FP5J.2

AN AIRBORNE DUAL-DOPPLER BACK-TRAJECTORY STUDY OF DOWNDRAFTS IN BOW-ECHOES DURING BAMEX

William C. Straka III^{+}, William R. Cotton*, and Ray McAnelly
Colorado State University, Fort Collins, Colorado
$^{+}$ Current affiliation: Space Science and Engineering Center, University of Wisconsin at Madison, Madison, WI

1. INTRODUCTION

Mesoscale convective systems (MCSs) have been observed to often produce severe windstorms, which can pose a significant hazard to life and property. These windstorms often occur in much of the United States during the spring and summer months, coincidentally the same time that most MCSs occur in the mid-west. Johns and Hirt (1987) defined the long-lived, large scale convectively produced windstorms, called derechos, basing their criteria on data available from the National Climatic Data Center (NCDC) and the National Severe Storms Forecast Center (the predecessor to the Storm Prediction Center; SPC). Johns and Hirt (1987) defined derecho events to be associated with an extratropical MCS that produces a "family of downburst clusters" (Fujita and Wakimoto, 1981). Based on the criteria of Johns and Hirt (1987), the geographical distribution of the 70 warm season events they observed suggest that most warm season derechos occur in a region from the upper Midwest to the Ohio valley and are relatively infrequent in other locations (Figure 1). It is thought that most derechos are manifestations of "bow-echoes," a type of MCS first described by Fujita (1978). These storms are easily identifiable by their bow-like shape of intense reflectivity, as observed by weather radars. Bow-echoes have been observed to be from tens to hundreds of kilometers in horizontal extent (Klimowski *et al.* 2003). They can be separate storms or be imbedded in larger squall lines and typically last several hours.

Bow-echoes have several key kinematic features including the strong leading line updraft, followed by an intense downdraft and cold divergent outflow at the surface. This divergent outflow has been shown to be accompanied by a strong rear inflow and a weak reflectivity "notch" behind the apex of the bow (Burgess and Smull 1993; Przbylinski 1995). In addition, there is both a cyclonic and a weaker anticyclonic rotation at the northern and southern ends of the bow, respectively. These vortexes are generally referred to as "bookend" or "line end" vortices (Weisman 1993) and are typically observed in the low to middle troposphere. In addition to the association between bow echoes and strong straight line winds, they also have been associated with the formation of tornados (e. g. Fujita 1978; Forbes and Walkimoto 1983; Przbylinski 1995)

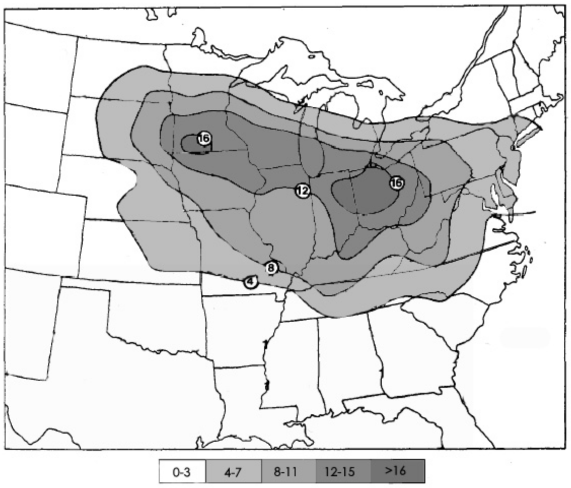

Figure 1. Total number of derechos in a 2^{o} x 2^{o} squares during May through August 1980-1981. Interpreted from Johns and Hirt (1987).

There have been few precursors to damaging winds documented by Doppler radars. A few that have been observed include: A midaltitude radial convergence (MARC) near the forward flank of the convective line preceding the bowing in the reflectivity field (Schmocker *et al*. 1996), and observations that derechos seemed to be due to high-precipitation (HP) supercells embedded in the convective line (Miller and Johns 2000).

There are many different theories as to the origins of the severe straight-line winds. The most well known theory on the formation of derechos is that they are a result from the acceleration of the surface wind within the pressure gradient caused by the mesohigh in the surface cold pool. This cold pool is dependant on the strength and structure of the rear-inflow jet. (e.g. Smull and Houze 1987). The rear-inflow jet, which is linked to the rear flow downdraft (RFD), entrains relatively dry midlevel air, which, along with the microphysical composition of the stratiform region, enhances the evaporative effects of the mesoscale downdrafts. An alternative theory, suggested by the simulations of Bernardet and Cotton (1998) and Trapp and Weisman (2003) is that derechos are a result of meso-γ-scale vortices. Trapp and Weisman (2003) contend that the meso- γ-scale

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**Corresponding author address:* Prof. W.R. Cotton, Colorado State Univ., Dept. of Atmospheric Science, Ft. Collins, CO 80523-1371; FAX: 970-491-8449; e-mail: cotton@atmos.colostate.edu vortices induce pressure gradients that drive the RFD to the surface whereas Schmidt (1991) and Bernardet and Cotton (1998) found that vertical pressure gradients associated with such vortices draw negatively buoyant air originating at low levels ahead of the squall line which then descends as an "up-down" downdraft.

In this study we analyze ELDORA dual-Doppler data from three case study days during BAMEX (Davis et al., 2004) to determine if the observations support or refute the up-down downdraft hypothesis. Dual-Doppler analysis for two of these cases, the 24 and 10 June, were performed using and interpolation and synthesis programs initially developed by Dr. John Gamache (NOAA, Hurricane Research Division; NOAA/HRD) and modified for improved memory usage by Dr. Hans Verlinde (Dept. of Meteorology, Pennsylvania State University; PSU). The last case study, 5 July, was synthesized using REORDER and CEDRIC from NCAR, and performed by Hanne Murphy and Dr. Roger Walkimoto at the University of California at Los Angeles (UCLA). Both of these programs will be briefly described later in this paper. The dual-Doppler vertical and storm-relative horizontal winds were then used to perform a back-trajectory analysis from the 3 lowest observed downdraft outflow levels (0.5, 1.0 and 1.5 km above ground level, AGL) to the source region of the air assuming steady-state winds for each leg analyzed. In addition, surface data from mesonets is used as an additional source of information to determine the origin of the air.

2. DATA AND METHODOLOGY

The Electra Doppler Radar (ELDORA), mounted on the NRL P-3 aircraft, was flown during BAMEX ahead (east) of the convective line to map the kinematic structure of the leading convective line as well as the rear-inflow immediately behind the line because of its rapid scanning characteristics. The NOAA P-3 was tasked to observe the map the rear (west) part of the convective line. In addition, spiral ascent and descent patterns were occasionally performed to collect vertical microphysical data.

There were three ground-based observing systems (GBOSs): the University of Alabama at Huntsville's (UAH) Mobile Integrated Profiling System (MIPS), three Mobile GPS/Loran Atmospheric Sounding System (MGLASS) units from the National Center for Atmospheric Research (NCAR) and a mobile probe vehicle (Davis *et al.* 2004). Radiosondes were launched from both the MGLASS and MIPS GBOS. The data from these observations were used for this study. In addition, the vast network of WSR-88 radars and state mesonets were employed in gathering data. Finally, detailed damage surveys were performed 1-2 days following a bow-echo. These were done by observations from the air, using small leased aircraft, as well as on the ground.

Two sets of instruments were used in this study. The first instrument is the ELDORA airborne Doppler radar, used to provide data for dual-Doppler analysis. The ELDORA radar is two radar transmitters currently mounted on the tail of NRL P-3 aircraft. The ELDORA makes use of the fact that there are two independent radars, one facing forward and the other aft, scanning continuously on all sides. The radar beams of the ELDORA radar have a separation angle of ~37^o between the beams, which is greater than the minimum separation required for dual-Doppler analysis, which is defined as a separation of greater than 30^o (Ray, 1990; Doviak and Zrnic, 1993). When the ELDORA radar is flying in a straight line, the scan pattern gives a "pseudo-dual-Doppler" field (termed in Jorgensen and DuGranrut, 1991). The ELDORA radar is designed to include three-dimensional resolution of 1-3 km diameter convective cores with higher resolution two-dimensional measurements for fine scale structures such as entrainment, turbulence and stratiform precipitation. For a P-3 aircraft at typical speeds (120 m s^{-1}), the time to cover the maximum range of the ELDORA takes about 15 min., or the time it takes to fly past a 100 km scale storm. During BAMEX, the ELDORA radar operated with a high rotation rate, allowing for dual-Doppler analysis to be done with upwards of 400m horizontal resolution, though this study used a resolution of 500m. Finally, ELDORA is designed so that it can process radar returns from up to five transmitted frequencies on both fore and aft radars. A further description of the ELDORA radar can be found in Hildebrand *et al.* (1996).

The second set of instruments was those that collected pressure, temperature and dew point and wind data from radiosonde and state mesonets. The Joint Office for Scientific Support (JOSS) at the University Corporation for Atmospheric Research (UCAR) compiled these data, along with the ELDORA and NEXRAD Level II radar data. Data from BAMEX are available off the BAMEX Field Catalog (online at http://www.joss.ucar.edu/bamex/catalog/). Using the mesonet and radiosonde data, theta-E, the Equivalent Potential Temperature, was calculated using the method described in Bolton (1980). Theta-E is the temperature that results after all latent heat is released in a parcel of air, brought adiabatically to the 1000 mb level. The mesonet data are a compilation of the Automated Surface Observing System (ASOS) stations as well as state mesonets in the BAMEX region. Data from these surface stations were gathered at one minute intervals. Documentation on the various ASOS and mesonet instruments as well as quality control algorithms for the one minute mesonet data can be found online at the JOSS website (http://www.joss.ucar.edu/data/bamex/docs/bamex_1minSfcComp.html). Documentation for the MGLASS radiosondes and WMI dropsondes as well as their respective quality control algorithms for both can also be found at the JOSS website

(http://www.joss.ucar.edu/data/bamex/docs/readme.bamex_mobile_glass
and
http://www.joss.ucar.edu/data/bamex/docs/readme.bamex_dropsondes.html, respectively)

3. CASE STUDY DESCRIPTION

During BAMEX, there were 18 Intensive Observing Periods (IOPs) and two non-IOP missions that investigated 26 different convective systems. Out of the 18 IOP missions, the NRL P-3 participated in all but one. During BAMEX, 11 bow-echoes were observed, nine of which were observed by aircraft. Radar signatures and damage surveys indicated that four of the nine observed bow-echoes produced severe winds.

Three case studies were selected from the seventeen IOPs in which the NRL P-3 participated. These cases were chosen from among several derecho-like, bow-echo MCS cases that produced extended tracks of severe surface winds and were well observed by the NRL P-3 aircraft's ELDORA Doppler radar. A “derecho-like” event was defined as ones that nearly met the conditions set forth in Johns and Hirt (1987). The days chosen were then compared with Davis et al. (2004) to see which were determined to be “severe” bow echo cases. The three case studies that were chosen occurred the 24 June, 10 June and 5 July 2003. For each of these cases, the ELDORA aircraft was operating and mesonet and radiosonde data were available. Hanne Murphy and Dr. Roger Walkimoto (UCLA) graciously provided three legs of dual-Doppler datasets to perform back trajectory analysis for 5 July. A description of the 5 July case study is the subject of an in-depth two-part case study analysis, currently in preparation (Walkimoto et al. 2005a, 2005b).

4. BACKTRAJECTORY DESCRIPTION

Back-trajectory analyses were used to determine the origin of the air in the downdraft regions and involved several steps to perform. The first step is to retrieve the horizontal and vertical wind from the radial Doppler measurement. This involves cleaning the data and performing a dual-Doppler analysis. The synthesis program used on for the 24 June and 10 June case study matches the dual-Doppler derived winds to the observed Doppler observations while satisfying the anelastic mass continuity equation. The software solves the system of equations, over the three-dimensional domain, in a variational manner, minimizing the error in the constraint equations used to produce the cost function. The cost function is a weighted sum of functionals derived from a least-square fit of the constraint equations. Once the cost function is minimized, a solution is achieved. For this study, 500m grid spacing in both the horizontal and vertical directions was used, slightly longer than the minimum 400m horizontal resolution that was available. Data for the 5 July case were extensively cleaned up and analyzed by Hanne Murphy and Dr. Roger Walkimoto (UCLA), using REORDER and CEDRIC programs, developed by the Mesoscale and Microscale Meteorology (MMM) at NCAR. Documentation on both programs are available on the NCAR/MMM Data Analysis Software (available online http://www.mmm.ucar.edu/pdas/pdas.html).

After the dual-Doppler data are computed, the u and v-storm motion, as determined by visual observations of NEXRAD Level II data, are subtracted from the dual-Doppler wind data to give storm-relative rinds. A simple back-trajectory model is then applied, where the data are held constant in time, since the length of the flight legs are roughly the same amount of time done in the time step. To perform the back trajectory, winds from all three dimensions are necessary. Data from the 8 surrounding grid points are tri-linearly weighted and then a new u, v and w are calculated. These data are then multiplied by the length of each time step to provide the new location. The length of the time step was chosen to be 10 s, as relatively fine resolution was desired for this study. This process was repeated over 100 to 200 timesteps, or roughly 17 to 33 minutes, to see what the parcels were doing over the length of each flight leg.

5. SUMMARY AND CONCLUSIONS

Twelve out of a total of 16 legs flown by the ELDORA on the 24 June 2003 were analyzed for this case study. This produced over 100 back trajectories that could be analyzed. An example of one of these trajectories is shown in Figure 2, taken during the leg at 0424-0433 UTC. As can be seen, parcels released at each of the lowest levels proceeds along a front-to-rear updown downfraft trajectory.

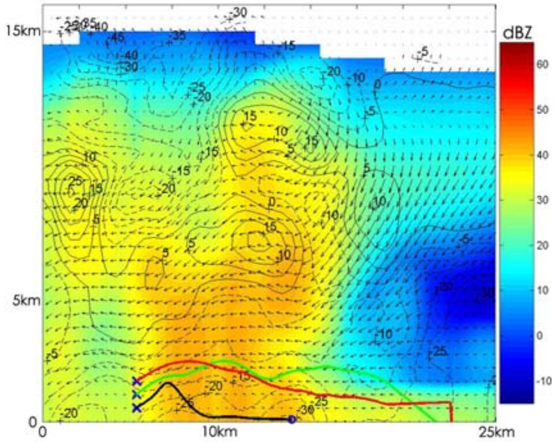

Figure 2. Cross-storm dBZ, along line storm relative and vertical winds, back-trajectory plot for 0424-0433 UTC on 24 June 2003. Contours of cross-line storm-relative winds. Origin located at 32 km N and 14.5 E of 41.95N, -97.05E oriented to the southeast. Axes are km AGL (y) and km along the line (x).

Because of optimum aircraft location, thirteen out of 23 total legs flown by the ELDORA on the 10 June 2003 were analyzed. However, this produced a similar number of back trajectories. In both cases, a majority of the parcels were found to be storm relative, front-to-rear "up-down" downdrafts, coincident with areas of strong to moderate winds at the lowest observed level (0.5 km AGL). One example of one of these trajectories is shown in Figure 3.

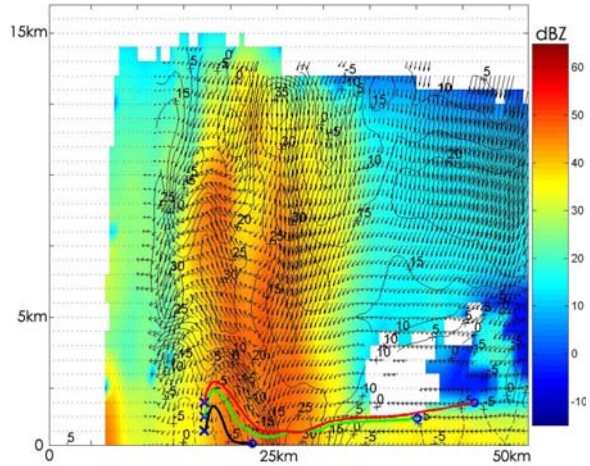

Figure 3. Cross-storm dBZ, along line storm relative and vertical winds, back-trajectory plot for 0850-0911 UTC on 10 June 2003. Contours of cross-line storm-relative winds. Origin located at 42.5 km N and 5 E of 38.85N, -93.57E oriented to the southeast. Axes are km AGL (y) and km along the line (x).

The 5 July case only had three legs provided for analysis, by Hanne Murphy at UCLA. This meant that a smaller number of parcels were analyzed. However, the legs that were analyzed took place during the period of most intense surface winds, as reported by the storm reports provided by the SPC as well as the post-storm damage surveys done by Dr. Roger Walkimoto (UCLA). Back-trajectory analysis based on the data from the 5 July dual-Doppler analysis performed by UCLA indicate that, of the 42 parcels analyzed, roughly 40% were in areas of weak winds. The remaining parcels were collocated in downdraft regions and areas of severe to moderate winds. Those parcels that were in the areas of weak winds were mainly storm relative rear-to-front downdrafts, while the majority of the parcels located in areas of strong to moderate winds were front to rear "up-down" downdrafts.

Further study into the origin of surface air beneath the Doppler-based downdraft regions is being done using the mesonet and sounding data described earlier. Preliminary analysis of the 24 June and 10 June cases suggests that surface theta-e values in the downdraft regions of both cases reflect both relatively high and low values that are consistent, respectively, with origins in relatively low levels ahead of the squall lines and mid-levels behind the lines. These theta-e values are consistent with the surfacing of both the low-level front-to-rear up-down downdraft trajectories and the mid-level rear-to-front downdraft trajectories found in this study.

From the data analyzed in this study, we can conclude that the front-to-rear, "up-down" downdraft is a significant contributor to strong surface winds. Areas attributed to the RFD were in fact areas of storm relative, front-to-rear "up-down" downdrafts. Thus, the observed effect of the RFD is a manifestation of the fact the storm is actually moving. It is, in actuality, the storm moving and drawing upward air in front of the storm that is the probable cause of the derecho events.

Acknowledgements
The authors wish to thank Hanne Murphy and Dr. Roger Walkimoto at UCLA for graciously providing data that they performed extensive cleanup and dual-Doppler analysis of ELDORA data on, so that back-trajectory analysis could be performed for this case study. They wish to thank Steve Williams and Scot Loehrer at JOSS/UCAR for providing the NEXRAD composite imagery in the BAMEX region. They also wish to thank Dr. Kevin Knupp and Dustin Phillips at the UAH for data from three legs on the 24 July for comparison. John Gamache at the HRD/ NOAA is thanked for providing his dual-Doppler interpolation and synthesis program. In addition, they wish to thank Brenda Thompson for preparing and reviewing this manuscript. Finally they wish to thank the people at JOSS/NCAR for their assistance on the dropsonde and radiosonde data. This research was supported by National Science Foundation grants ATM-0324324 and ATM-9900929.

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