

Factors Leading to the Development of the July 4, 1999 Boundary Waters Canoe Area Derecho

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ABSTRACT

On July 4, 1999 an intense and long-lasting derecho passed through the Boundary Waters Canoe Area Wilderness (BWCAW), causing widespread damage, injuring dozens, and many casualties. This storm developed due to interplay between synoptic forcing and mesoscale features which created a highly unstable environment and vertical forcing. In the early morning hours of July 4, 1999, thunderstorm that formed in South Dakota due to a cold front, merged into an MCS and linearly organized into a squall line near Fargo, ND. Near Ely, Minnesota, this squall line encountered highly unstable air, due to abundant low-level moisture and heat, and additional vertical forcing due to the positioning downstream of a shortwave trough and location near the right entrance region of an upper level jet, causing the storm band to accelerate into a bow echo over the Boundary Waters Canoe Area Wilderness. This derecho event can be directly attributed to synoptic and mesoscale features, such as a vorticity max at mid levels, and density current that intensified the squall line's updraft. And a surface front south of the storms development that helped force stable frontal air into the updraft and get drawn passed the level of inhibition and break into the convective available potential energy aloft, before the intensified downdraft lead stable air being held aloft to crash to the surface.

1. Introduction

The Boundary Waters Canoe Area Wilderness (BWCAW) is located in the northeast corner of Minnesota along the Ontario border of Canada. Just after 12:00pm CST on July 4, 1999, a derecho that originated in North Dakota swept through the BWCAW and left a startling amount of damage in its wake. This derecho event, commonly referred to as the “Boundary Waters Blowdown,” occurred due to an interplay of synoptic and mesoscale features creating a highly unstable environment and instigating vertical motion (Parke).

This study strives to identify the major synoptic features that prefaced this particularly severe derecho event, and diagnose the mesoscale components that lead to the storm outbreak, intensification, and progression through the Boundary Waters area. Significant features include

placement above the right entrance region of a 300mb jet, positioning downstream of a mid level shortwave trough, an inversion layer at 700mb, a low level southerly jet, location ahead of a cold front, and pooling low level moisture, (see Figure 1) as well as vertical wind shear, the existence of a density current, and mid-level vorticity (not pictured). While the 500mb shortwave trough suggests supplementary atmospheric interactions forcing this event, it is still primarily characteristic of a progressive derecho.

2. Background

A derecho is a widespread wind event that is characterized by strong straight-line winds of at least 58mph, in association with a squall line, or band of severe thunderstorms, which creates a path of damage that is at least 250 miles in length

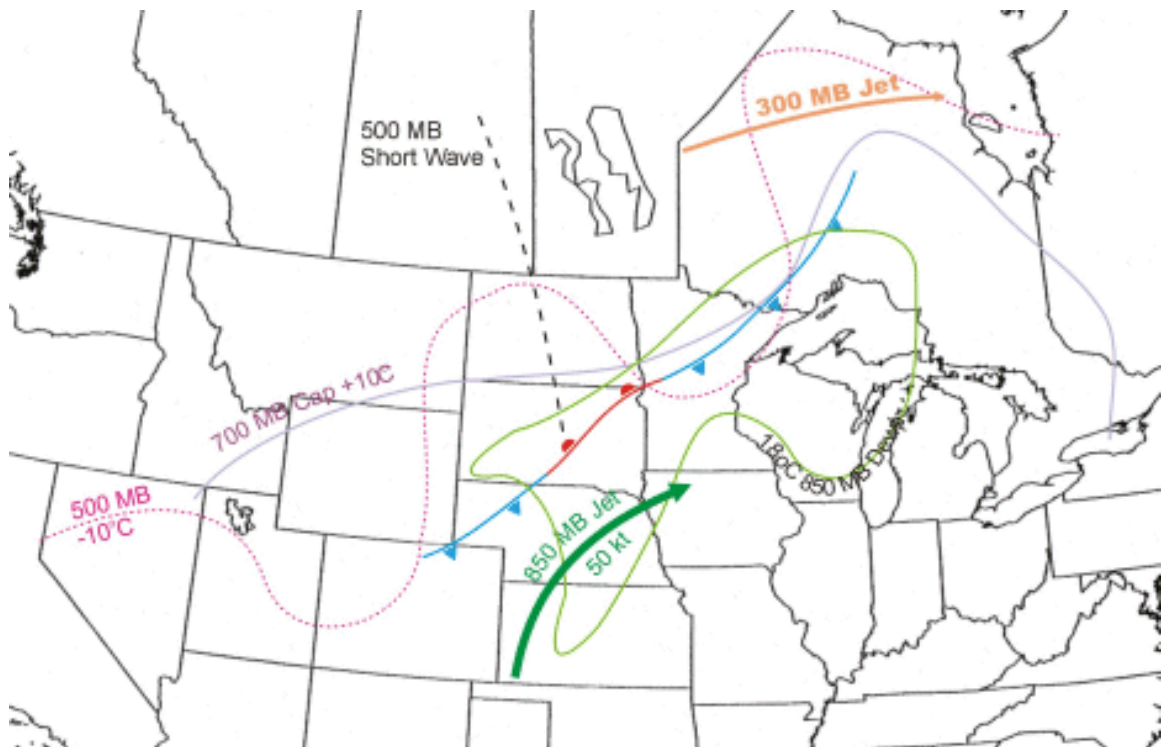


Figure 1: Miller Diagram of mesoscale and synoptic features contributing to the July 4, 1999 Boundary Waters derecho.

(Parke). In a derecho event, clusters of downbursts produce a streak of straight-line winds that have been known to exceed 130mph for sustained periods of time (Johns).

a. Mesoscale Convective Systems

Derechos develop from squall lines as part of a mesoscale convective system (MCS). An MCS is a complex of thunderstorms that merge to form a convective system that is larger than any individual storm (Tripoli 3/28/09). Since MCSs are made of individual t-storms, it is understandable that they would need similar features, such as large CAPE values to form. However, without additional environmental features, such as vertical wind shear, individual storms cannot organize to create an MCS (Cotton).

b. Squall Lines

Squall lines are simply MCSs that organize into a linear band of convective cells that forms along some pre-existing convergence boundary (Tripoli 3/28/09). These convective lines can grow from both groups of thunderstorms and groups of supercells, and generally will propagate in the direction of the mean wind due to the advection of individual convective cells. This motion can also be altered by the formation (or lack thereof) of new cells which are significantly influenced by the favorability of environmental conditions (Mesoscale Convective Systems: Squall Lines and Bow Echoes).

Although squall lines form in a variety of settings, conditionally unstable air and vertical wind shear are important components that affect the formation, strength, and longevity of the storm band. Large convective available potential energy or CAPE values are important since the

release energy if parcels can break through the negatively buoyant areas of convective inhibition, or CIN. Slightly more important than CAPE is the wind shear (discussed in detail later), which effects the strength and positioning of the updraft (Structure and Evolution of Squall Line and Bow Echo Convective Systems).

One of the major features in a squall line is a cold pool, or “density current” that sets up due to the sinking of rain-cooled air from the rear inflow, which can be seen in figure 2 (Tripoli 3/28/09). This density current is created during the preliminary organization of the storm (Sasaki) when convectively cooled air, or air cooled by evaporative cooling by falling through a layer of unsaturated air, as seen in figure 2, reaches the surface and pools. This cold bubble of air establishes an anti-cyclonic rotation and forms an area of surface high pressure known as a “meso-high” (Evans). Without environmental wind shear in a squall line, the meso-high circulation can cause the updraft to lean towards the cold pool. If it becomes too slanted, the updraft will eventually collapse. By adding wind shear, the updraft maintains a more upright position and sustains the system. (Evans)

The cold pool persists long after individual storms die, forming a basis on which additional cells of convection can form (Tripoli 4/28/09). Eventually, this arrangement allows individual density currents to organize into one, and form an effectively two-dimensional squall line event (Tripoli 2/17/09) as is pictured in figure 2. Additionally, density currents support lifting from below that is assisted by a dynamic low aloft to reinforce and strengthen the updrafts (Tripoli 3/28/09) which will be discussed later.

After initial convection occurs, vorticity is generated in mid levels leading to the formation of a dynamic low pressure center which acts to draw air from the

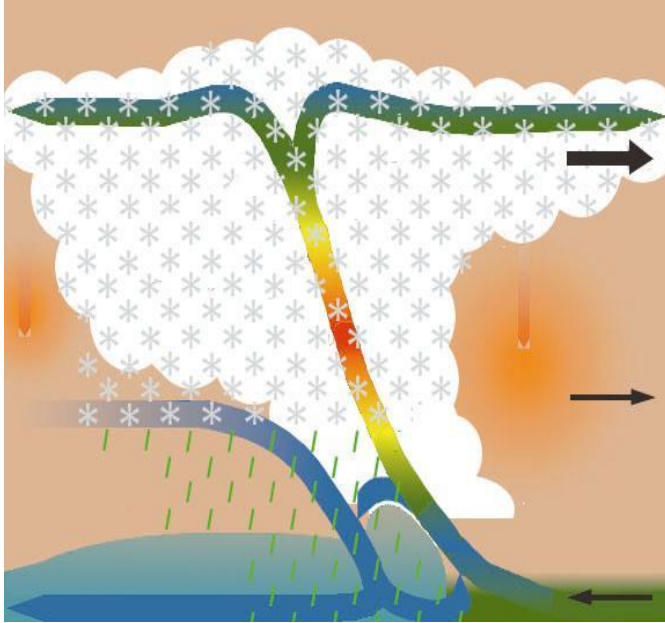


Figure 2: Classic two-dimensional view of a squall line depicting the flow of the two major airstreams within the storm, storm motion, and vertical wind shear. Airflow heading from the rear side of the storm towards the front and then diving downward is the rear inflow jet/downdraft. Airflow heading towards the rear side of the storm and heading upward is the updraft. Cold pool can be seen beneath rear inflow due to evaporation cooling. Note that rear inflow spreads out in all directions upon impact with the surface, part of which feeds back into system through the updraft.

surface upward which intensifies the up-down draft seen between the two major airstreams in figure 2. This vorticity sets up primarily due to the interaction between the mid level zonal flow, and the low level jet. The two opposing motions create a shear line in mid levels (generally around 700mb) along which strong vorticity is generated, causing a pressure gradient and the formation of the dynamic low (Tripoli 3/28/09).

Another component of the squall line is the rear inflow jet. The rear inflow jet is created due to the density difference that exists between the cold, dry air in the outflow, and the warm moist air in the

inflow (Park) and is depicted in figure 2. This air is accelerated towards the surface due to the low pressure that exists at the base of the updraft, and generates horizontal vorticity in the inflowing warm, moist air due to friction with the surface. The spin that is created at the updraft base acts to further accelerate the rear inflow jet forward and downward towards the surface, enhancing the gust front.

c. *Derechos*

In a derecho, the high velocity winds are created from downbursts (strong downdrafts) that are associated with deep convection outflow in a squall line (Evans). The leading edge of the downdraft is known as the “gust front” and separates the cold outflow air in the downdraft from the warm inflow air in the updraft.

Progressive derechos are very similar in structure to squall lines, but with a much more active up-downdraft (see figure 3) (Tripoli 3/28/09). This occurs due to the interaction of the rear inflow jet with the production of mid level vorticity max which enhances and the up-down draft. These events tend to occur north of a stationary front in environments with unstable capped air towards the south in the northern hemisphere. Derecho development occurs when unstable air is advected over the front and into the updraft. Because of the increased dynamic forcing due to the up-downdraft, negatively buoyant frontal air is forced to rise through a large area of CIN marked by strong inversion layers, into areas of high CAPE values (Tripoli 3/28/09). This air is cooled as it is lifted which further increases its stability and negative buoyancy. Dynamic pressure holds this air aloft although it is very negatively buoyant. Eventually, this air will no longer be able to be supported by convective energy or will get shifted out of the updraft (Tripoli

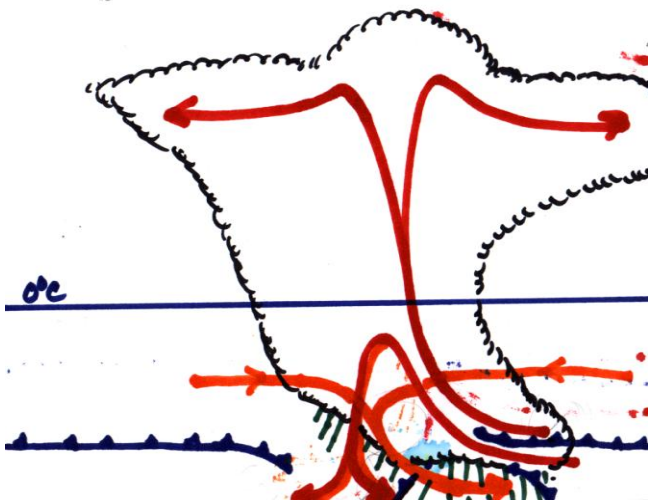


Figure 3: Conceptual model of a progressive derecho. In many ways the progressive derecho structure is very similar to that of a squall line. However the few differences, such as the energized up-down draft lead to a very different kind of storm forming. Cold pool associated with evaporative cooling is still present on precipitating side of cell signified by a cold front symbol, as is a rear inflow jet (orange arrow heading from the rear of the storm to the front), and updraft (red arrows forming the overshooting cloud tops). Note the addition of the surface cold front in this model (signified by a cold front symbol above the gust front) and the intensification of the up-down draft located between the updraft and rear inflow. While warm moist air is able to advect above the surface front and convect high into storm, the up down draft forces air from the rear inflow and stable air from the surface front to be lifted and then forced to the surface.

2/17/09). When this occurs, this cold, dry, highly stable air accelerates downward and the downdraft comes crashing to the surface. The impact causes high velocity winds to spread out at the surface. Interestingly, these downdraft-generated winds also sustain the derecho system (Tripoli 3/28/09) by forcing additional stable air upward and into the updraft (Tripoli 4/28/09).

These events can be observed as a “bow echo” radar signature, or a region

within a squall line that bows out ahead of the band of thunderstorms (Funk). This signature forms due to the accelerated surface winds found during these events.

3. Data

Much of the information gathered for this case study was accessed through the National Weather Service website and the Storm Prediction Center website. Both sources contained general information about derechos, numerous case studies of derecho events, as well as specific facts concerning the July 4, 1999 storm that hit the Boundary Waters. Nearly all of the information in the synoptic and mesoscale discussion specific to the Boundary Waters Blowdown, was gathered from the National Weather Service’s Peter S Park and Norvan J Larson’s paper “Boundary Waters Windstorm - The Blowdown of July 4th, 1999”. Other internet information regarding meso-scale convective systems, (MCS’s), squall lines, derecho events, etc was gathered from the University Corporation for Atmospheric Research (UCAR) website, under the MetEd internet modules, university meteorology websites, meteorologists’ personal webpages, and through the American Meteorological Society online journal articles. In addition to this, an overwhelming amount of information was gathered through the lectures of Professor Greg Tripoli as part of the University of Wisconsin – Madison AOS453 class in the spring of 2009.

Images in this case study were gathered from the sources mentioned above, primarily from Greg Tripoli’s lectures and the Park and Larson paper, as well as data gathered from the 00Z to 18Z ETA forecast model for July 4, 1999, through the use of the programs GEMPAK and GARP. Due to this paper’s focus on the BWCA and the

pre-storm environment, images and analysis presented in this paper in this paper will focus on the 06 hour forecast from the 12Z ETA run on July 4, 1999, which corresponds to 18Z or 12pm local time; just prior to the storm hitting the BWCAW or 12Z forecasts if 18Z is unavailable. Cross-sections are generated from Omaha, NE (OAX) to Pickle Lake, ON (WPL) and horizontal plots were either centered on the Minneapolis/St Paul (MSP) airport in Minnesota, or encompassed the continental United States to show large scale features. Plotted data is displayed in International System (SI) units unless otherwise noted.

4. Synoptic Overview

Synoptically, there were four major components in the pre-storm environment that set the stage for the BWCAW derecho; a strong 300mb jet located on the southern edge of an unseasonably cool pool of air, unusually warm temperatures at 700mb, and a surface front stretching from northern Nebraska, South Dakota, Minnesota and into Ontario.

First, at 300mb a strong jet; with maximum speeds over 130 knots, stretched from southern Saskatchewan east-south-east into Ontario shown in figure 4. This placed the BWCAW in the right entrance region of the jet, an area characterized by surface convergence due to divergence aloft. Moreover, this jet was located on the southern boundary of a pool of very cold air (Park). While the atmosphere below the right entrance region was experiencing rising motion and pulling warmer air from lower levels aloft, the section below the left jet entrance region was experiencing sinking motion and pushing cold, dry air towards the surface. This caused the formation of an intense horizontal temperature gradient at 500mb and a negatively tilted shortwave

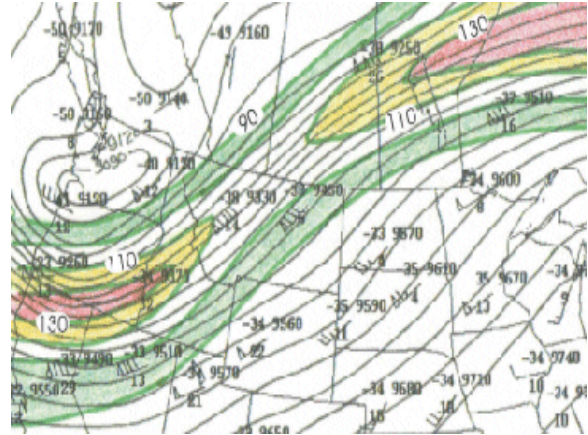


Figure 4: 300mb height in decameters (black) and isotachs in knots (colored) over the BWCAW for 12Z July 4, 1999. BWCAW located in northern Minnesota is located in the right entrance region of the jet, which is characterized by rising motion.

trough, which plays an important role in the mesoscale interaction and will be discussed in depth in section 5 (Park).

Second, abnormally high temperatures at 700mb seen in figure 5 created a capping inversion at 700mb demonstrated in figure 6. This trapped an

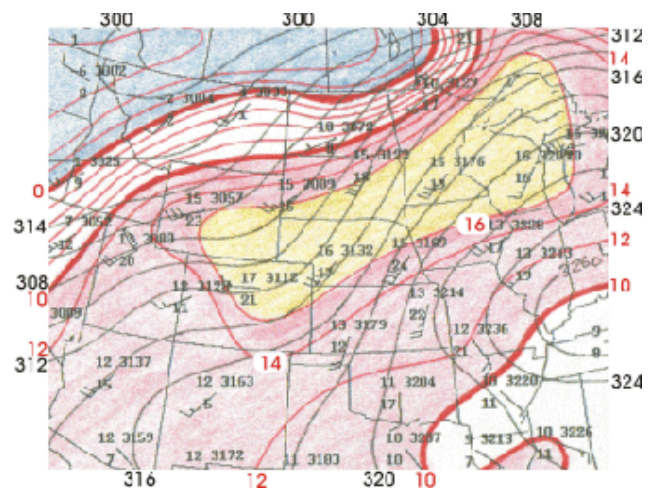


Figure 5: 700mb heights in decameters (black) and temperatures in degrees Celsius (colored) at 12Z, July 4, 1999. Temperature maximum located over eastern portion of BWCAW creating a strong capping inversion. Strong horizontal temperature gradient north of the temperature maximum reflects weaker capping inversions that were present in the vicinity of the BWCAW.

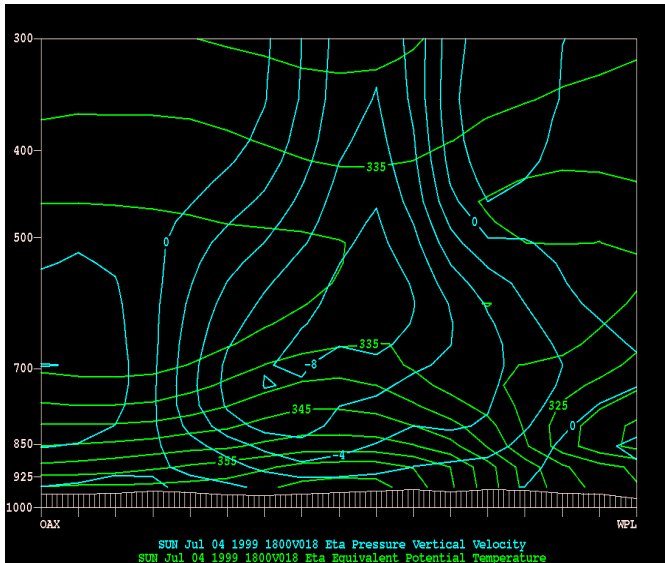


Figure 6: Cross section depicting equivalent potential temperature (green) and vertical motion (blue) at 18Z (just prior to the derecho event) on July 4, 1999 from Omaha, Nebraska to Pickle Lake, Ontario; Boundary Waters area is located in the dead center of cross section. Cross section demonstrates the importance of the 700mb capping inversion that formed over the BWCAW. Capping inversion causes unstable air, indicated by the decrease of theta e with height from the surface to 700mb, to become trapped in lower levels in the absence of ample vertical forcing mechanisms. The equivalent potential temperature assesses the stability of the atmosphere based on temperature and moisture by determining the temperature a parcel would be after releasing all of its latent energy and being brought dry adiabatically down to 1000mb. Higher values of equivalent potential temperature are indicative of unstable warm, moist air, and in a statically stable environment we would expect to see theta e increase with height.

enormous amount of moisture in lower levels, and dramatically decreased the stability of the atmosphere. In fact, as the bow echo moved into this region of excessive lower level moisture, it dramatically intensified before it progressed over the BWCAW where the most severe winds were recorded.

Lastly, the surface cold front that was located near the South Dakota and North Dakota boarder, through Minnesota

and into Ontario, provided a lifting mechanism for the initial storms that formed in lieu of other forcing mechanisms that were present in later portions of the storm. Moreover, after the storm intensified into a bow echo, this surface front fed the updraft with negatively buoyant frontal air as discussed earlier in figure 3.

5. Mesoscale Analysis

The BWCAW derecho was a primarily mesoscale event, and thus a large array of small-scale interactions occurred between the surface and 500mb.

First, as alluded to earlier, vertical lifting and sinking air due to the 300mb jet, lead to the formation of a horizontal temperature gradient, the pooling of cold air, and a negatively tilted shortwave trough at 500mb which can be seen in figure 7.

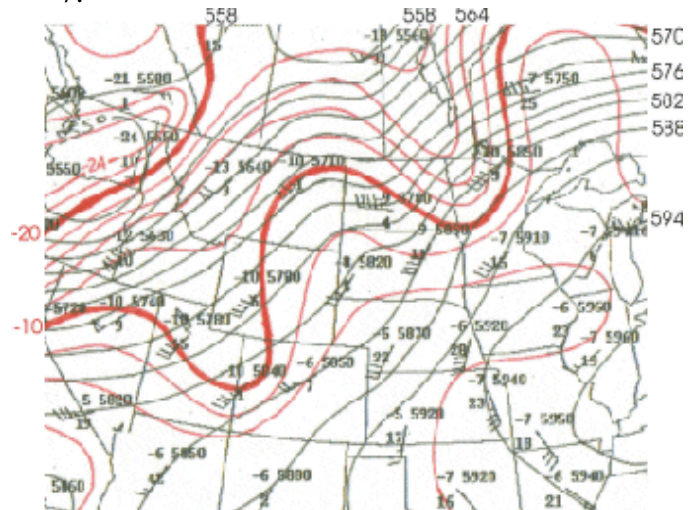


Figure 7: 500mb height contoured in decameters (black) and isotherms in degrees Celsius (red) for 12Z July 4, 1999 depicting a negatively tilted shortwave trough. Isotherms over northern Minnesota and into Canada are oriented perpendicular to height illustrating motion of cold air being forced south towards the BWCAW and pushing these temperatures lower in the atmosphere. Location shortwave trough axes and formation of cold pools at 500mb coincident to location of 300mb jets in figure 4.

This forced the northwest edge of the 700mb cap downward, causing cooling lower in the atmosphere and thermally destabilized the atmosphere. This feature generated curvature vorticity and positive shear vorticity and positive vorticity advection downstream of the trough axis. This rising motion lead to additional rising motion, which, like the right entrance region of the 300mb jet was located directly above the BWCAW during the derecho event (Haby). As this feature developed in the early morning on July 4, 1999, the shortwave deepened, increasing the negative tilt of the axis, and accelerating its propagation. This caused the cold air pool and be pushed towards the Minnesota/Canada border with more force and instigated extra lifting.

Second, a strong low level jet at 850mb seen extended through the central United States stretching from the Gulf of Mexico, into the western coast of Texas, through the central Great Plains and into Minnesota shown in figure 8. Although experiencing a drastic de-intensification right before the blowdown event, less than seven hours prior to the onset of the storm this jet experienced winds in excess of 55kts. This allowed large quantities of warm, moist maritime air to be advected northward from the Gulf and into the BWCAW just prior to the derecho as seen in figure 9. This jet feature is reflected at the surface by a warm tongue of air heading north-west from the Great Plains region. Moreover, the interaction between the advected moisture into lower levels and the 700mb cap can be seen in FIGURE__ . When the cold air supplied by the 500mb shortwave trough reached the boundary of the low level temperature ridge and the trapped low level moisture generated by warm air advection from the 850mb jet at the edge of the 700mb cap, a dramatic destabilization of the atmosphere occurred. As this cold air continued to move with the

shortwave trough along the 700mb cap boundary, rising motion induced from positive vorticity causes large amounts of energy were released and the bow echo accelerated over the BWCAW.

In addition to the mid and lower level features discussed above, a number of surface mesoscale processes occurred to decrease the stability of the atmosphere,

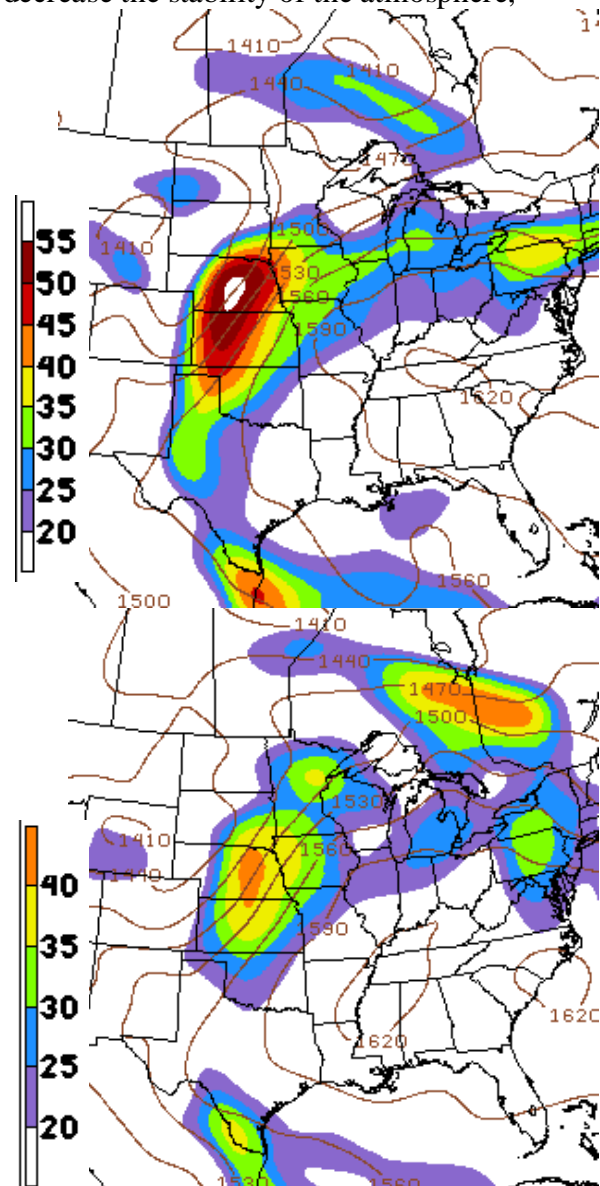


Figure 8: 850mb Jet from 00Z, 4 July 1999(top) and 12Z, 4 July 1999 (bottom). Strong low level jet is seen extending from the Gulf of Mexico through the Great Plains region at and arriving in northern Minnesota by 12Z before derecho event.

enhance squall line strength and sustainability.

As mentioned earlier, the 850mb jet advected warm air towards Minnesota causing a finger of warm air to extend from Colorado to southwest Minnesota and increasing the vertical thermal instability.

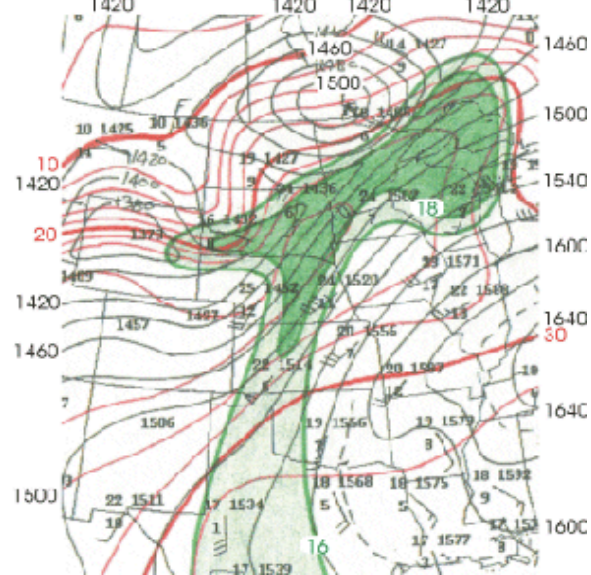


Figure 9: 850mb heights in decameters (black), temperature in degrees Celsius (red) and dewpoint in degrees Celsius (shaded green) on 12Z July 4 1999. Warm moist air was advected into the area due to the 850mb jet extending from the Gulf of Mexico to the BWCA and causing low level destabilization before the derecho

Wind in this area is flowing northwest towards the BWCAW and perpendicular to isotherms indicating warm air advection, while winds in southern Canada, just north of the BWCAW are blowing westerly along a baroclinic zone and nearly parallel to isotherms. This flow pattern illustrates an area of confluence, or a shear line near the Minnesota and Canada border. The opposing flow generates vorticity along this line which

Besides the warm, moist air advected from the Gulf, the BWCAW also experienced increased low level moisture due to evapotranspiration from vegetation seen in figure 10. Two months leading up to the storm, the upper Great Plains and

Midwest regions had near record rainfall and abnormally high temperatures. This created an oasis of well-watered vegetation with a readily available water source.

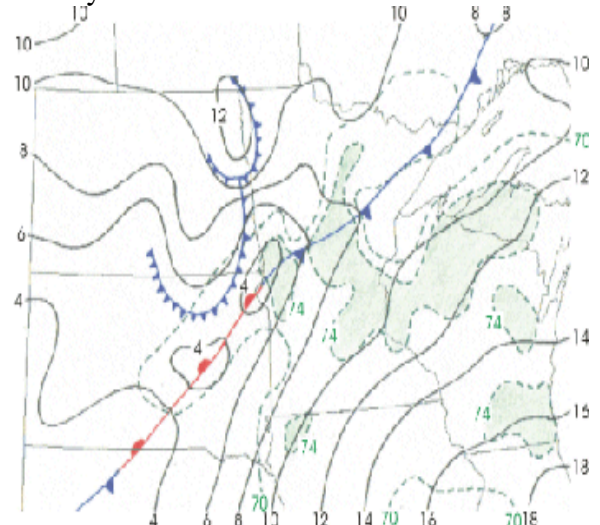


Figure 10: Surface pressure in mb (black), dewpoint temperature in Fahrenheit (dashed green) and surface fronts for 12Z July 4, 1999. High surface dewpoints are seen in a finger extending from the Dakotas and associated with surface evapotranspiration and effects from the 850mb jet.

Reconsidering figure 6, the instability trapped by the 700mb cap can now be attributed to surface evapotranspiration and the 850mb jet advecting moisture and warm air northward

Lastly, within the storm's development, vertical wind shear and high CAPE values are both present as seen in FIGURE SOUNDING. Due to the interaction between these features and the dynamics of derecho events discussed earlier, a convectively induced rear inflow jet developed after the storm intensified into a bow echo causing the high surface winds seen at the surface.

6. Conclusion

The BWCAW derecho, commonly called the "Boundary Waters Blowdown"

was remarkable for many reasons. First, this is one of the only recorded progressive derecho events to have evolved at such a high latitude. Second, in a 22 hour period this storm traveled an incredible 1300 miles with speeds averaging nearly 60mph. Third, this storm caused millions of dollars in damage, destroyed acres of pristine forests turning them into fire wood, and caused hundreds of injuries and a number of casualties as it swept through the United States and Canada (Johns). And fourth, while embodying characteristic progressive derecho features, this storm had a number of additional vertical forcing and instability mechanisms. Synoptic and mesoscale features included the positioning of the BWCAW below the right entrance region of a 300mb jet, location downstream of a mid level shortwave trough, presence of a strong cap at 700mb, a strong 850mb low level southerly jet, situated just ahead of a cold front and pooling low level moisture. In addition, environmental conditions such as vertical wind shea, the organization of a density current, and mid-level vorticity, which played an important role in the formation, intensification, and long life of the storm.

Due to the astonishingly long life of the storm and the amount of damage and bodily harm it left behind, a number of social issues must be considered in addition to the science behind the storm.

First, this storm left a large degree of personal, public and environmental damage in its wake creating an enormous economic burden on communities that were in the storm's path. Besides property damage, a large amount time and resources had to be invested in helicopters and personnel to rescue campers and hikers in the Boundary Waters. Moreover after the event, fallen trees, and other sometimes very large debris hindered transportation and had to be hastily removed from roads, homes etc at great

expense, and lower the attractiveness of this area for campers harming local businesses.

Another issue that must be addressed is the large amount of injuries and the fatalities that occurred in the Boundary Waters Canoe Area due to ineffective communication of the severe weather and the dangers associated with it. With so many people camping, fishing, and hiking in the BWCAW each year it is essential that better communications methods are developed so this many people aren't struck unaware of dangerous approaching weather and given ample time to prepare. Moreover, besides saving lives, this would drastically decrease costs associated with search and rescue missions making this a safety issue and an economic advantage.

Lastly, environmental impacts must be considered due to the large number of trees that were uprooted. Not only did this decimate acres of pristine forest and destroy the habitats of many plants and animals that live in the unique northern environment but also drastically increased the threat of uncontrolled wildfires for years to come.

Acknowledgements.

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