCS life-cycle observations.



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2001. Magenta arrowed lines indicate hypothetical track of the dropsonde aircraft; white circles indicate dropsonde locations; black line segments represent the track of the NOAA P-3 and yellow line segments represent track of the NRL P-3 with ELDORA. The thick white dashed and arrowed line indicates approximate track of the centroid of the convective system during the past 6-8 h.

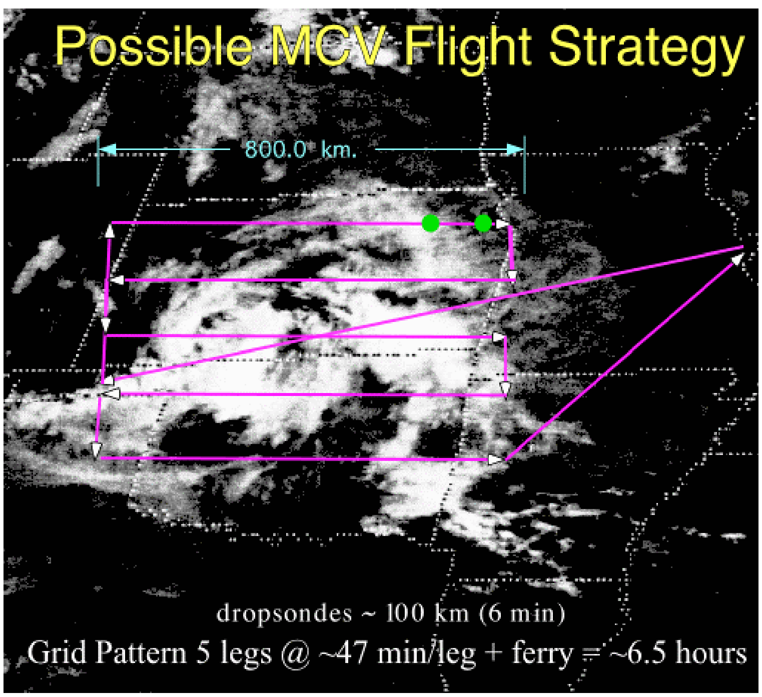
A schematic illustration of an "ideal" BAMEX flight operation involving all three aircraft during the mature MCS phase is shown in Fig. 3.2. The most efficient strategy will be to use the P-3s on either side of the leading line convection of the bow-echo system in order to map the complete circulation near the leading line and rearward into the stratiform region. The aircraft "ahead" of the line (NRL P-3) would sample the inflow air near the top of the boundary layer and document the evolution of the leading line convection. Because of expected severe radar beam attenuation at X-band the ELDORA radar would not probe very far to the rear of the convective line. The NOAA P-3, being behind the line, would fly a staggered pattern (relative to the moving line) to map the air motions up to 80 km to the rear of the line. Together, the P-3s will provide 3-dimensional air motion and reflectivity observations over the domain of the precipitation region of the system, emphasizing the system-scale structure and evolution.

The flight paths for the "trailing" Doppler aircraft and the dropsonde aircraft will likely extend beyond the periphery of the MCS precipitation shield, especially in the case of MCVs. In all likelihood, less than half of the MCV circulation is embedded within a precipitation region, especially during the dissipation stages of an MCS. Thus, flight legs for these aircraft will range from 50 km in the case of small bow echoes to 300 km for large MCVs. The dropsonde aircraft will probe the area behind the convective line, taking in-situ measurements around 30,000 to 45,000 feet and dropping sondes to help document the thermodynamic structure of the stratiform region. To date, there have been almost no thermodynamic measurements of this region of MCSs.

We plan to lag the takeoff of the NRL P-3 with respect to the deployment of the NOAA P-3 by 2-3 hours. This would maximize the total time spent sampling a convective system while allowing significant overlap (depending on the ferry time). For the situation of an MCS forecasted to be at the extreme ferry range a 3 hour stagger would yield a 3 hour overlap of the Doppler aircraft and an overall observation period of over 10 hours with at least one Doppler aircraft. A much closer MCS would produce a longer period of life-cycle observation with at least one aircraft, or a longer overlap period.

A somewhat different set of measurements is needed to document the scientific objectives related to the structure and evolution of MCVs that persist beyond the decay of their parent convection. Often these MCVs feature visible rotation in satellite animations by late morning after the cirrus associated with the previous night's MCS dissipates. On many occasions, new convection will form within or on the periphery of the MCV circulation by late afternoon. This convection may lead to a reintensification of the vortex if it becomes organized into another MCS during the evening.

Pertaining to MCV objectives 2 and 3 (Sec. 2), the most important aircraft for this phase is the dropsonde jet and the most important portions of the GBOS will be those measuring low-level winds and thermodynamic properties of the boundary layer and lower troposphere. The dropsondes will be critical for documenting the structure of the MCV, including identifying regions of horizontal temperature advection, which are likely associated with mesoscale vertical motion (on the scale of the MCV itself). The dropsondes and surface soundings will also be examined for evidence of lapse-rate changes above the boundary layer induced by the MCV.



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A possible flight track of the dropsonde aircraft used to sample the structure of a mature MCV with scattered convection around it is shown in Fig. 3.3. While the green dots indicate the minimum dropsonde spacing, the actual spacing will vary spatially. Note that the dropsonde aircraft will probably have a greater maximum airspeed than either the NRL P-3 or P-3 and hence a greater range. To obtain an in-situ mapping of the low-level winds, one of the two Doppler aircraft will be used to fly near and below the level of maximum MCV intensity. The flight pattern will qualitatively resemble that in Fig 3.2, but the flight legs will be more restricted owing for the need to sample more than a single altitude. These flight tracks may closely resemble those for incipient tropical cyclones.

To the extent that convective activity is minimal near the MCV in the early and mid-afternoon, we will delay the deployment of the Doppler aircraft relative to the jet. Some temporal overlap with the jet is necessary, but it will be equally important to map out developing convection which will tend to occur later in the jet's mission or after its mission is completed. In some cases the new convection will not organize extensively, probably dissipating near sunset. In these instances, the mission of the Doppler aircraft will be brief. However, it is still important to document cases where the new convection fails to organize to better understand the critical factors involved.

In cases where it is apparent that convection is becoming more organized near the MCV, we will deploy both Doppler aircraft to document the convective evolution and the induced changes in intensity of the MCV. This would primarily be an evening mission with a general flight strategy similar to that shown in Fig. 3.2. Exceptions might be a slightly larger area of coverage for the trailing Doppler aircraft and a reduced role of the dropsonde aircraft because we will likely be approaching the limit of its flight duration as the new convection matures.

3.2 Ground-based Measurements

For mature MCSs, the GBOS will be used to:

1. Provide three-dimensional wind mapping of convective systems with emphasis on the middle-to-lower troposphere.
2. Sample boundary-layer evolution during nocturnal wind events.
3. Provide in-situ measurements of near-surface temperature, pressure and wind ahead of and within mature MCSs.
4. Document, monitor and map the structure of boundaries.
    - measure properties prior to approach of convection.
    - relate severe weather to the presence of boundaries.
    - reconcile lower-tropospheric destabilization and boundary layer forcing.

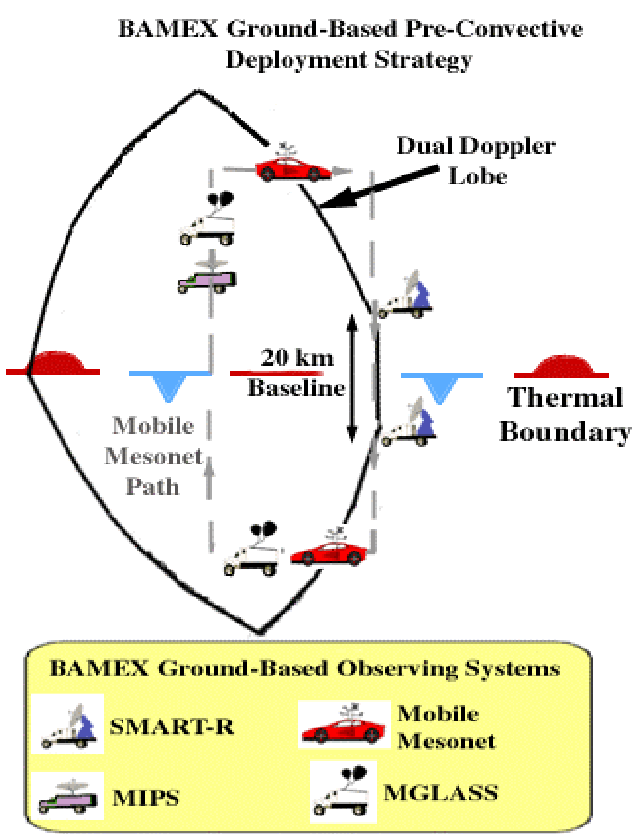

Fig. 3.4a Schematic GBOS deployment for

The GBOS experimental design is well suited for meeting the severe wind precursor objectives. The MIPS, mobile mesonets and the MGLASS units will allow measurement of the downdraft potential energy. These measurements will be coupled with modeling studies to address the relative contribution of thermodynamic and dynamic forcing in transporting damaging winds to the surface. Together with the Doppler derived winds, we will be able to evaluate the strength and depth of mid-level convergence relative to low-level stability. This will serve as a test to determine if the mid-altitude radial convergence (MARC) signature (Schmocker et al. 1996) warning threshold needs to be a function of the low level stability and whether or not the routine operational observations are sufficient for estimating the static stability ahead of mature bow echo storm systems. Direct measurements of near-surface winds can help verify and quantify the relationship of MARC and other precursors to severe wind occurrence such as Line Echo Wave Patterns (LEWPs, Nolen 1959).

In the presence of thermodynamic boundaries, the deployment of the ground-based instrumentation is designed to examine the strength of the boundary and the vertical structure of the boundary layer. The MIPS will provide continuous profiles of the winds and depth of the boundary layer on the cool side where the low-level static stability is most likely to alter the strength and distribution of severe winds in the case of bow echoes. Thermodynamic contrast across the boundary will be monitored and balloon launches every 90 minutes will capture the environment ahead of an approaching system. Without storms present, the two Doppler radars operate in clear-air mode along a short baseline to study the structure and evolution of the low-level thermal boundary (Fig. 3.4a).

If storms are present, the systems will be deployed on the scale shown in Fig. 3.4b. In this latter configuration, the Doppler radars are 30-40 km apart to provide a larger region of coverage. Much of the relevant storm dynamics are tied to the mid-to-low-level flow. Aircraft wind retrievals are often limited at low levels by ground clutter contamination and beam geometry. Assuming that the aircraft are present, the GBOS radars will focus strictly on obtaining detailed mid-to-low level winds. If the aircraft are unavailable, the radars will periodically sample the full depth of the storm system. In both situations, particular emphasis will be placed on documenting the variability and evolution in convective cell structure and mesoscale flows from just south of the bow to well north of the bow. By sampling cells on both sides of any existing boundary, we will be able to address the influence of the boundary on the structure and intensity of convection within bow echoes. Because the effective range of the C-band SMART-Rs is greater than the X-band airborne Doppler radars, there is a better chance that the SMART-Rs can sample mesoscale flow structure along the rear of the convective line as well.

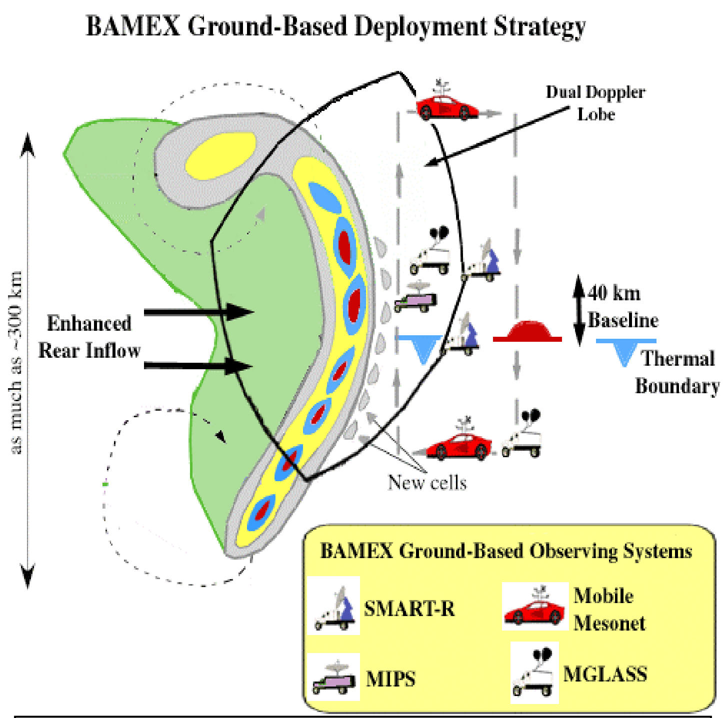

Fig. 3.3b Schematic GBOS deployment for boundary studies during storm passage.

As the storm passes, the GBOS will remain stationary and continue sampling the storm structure from a position behind the leading convective line. The SMART-Rs will be pointed to scan the retreating storm and continue to map the storm structure. The MIPS will continue scanning in the stratiform region. Assuming surface conditions are not too adverse, mobile soundings will be launched to augment dropsondes. Finally, the mobile mesonet will document the pressure, wind and temperature within the cold pool.

4. Simulations

BAMEX has important objectives that involve the predictability of bow echoes and MCVs (sec. 2). These objectives are best addressed through numerical simulations. In general, both idealized and real-case simulations will be performed in a research mode. In addition, important insights about the predictability of these convective systems will be obtained from near-real-time simulations.

The rapid advancement in computational power during the past decade has created a situation wherein numerical models are now able to simulate atmospheric phenomena with resolutions much higher than our current ability to observe them. As a result, numerical model simulations have provided much information about mesoscale and cloud-scale processes and, therefore, have been instrumental in creating the foundations for many of our theories on how mesoscale weather systems develop and organize. In order to verify the fidelity of the numerical models and, by extension, our hypotheses and conceptual models, there is now a great need to conduct special observing programs to provide observations with resolutions equivalent to or better than that of our numerical models. This is especially true for convective weather systems wherein the available evidence indicates that these systems are influenced significantly by scales ranging from synoptic to microphysical.

There are numerous research groups that will participate in numerical simulations and data assimilation experiments, Colorado State University (M. Montgomery, P. Reasor), Texas A&M University (F. Zhang), NSSL (Trapp, Stensrud), NCAR (Weisman, Trier), Penn State (Bryan, Fritsch), and the University of Wisconsin, Milwaukee (P. Roebber). The objectives of these experiments are:

(1) To evaluate the ability of current high-resolution numerical models to accurately reproduce the cloud-scale and mesoscale thermodynamic, kinematic, microphysical, and dynamical structures associated with moist convection.

(2) To isolate the processes that play significant roles in determining the structure and evolution of convective events.

(3) To assess model sensitivity to variations in the type and resolution of the observations. Convective initiation may be strongly influenced by small-scale features such as boundaries, mid-level short waves, and local regions of favorable humidity, stability, or wind shear. The dropsondes collected during BAMEX will be used with current model initialization procedures to examine the impact of high-resolution observations on cloud-scale and mesoscale model forecasts.

(4) To supplement the BAMEX observational database. Temperature, and moisture measurements from dropsondes will have much lower spatial resolution than that of Doppler-radar-derived wind fields. Therefore, numerical models, via their governing system of equations, can provide meaningful estimates of the thermodynamic and moisture fields in data-sparse regions. Such dynamically-consistent interpolations may be crucial for understanding BAMEX cases. Furthermore, model simulations can provide estimates of terms that are difficult to measure with the observed data sets (such as, for example, the solenoidal term in the vorticity budget).

(5) To assess the predictability of MCSs and MCVs using operational NWP models with variational data assimilation (both three- and four-dimensional). Run in research mode, models such as Eta and the Weather Research and Forecast model (WRF) can be used to assess optimal strategies for observing convective systems and assimilating observations to improve the 6-24 hour prediction. With high-resolution models and state-of-the-art data assimilation, estimates of the practical limits of predictability of MCSs may be obtained.

5. Summary

BAMEX is a study using highly mobile platforms to examine the life cycles of mesoscale convective systems. It represents a combination of two related programs to investigate (a) bow echoes, principally those which produce damaging surface winds and last at least 4 hours and (b) larger convective systems which produce long lived mesoscale convective vortices (MCVs). MCVs can focus new convection and play a key role in multi-day convective events affecting a swath sometimes more than 1000 km in length with heavy to perhaps flooding rains. The main objectives regarding bow echoes are to understand and improve prediction of the mesoscale and cell-scale processes that produce severe winds. For MCV producing systems the objectives are to understand MCV formation within MCSs, the role of MCVs in initiating and modulating convection, the feedback of convection onto MCV intensity, and to improve the overall predictability of the vortex-convection coupled system.

We propose to use three aircraft, two equipped with dual Doppler radar capability, the third equipped with dropsondes, to map the mesoscale evolution of long-lived MCSs including the development of mesoscale vortices and rear-inflow jets. Dropsondes will be used to document environmental structure, thermodynamic structure of the stratiform region (where rear-inflow jets and MCVs reside) and to capture the structure of mature MCVs in the absence of convection. In addition, a mobile array of ground-based instruments will be used to augment airborne radar coverage, document the thermodynamic structure of the PBL, including any existing convergence boundaries, probe the surface cold pool, and measure surface horizontal pressure and wind variations behind the leading convective line. The combination of aircraft and ground-based measurements is important for understanding the coupling between boundary-layer and free-tropospheric circulations within MCSs, and, in particular, how the rear-inflow penetrates to the surface in nocturnal severe wind cases.

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Appendix: List of Participants

Participant	Affiliation	Research Area
Nolan Atkins	Lyndon State College, Lyndonville, Vermont	Radar analysis and simulations of tornadogenesis within bow echoes
Michael Biggerstaff	University of Oklahoma, Norman, Oklahoma	Mobile Doppler radar observations; convective evolution
Lance Bosart	The University at Albany, SUNY, New York	Mesoscale aspects of severe convection
George Bryan	The Pennsylvania State University, State College, Pennsylvania	Numerical modeling of MCSs at cloud-resolving resolution
Michael Coniglio	University of Oklahoma, Norman, Oklahoma	Numerical modeling and mesoscale observations of severe bow echoes
Christopher Davis	NCAR, Boulder, Colorado	Dropsonde analysis; MCS lifecycles and MCV dynamics
David Dowell	NSSL, Norman, Oklahoma	MCV Observations
Jeffery Evans	Storm Prediction Center, Norman, Oklahoma	Prediction of severe bow echoes
J. Michael Fritsch	The Pennsylvania State University, State College, Pennsylvania	Lifecycles of MCSs
William Gallus	Iowa State University	Surface observations, MCS predictability
Brian Jewett	University of Illinois, Champaign-Urbana, Illinois	Mesoscale gravity waves and wake lows with mature MCSs
Robert Johns	Storm Prediction Center, Norman, Oklahoma	Prediction of severe bow echoes
Richard Johnson	Colorado State University, Fort Collins, Colorado	MCS morphology and evolution
David Jorgensen	NSSL, Boulder, Colorado	Airborne Doppler radar; MCS structure and evolution
Brian Klimowski	NWFSO, Rapid City, South Dakota	Bow Echo morphology and severe weather
Jason Knievel	NCAR, Boulder, Colorado	MCV dynamics and related convection
Kevin Knupp	University of Alabama, Huntsville, Alabama	Boundary layer profiling; high time-resolution observations of convection
Wen-Chau Lee	NCAR, Boulder, Colorado	Airborne Doppler radar; MCS structure and evolution
Gregory McFarquhar	University of Illinois, Champaign-Urbana, Illinois	Microphysics of stratiform regions

Michael Montgomery	Colorado State University, Fort Collins Colorado	Dynamics of vortices and convection
Matthew Parker	University of Nebraska, Lincoln, Nebraska	MCVs in non-classical MCSs
Robert Pasken	St. Louis University, St. Louis, Missouri	Soundings in and near MCSs; MCS evolution
Paul Reasor	Colorado State University, Fort Collins Colorado	Dynamics of vortices and convection
Ron Przybylinski	NWFSO, St. Louis, Missouri	Precursors to severe weather in bow echoes
Mohan Ramamurthy	University of Illinois, Champaign-Urbana, Illinois	Mesoscale gravity waves and wake lows with mature MCSs
Bob Rauber	University of Illinois, Champaign-Urbana, Illinois	Mesoscale gravity waves and wake lows with mature MCSs
Paul Roebber	University of Wisconsin, Milwaukee	Prediction of MCSs; ensemble forecasting
Gary Schmocker	NWFSO, St. Louis, Missouri	Precursors to severe weather in bow echoes
David Stensrud	NSSL, Norman, Oklahoma	Predictability of MCSs and MCVs
Dennis Todey	Iowa State University	Surface observations in MCSs
Edward Tollerud	NOAA Forecast Systems Laboratory, Boulder, Colorado	Potential vorticity streamers and MCSs
Jeffrey Trapp	NSSL, Boulder, Colorado	Tornadogenesis; severe winds in bow echoes
Stanley Trier	NCAR, Boulder, Colorado	Analysis and simulation of MCV producing MCSs
Roger Wakimoto	UCLA, Los Angeles, California	Mechanisms of severe weather production in bow echoes; damage surveys
Morris Weisman	NCAR, Boulder, Colorado	Kinematic structure and severe weather production in bow echoes
Ray Wolf	NWSFO, Davenport, Iowa	Tornadogenesis within bow echoes
Conrad Ziegler	NSSL, Norman, Oklahoma	Kinematic structure and severe weather production in bow echoes
Fuqing Zhang	Texas A&M University, College Station, Texas	Variational assimilation of dropsonde and Doppler radar data