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THE HYBRID HIGH WIND EVENT OF MARCH 7, 2004 IN THE PIEDMONT OF THE WESTERN CAROLINAS

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Abstract

Widespread, damaging winds struck the Piedmont of the western Carolinas on 7 March 2004 as a cold front passed through the region. The intensity of the event was largely unanticipated by forecasters and the numerical guidance. Wind damage due to a tight pressure gradient following the passage of a cold front is typically confined to the higher elevations of the southern Appalachians. However, such wind damage has also occasionally extended into the adjacent Piedmont. Although weak thunderstorms were present around the time of the cold frontal passage on 7 March 2004, they appeared to be largely unrelated to the damaging winds. These rare, but substantial, Piedmont high wind events are herein referred to as "hybrid" events since they appear to be largely due to gradient winds, but with a convective component. Observed and model data were used to examine the processes that may have played a role in the development of the damaging winds. Similar Piedmont high wind cases from 28 March 2000 and 4 February 2002 were also examined and compared in an effort to formulate guidance for forecasting such events in the future.

1. Introduction

The passage of a late winter cold front brought widespread damaging winds to the western Carolinas during the early evening hours of 7 March 2004. The impact upon the region was substantial. A steeple was ripped from atop a church in Hickory, North Carolina (Gilliland 2004). Roofing shingles were peeled from houses in Concord, North Carolina and deposited several blocks downwind (Knox 2004). Blazes started by sparking transformers rapidly spread as grass fires (Cruz 2004). Railroad crossing arms and billboards were torn from their supports (Mackie 2004). Several residents reported near-misses from large tree limbs crashing through roofs into kitchens and bedrooms, and a few homeowners in Salisbury, North Carolina had to saw through trees and limbs to exit their homes (Burchette and Wineka 2004). Power outages were widespread, with over 30,000 people affected in the Charlotte metropolitan area - some for over 24 hours (Crouch 2004). Barns and trailers were blown over by the winds, and an historic church in Gastonia, North Carolina was blown off its foundation (Moore 2004). The air traffic control tower at the Charlotte-Douglas International Airport was evacuated when winds gusted to 55 mph (Horne 2004). Many in Concord, North Carolina remarked that the winds were "worse than when Hurricane Hugo came through town" (Knox 2004). And, most tragically, a Huntersville, North Carolina man was killed by a falling tree limb, and a thirteen year-old boy drowned when his boat overturned on Lake Greenwood in South Carolina (National Weather Service 2004).

The intense nature of the prolonged, damaging winds was largely unanticipated by forecasters and the numerical guidance. For example, the 1200 UTC 7 March 2004 GFS MOS for Hickory, NC (Table 1) predicted sustained winds no greater than 15 knots (highlighted) during the period of damaging winds from 2100 UTC 7 March 2004 to 0300 UTC 8 March 2004. Although weak thunderstorm development may have contributed to localized gusts, much of the damage occurred in locations relatively free of deep convection. Experience has shown that damage produced by winds associated with a strong, synoptic scale pressure gradient (hereafter referred to as gradient winds) following the passage of a cold front is typically confined to the higher elevations of the southern Appalachians. However, such wind damage has, as on this occasion, also been observed in the Piedmont of the western Carolinas.

To investigate this phenomenon, observed and model data available up to 12 hours before the onset of the strongest winds were examined to understand the processes that may have played a role in the development of damaging winds. Two other Piedmont high wind events were also considered at some length in an effort to offer guidance for forecasting similar wind events in the future. It will be shown that these events appear to have the following important features in common: (A) a thermodynamic profile exhibiting a deep, surface-based, dry-adiabatic mixed layer topped by a narrow moist zone, coincident with (B) the arrival of a strong midtropospheric speed maximum, during (C) the onset of significant downward omega in the lower troposphere. Consideration is also given to the role of downwardly buoyant forces in locally enhancing the gradient winds produced by this synoptic setup.

2. Methodology

A search of local office storm event files dating back to 1998 revealed nine events in which wind damage was fairly widespread across the Piedmont of the Western Carolinas, but where little or no deep convection was observed (Jones 2004). The local RAOB soundings nearest in time and distance to the damage reports were gathered and examined for each of these events (not shown). Eight of the nine cases exhibited very similar soundings to the 7 March 2004 event, with winds of 50 knots or greater near 700 hPa and a deep, surface-based mixed layer present. The dissimilar case exhibited strong indications of a favorable setup for amplified gravity waves in low-level easterly flow. Since the sounding in the latter case suggested a very different mechanism for the production of damaging winds, it was not considered for comparison to the 7 March 2004 event. From the eight similar cases, the two events with the most prolific damage reports were selected for further examination, since these cases might present the strongest signals of the processes responsible for producing the wind damage. Datasets including observed and model data were obtained for the 7 March 2004 event, and for the two case studies: 4 February 2002 and 28 March 2000. These datasets were then examined to uncover similar features in the three high wind events.

3. Analysis

On 7 March 2004, a deep low pressure system over the Great Lakes region produced an intense midlevel speed maximum, which was forecast to cross the southern Appalachians during the evening hours that day. The 1200 UTC Eta depicted this 120 knot speed maximum at 500 hPa rounding the trough over the extreme southern Appalachians by 0000 UTC 8 March 2004 (Fig. 1). The swift flow around the deep upper low was expected to push a strong cold front through the southern Appalachians, and the adjacent Piedmont, during the evening hours.

Marginal instability at the time of the frontal passage was expected to limit the coverage and strength of any convection. Figure 2 shows surface dewpoints mostly in the 30s and 40s (°F) across the foothills and Piedmont of western North Carolina[1], with some cumulus buildup over the Piedmont by 2000 UTC 7 March 2004. Insolation and downslope warming through the afternoon allowed temperatures to surge to near 70 °F in the pre-frontal air mass producing Convective Available Potential Energy (CAPE) values between 100 and 200 J kg^{-1} (Fig. 4). Scattered thunderstorm chances were determined to be highest across the northern tier of the forecast area, from Hickory to north of Charlotte, where the closer proximity to cooler 500 hPa temperatures (not shown) would produce steeper midlevel lapse rates around the time of the early-evening frontal passage.

Following the frontal passage, cold air advection was forecast to gradually strengthen across the southern Appalachians, maximizing with the arrival of a 45 to 50 knot 850 hPa jet axis by 1200 UTC on 8 March 2004 (Fig. 5). Under such northwest flow cold advection regimes, damaging winds are generally confined to the higher terrain of the North Carolina mountains, and are usually observed to occur coincident with the strongest synoptic-scale 850 hPa winds. Surface wind speeds in these cases are typically quite a bit less in the lower elevations of the adjacent Piedmont, and mountain lee-troughing sometimes produces a further relaxation of the surface pressure gradient. The setup for this event seemed to follow the traditional pattern for producing damaging winds across the higher elevations of the southern Appalachians.

The main forcing mechanism for precipitation during the afternoon and evening hours appeared to be strong frontogenesis, which the Eta forecast to set up near the eastern escarpment of the

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[1] See Figure 3 for details of the topography of the GSP County Warning and Forecast Area (CWFA).

Blue Ridge by 0000 UTC 8 March 2004 (Fig. 6). A deep, vertical, ageostrophic circulation in response to the forcing is evident in a cross-section view of the western Carolinas (Fig. 7). Frontogenetical forcing has frequently been used as a diagnostic tool for assessing areas of upward vertical motion, especially with regard to winter storms and the potential for banded precipitation (Novak et al. 2004). However, the downward directed part of the resulting vertical circulation has generally been given much less attention. This component of the ageostrophic circulation appears to have contributed to substantial downward motion through the lower troposphere near the onset of the damaging winds.

The thermodynamic profile across the region at the time of the strong subsidence was very favorable for the transport of higher momentum aloft to the surface. Figure 8 shows the 0000 UTC 8 March 2004 sounding from Greensboro, NC (GSO). A very deep, dry-adiabatic lapse rate is evident on the sounding from the surface to above 700 hPa, with a narrow moist zone just above that, and very dry air near the surface. This sounding exhibited fairly weak buoyancy with respect to upward vertical displacements, largely due to dry low-level dewpoints. However, evaporation of any precipitation produced by shallow convection in the moist layer just above 700 hPa would likely have contributed some measure of downward buoyancy to the descending air. The presence of relatively light radar echoes across the region (Fig. 9) supports the notion that evaporative cooling may have played a role in accelerating parcels earthward.

Figure 10 shows a cross section of potential temperature surfaces, vertical velocity, and winds at 0000 UTC 8 March 2004 taken along the same line as in Figure 7. A general downward slope of the isentropic surfaces is evident over the mountains; however, the steep vertical orientation of the surfaces just east of the escarpment is quite striking. The nearly vertical nature of the isentropic surfaces from the ground to nearly 700 hPa in this region is very consistent with the sounding from Figure 8. Such a well-mixed boundary layer exhibiting a deep, dry-adiabatic lapse rate in a region of strong subsidence would be highly supportive of momentum transport to the surface. In fact, the arrival of the strongest wind gusts at the Charlotte-Douglas International Airport produced a surface observation quite similar to what might be observed with a convectively-induced gust front- even though no thunderstorms were in the vicinity:

METAR KCLT 080051Z 32030G44KT 10SM -RA FEW035 BKN060 OVC085 10/03
A2991 RMK AO2 PK WND 31047/0035 WSHFT 0028 RAB30 PRESRR SLP125
OCNL LTGIC DSNT NW-N P0000 T01000033

In convective wind events, it is observed that straight-line wind speeds along the ground may match or exceed the downdraft velocity of the parcels. In events involving the downward transport of synoptic scale flow, if descending parcels also experience downwardly buoyant convective forces, then downward momentum transport, and subsequent surface wind speeds, should be further enhanced. An examination of downward convective available potential energy (DCAPE) at 2100 UTC 7 March 2004 (Fig. 11) did indicate favorable values ranging from 500 to 1000 J/kg across the North Carolina foothills and Piedmont.

High wind events such as 7 March 2004 may thus be appropriately termed “hybrid” since they appear to be largely due to strong, synoptic scale gradient winds aloft, but with a convective component arising from downward buoyancy in the mixed layer. This downward buoyancy may be further enhanced if shallow convection at the top of the mixed layer produces light precipitation to aid evaporative cooling of parcels.

4. Case Studies

The deep, surface-based, dry-adiabatic mixed layer, the midtropospheric speed maximum, and the strong downward omega in the lower troposphere seem to be quite prominent features of the 7 March 2004 high wind event. Two other high wind cases, 4 February 2002 and 28 March 2000, were also examined to identify similar features in order to better understand the evolution of these types of events.

A. 4 February 2002

On 4 February 2002, high winds developed across the western Carolinas during the afternoon hours. Many trees and structures were damaged, several wildfires spread, and one fatality was reported. Examination of the 0000 UTC 5 February 2002 sounding (Fig. 12) from Blacksburg, Virginia (GSO was not available) reveals a similar deep, surface-based, dry-adiabatic layer terminating at 700 hPa in a narrow zone of small dewpoint depressions. Unlike the 7 March 2004 event, lower levels were not exceptionally dry- with dewpoint depressions around 5 °C at a few levels in the mixed layer. Winds near the top of the mixed layer were approximately 50 kt. Figure 13 reveals a 110 kt 500 hPa speed maximum moving across the southern Appalachians at 1800 UTC, while Figure 14 shows weak radar returns moving east of the Blue Ridge around 1900 UTC.

A west-northwest to east-southeast cross section valid at 2100 UTC from the 1800 UTC 4 February 2002 Eta (Fig. 15) reveals potential temperatures surfaces extending vertically from the surface to near the base of the 50 kt winds aloft, with strong downward omega through a deep layer of the atmosphere. No evidence of frontogenesis was found in this case. The totality of the deep downward forcing was primarily associated with quasi-geostrophic processes, mainly cold air advection. This appears to indicate that the particular source of the low-level downward omega that impacts the mixed layer is relatively unimportant.

B. 28 March 2000

Another similar event occurred on 28 March 2000. High winds caused widespread damage to trees and buildings, several wildfires, and one serious injury. The worst wind damage occurred in the foothills and Piedmont of the western Carolinas during the afternoon hours. The evening sounding at 0000 UTC 29 March 2000 from GSO indicated a nearly dry-adiabatic profile extending to 700 hPa, capped by a region of small dewpoint depressions, with 50 kt of wind near the top of the mixed layer (Fig. 16). The afternoon timing does not appear to be coincidental. Although a deep, surface-based, dry-adiabatic layer can persist into the overnight hours during strong cold advection, the most likely period for such a profile to set up is the diurnally favored window of deep mixing from the afternoon through the early evening hours.

A 500 hPa speed maximum in excess of 100 kt was forecast to cross the southern Appalachians about the time of the onset of the damaging winds (Fig. 17). Spotty, light precipitation was observed on radar at 1835 UTC, with reflectivities generally too weak to trigger a radar switch from clear air mode (Fig. 18). The light returns at 0.5 degrees on the KGSP radar suggest the presence of virga falling from the base of the moist layer at the top of the mixed layer. A west-northwest to east-southeast cross section depicts nearly vertical potential temperature surfaces tapping into 50 knots of flow aloft, with significant downward omega from 500 hPa to the surface associated with synoptic scale subsidence (Fig. 19).

5. Discussion

A comparison of the 7 March 2004, 4 February 2002, and 28 March 2000 events reveals several common features that may prove useful in diagnosing and forecasting high wind events in the Piedmont of the Carolinas.

A. Deep Mixed Layer

Proximity soundings in all such events exhibited a deep, surface-based, dry-adiabatic mixed layer extending above 800 hPa, and in some cases above 700 hPa. This profile is most common during the diurnally favored deep-mixing period from early afternoon through early evening. Indeed, the bulk of the damaging winds in Piedmont locations occurred between the hours of 1700 UTC and 0100 UTC (noon to 8 pm EST) in all cases examined.

The surface-based mixed layer was observed to be topped by a narrow moist zone. In all cases, very light precipitation or virga was indicated by radar as falling from the base of this moist zone into the mixed layer. The dryness of the air in the mixed layer, however, was quite variable from case to case. Some cases exhibited abundant near-ground dry air- similar to the familiar “inverted-V” sounding, while other cases contained more low level moisture. The presence of moisture in the mixed layer, then, does not appear to be a limiting factor in the production of damaging wind gusts. It could well be the case that downward-directed buoyancy of descending air parcels undergoing evaporation exists in either case since the ambient temperature profile is dry adiabatic (Srivastava 1985).

B. Strong MidTropospheric Speed Maximum

A belt of strong midtropospheric winds was found to be present in the area during each damaging wind event. If the deep mixed layer is coincident with the arrival of this speed maximum, momentum transport will likely produce strongly increased surface winds, along with very gusty conditions. The collocation of 700 hPa winds of 50 kt or greater near the top of the mixed layer, along with 500 hPa wind speeds of 100 kt, appears to be very conducive to transporting strong to damaging winds to the surface.

C. Downward Omega

A third key ingredient appears to be the onset of substantial downward omega in the lower troposphere. This subsidence can arise from varied mechanisms, but a relatively strong downward component through the lowest 300 hPa is common in these events. Cold advection is a typical source of such downward omega, but differential negative vorticity advection, or ageostrophic frontogenetical circulations can also provide the needed subsidence.

6. Other Possible Mechanisms

While the three factors mentioned above appear to be primary ingredients in the development of high winds across the Piedmont of the western Carolinas, other mechanisms could also be contributors. For example, the higher terrain of the southern Appalachians can contribute to the formation of mountain-induced gravity waves. Also, local members of the Collaborative Science, Technology, and Applied Research (CSTAR) community have suggested that a stratospheric intrusion may have played a role in part of the March 7, 2004 event, especially in locations immediately east of the GSP CWFA. While an in-depth treatment of these topics is beyond the scope of this paper, brief consideration is warranted.

A. Mountain Waves

The southern Appalachians, with their relatively gradual western slopes and steeper eastern slopes, are favorable for the generation of large-amplitude mountain waves under strong northwest flow regimes (Lilly and Klemp 1979; Manuel and Keighton 2003). It is thus of interest to examine if the lee-side strengthening of the winds resulted from the development and amplification of mountain waves.

The preferred profile for the amplification of mountain waves includes: an inversion just above the ridge top, a deep unstable layer extending from just above the inversion through the midtroposphere, and a general decrease in the cross barrier wind speeds with height (Colman and Dierking 1992; Klemp and Lilly 1975). To approximate the sounding profile across the southern Appalachians on the evening of March 7 2004, both the 1200 UTC 7 March 2004 sounding from Nashville, Tennessee (not shown) and the 0000 UTC 8 March 2004 sounding from GSO (Fig. 8) were examined. Both soundings indicated a deep, surface-based, dry-adiabatic layer extending well above the ridge tops in the region, with any inversion layer well above 700 hPa. Further, midtropospheric air was not particularly unstable, and wind speeds were observed to increase to the tropopause. This profile would not be considered favorable for the development of highly amplified mountain waves (Lackmann 2004).

B. Stratospheric Intrusion

Another mechanism under consideration is that an intrusion of stratospheric air could have led to rapid intensification of midlevel vorticity, along with deepening surface low pressure (Hartfield 2004). This, in turn, could produce more intense convection and associated downdrafts. The 7 March 2004 event did become more convectively driven as it progressed eastward into the coastal plain of the Carolinas (not shown). However, as previously noted, deep convection was very limited in the western Carolinas.

An investigation into the intrusion of higher potential vorticity air into the lower troposphere during this event is being conducted by the National Weather Service in Raleigh, NC, in collaboration with the North Carolina State University (Hartfield et al. 2004).

7. Conclusion

Aspects of the 7 March 2004 high wind event in the Piedmont of the western Carolinas were examined, and case studies were presented from similar events on 4 February 2002 and 28 March 2000. Three prominent conditions were present around the time of the damaging winds in all three cases: (A) a deep, surface-based, dry-adiabatic mixed layer extending above 800 hPa, and in some cases above 700 hPa, capped by a narrow zone of higher moisture; (B) a midtropospheric speed maximum consisting of 700 hPa winds of 50 kt or greater, along with 500 hPa winds of 100 kt or greater; and (C) substantial downward omega in the lowest 300 hPa of the atmosphere.

Recognizing the development of these three conditions within the forecast area can assist forecasters in preparing a more accurate wind forecast. If it is suspected that a hybrid high wind setup is possible during a favored period of deep mixing, a model sounding from a location of interest should be examined to see if condition (A) is met. This preliminary indication should be followed by an investigation of the mid-tropospheric winds by utilizing a composite chart of 700 and 500 hPa isotachs. The collocation of these midlevel isotach maxima such that condition (B) is met would suggest that sufficient wind energy is present to produce surface wind damage if a mechanism of downward transport is available. A confirmatory cross section of omega and potential temperature can then be drawn through the area of interest for the time of concern. If the necessary low-level downward omega of condition (C) intersects the vertically-sloped potential temperature surfaces of the mixed layer, then a hybrid high wind event would be quite possible. When all of these conditions are found to exist simultaneously, a High Wind Watch or High Wind Warning should be seriously considered- even if model and MOS guidance winds are fairly unimpressive.

References

Burchette, J. and M. Wineka. Residents Assess Damage, Wait for Power to Return. *Salisbury Post*, Mar. 9, 2004.

Colman, B. R., and C. F. Dierking, 1992: The Taku wind of southeast Alaska: Its identification and prediction. *Weather and Forecasting,* **7,** 49–64.

Crouch, M., S. Lyttle, R. Moore, and H.P. Hartnett. Powerful Winds Batter Carolinas. *Charlotte Observer,* Mar. 8, 2004.

Cruz, D. Big Blow: Sunday's ill winds brought damage; more snow forecast today. *Lenoir [NC] News-Topic*, Mar. 9, 2004.

Gilliland, K. Wind-toppled steeple leaves churchgoers scared, but not scarred. *Hickory [NC] Daily Record*, Mar. 9, 2004

Hartfield, G., cited 2004: The potential role of a stratospheric intrusion in the March 7, 2004 high wind event. [Available online at http://www4.ncsu.edu/~nwsfo/storage/cases/20040307/20040307.strato.intrusion.pdf]

________, B. Locklear, and M. Brennan, cited 2004: An unusual "dry" downburst damaging wind event in North Carolina: 7 March 2004. [Available as a Powerpoint Presentation file]

Horne, C., March 10, 2004: E-mail correspondence.

Jones, W., April 2004: Personal correspondence.

Klemp, J. B., and D. K. Lilly, 1975: The dynamics of wave induced downslope winds. *Journal of Atmospheric Science.*, **32,** 320–339.

Knox, M. County begins cleanup: Strong winds whip across state tearing down trees. *Concord [NC] Independent Tribune*, Mar. 9, 2004.

Lackmann, G., Mar. 9, 2004: E-mail correspondence.

Lilly, D.K., and J.B. Klemp, 1979: The Effects of Terrain Shape on Non-Linear Hydrostatic mountain Waves. *Journal of Fluid Mechanics*., **95**, 241-261.

Mackie, A. Storm blows in, wreaks havoc. *Hickory [NC] Daily Record*, Mar. 8, 2004.

Manuel, P. and S. Keighton, 2003: Anticipating damaging Foehn windstorms east of the central Appalachians, *10th Conference on Mesoscale Processes*, Seattle, WA, Amer. Meteor. Soc., P2.20.

Moore, N. Wind shoves historic church off blocks. *Gaston [NC.] Gazette*, Mar. 11, 2004.

National Weather Service, Mar. 2004. *Storm Data and Unusual Weather Phenomena*.

Novak, D. R., J.S. Waldstreicher, and L.F. Bosart, 2004: A forecast strategy for anticipating cold season mesoscale band formation within developing extratropical cyclones, *20th Conference on Weather Analysis and Forecasting*, Seattle, WA, Amer. Meteor. Soc., 8.1.

Srivastava, R.C., 1985: A simple model of evaporatively driven downdraft: Application to microburst downdraft. *J. Atmos. Sci*., **42**, 1004-1023.

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Table 1: 1200 UTC GFS MOS Guidance for Hickory, NC from March 7, 2004.

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KHKY   GFS MOS GUIDANCE    3/07/2004  1200 UTC
DT /MAR   7/MAR   8                /MAR   9                /MAR  10
HR   18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 06 12
N/X                    38          55          32          45    27
TMP  66 66 58 51 47 44 40 49 51 52 46 40 37 35 34 40 42 43 40 31 29
DPT  40 36 33 31 27 24 23 24 24 23 22 22 24 23 23 24 26 26 26 24 22
CLD  SC SC OV CL CL CL CL CL SC SC CL CL SC SC OV OV OV OV OV OV SC
WDR  25 27 30 31 30 30 30 32 32 32 32 32 32 32 33 00 10 05 03 36 35
WSP  09 12 15 15 15 14 12 16 15 13 10 07 06 04 01 00 01 01 03 07 07
P06        27    16     8     4     1     1     3    17    52 27 15
P12                    18           4           3          52    31
Q06         1     0     0     0     0     0     0     0     1  1  0
Q12                     0           0           0           1     0
T06      2/ 6  0/ 6  0/ 2  0/ 0  0/ 0  0/ 3  1/ 0  3/ 0  2/ 0  1/ 0
T12            2/ 7        0/ 2        0/ 3        3/ 0     2/ 0
POZ   1  1  2  0  0  0  0  2  3  2  2  0  0  0  0  0  0  0  1  0  1
POS   0  1  0  1 17 58 81 82 39 26 57 73 88 84 65 65 67 58 69 87 89
TYP   R  R  R  R  R  S  S  S  R  R  S  S  S  S  S  S  S  S  S  S  S
SNW                     0                       0                 0
CIG   7  7  6  7  7  7  7  7  7  7  7  7  7  7  6  6  5  5  5  5  6
VIS   7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7
OBV   N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N
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Figures

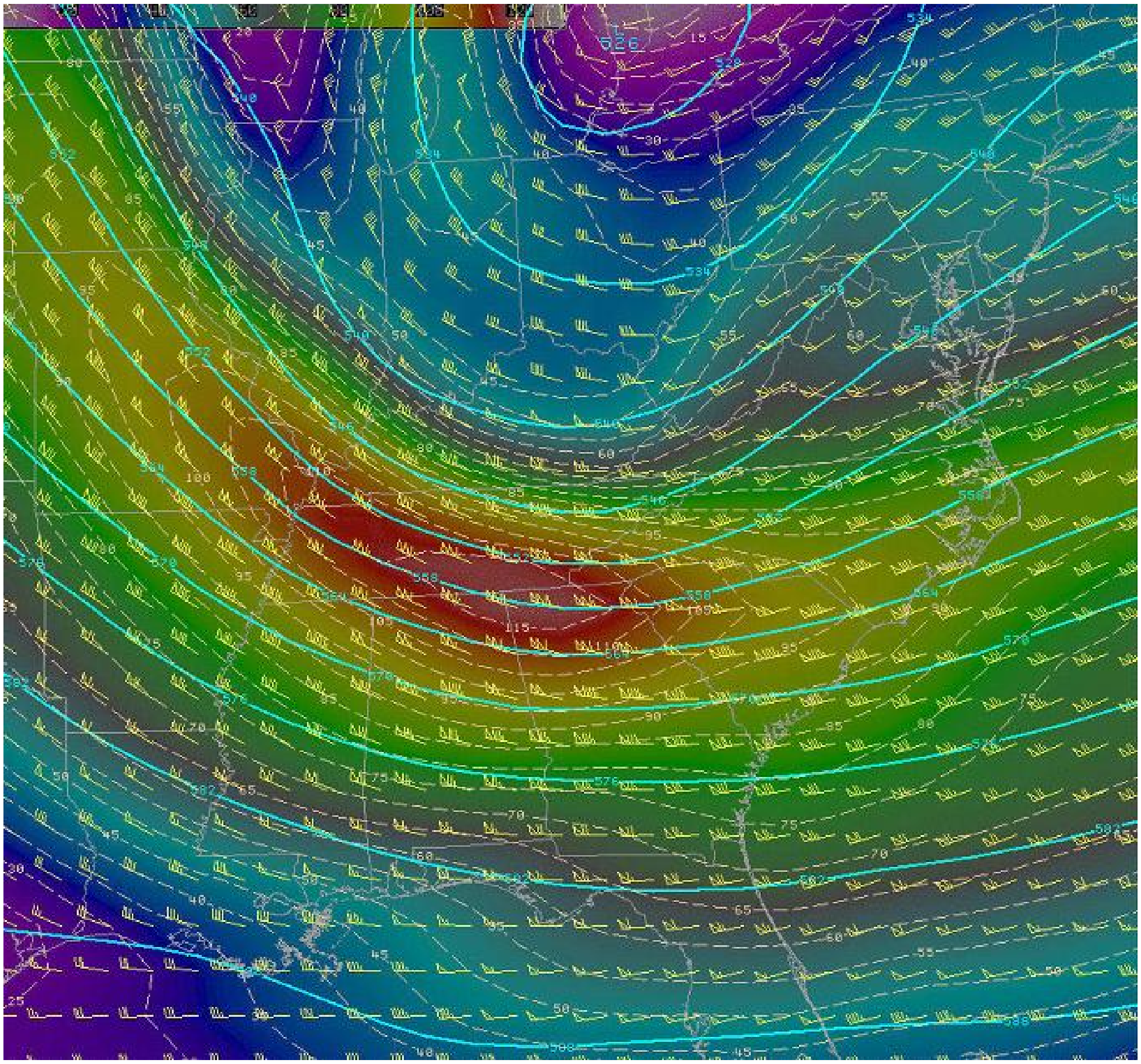

Figure 1: 12-hour Eta forecast of 500 hPa heights (solid, dm), winds (barbs, kt), and isotachs (dashed and image, kt) valid at 0000 UTC 8 March 2004.

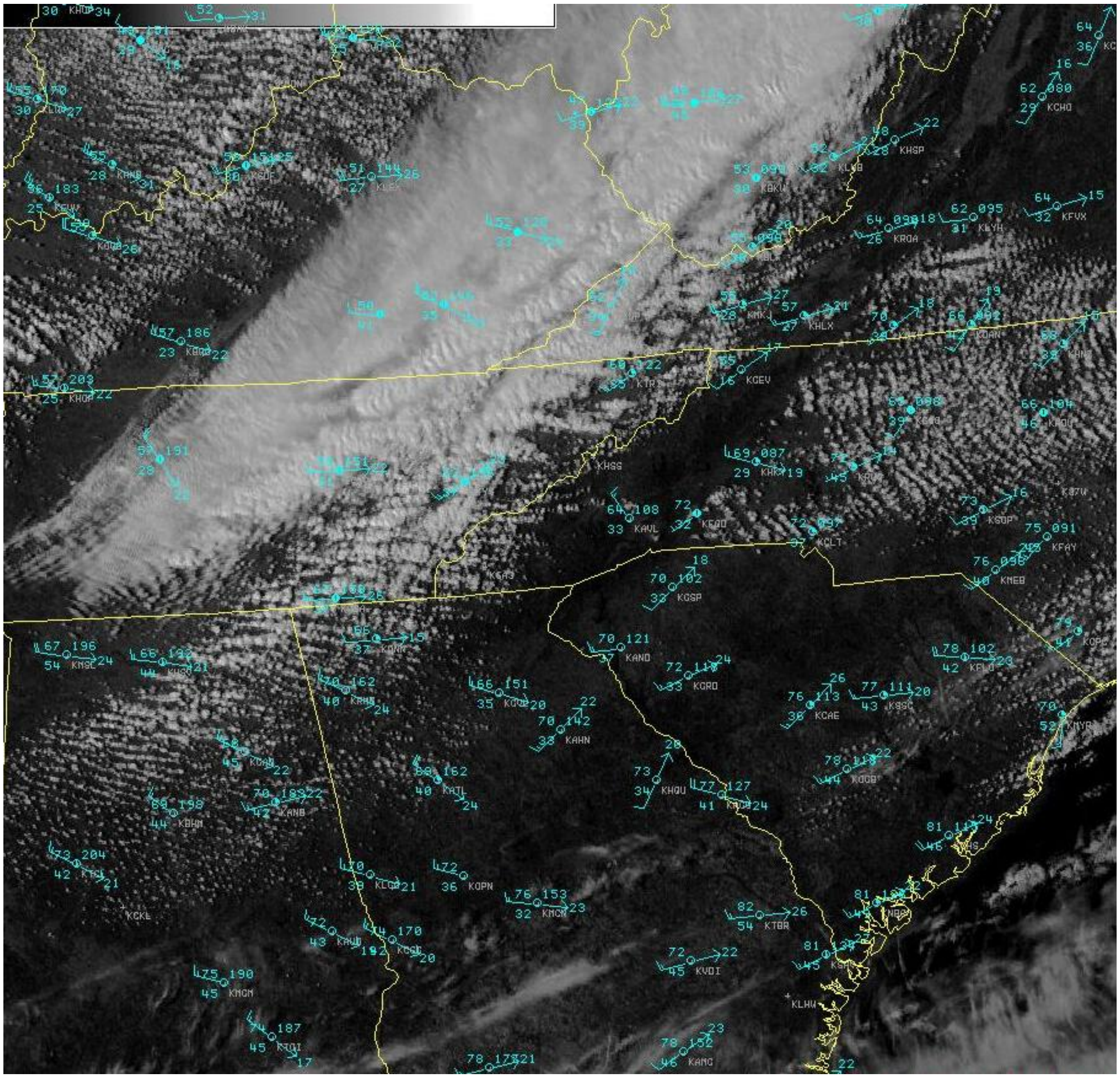

Figure 2: Visible satellite imagery at 2000 UTC 7 March 2004, with surface observations overlaid.

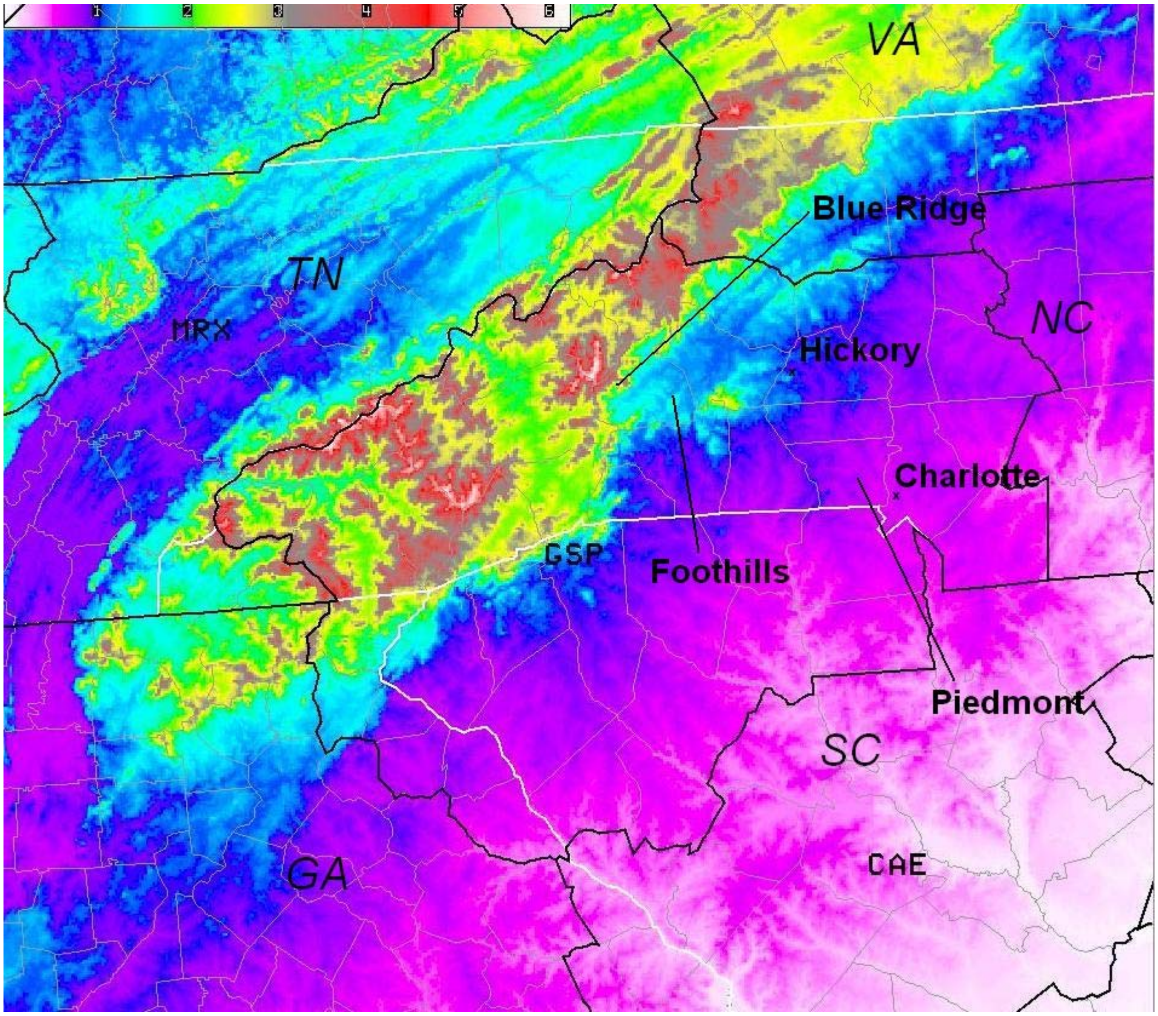

Figure 3: Topographic map of the GSP County Warning and Forecast Area (CWFA), outlined in black. State boundaries are in white, where visible. Legend is in thousands of feet, with the highest terrain points over 6,000 feet MSL.

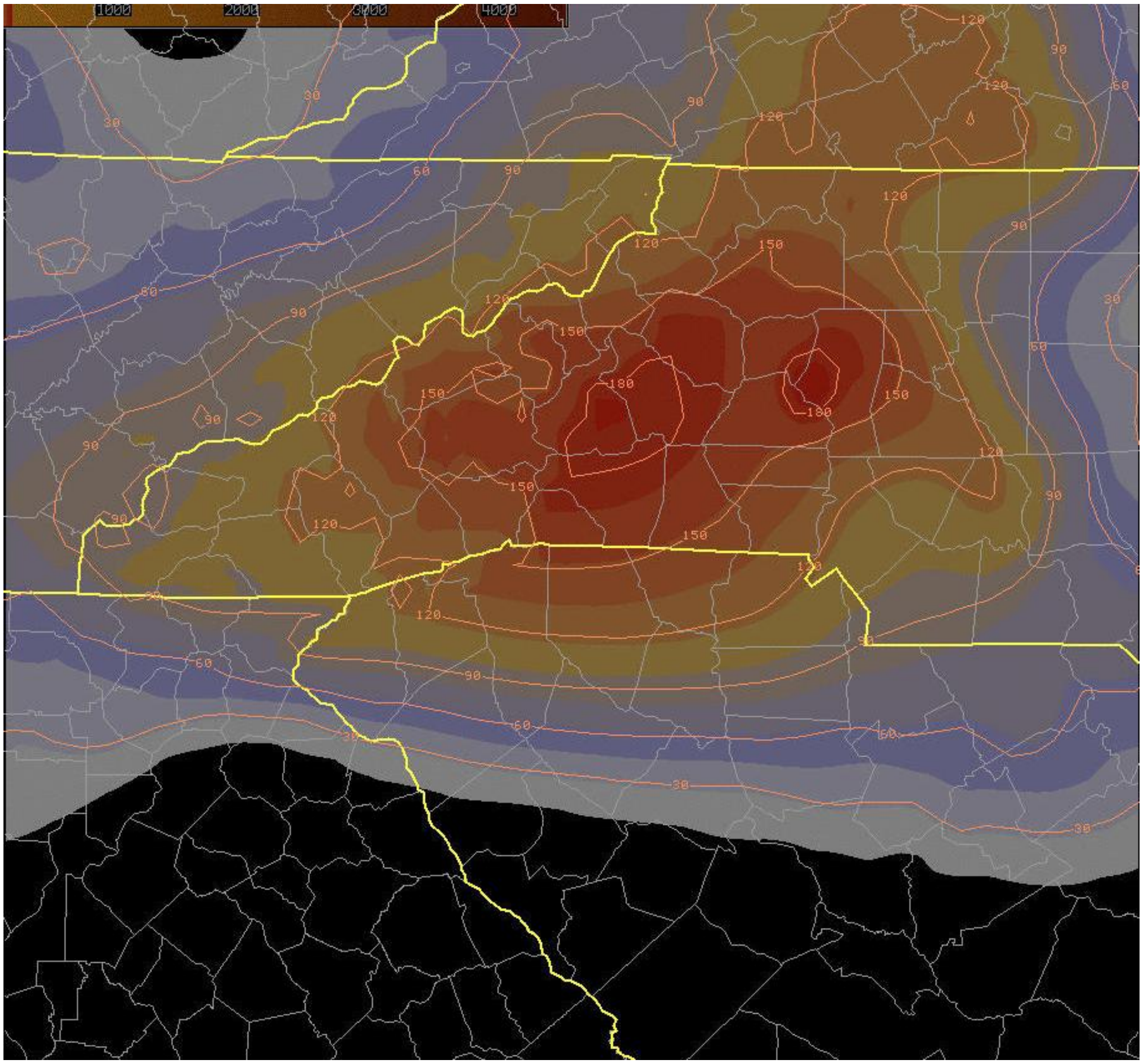

Figure 4: LAPS CAPE (J kg^{-1}) at 2000 UTC 8 March 2004

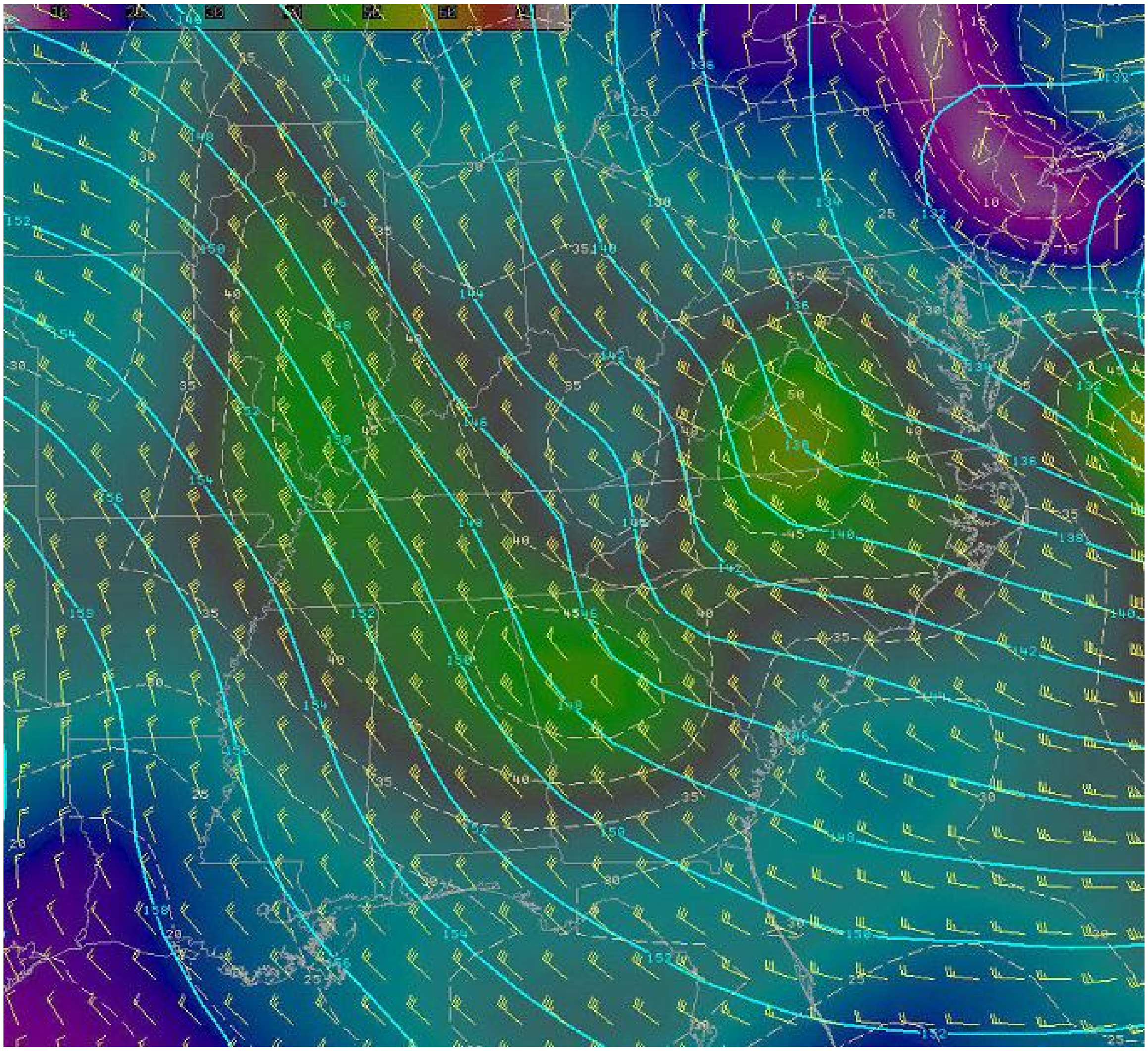

Figure 5: 24-hour Eta forecast of 850 hPa heights (solid, dm), winds (barbs, kt), and isotachs (dashed and image, kt) valid at 1200 UTC 8 March 2004.

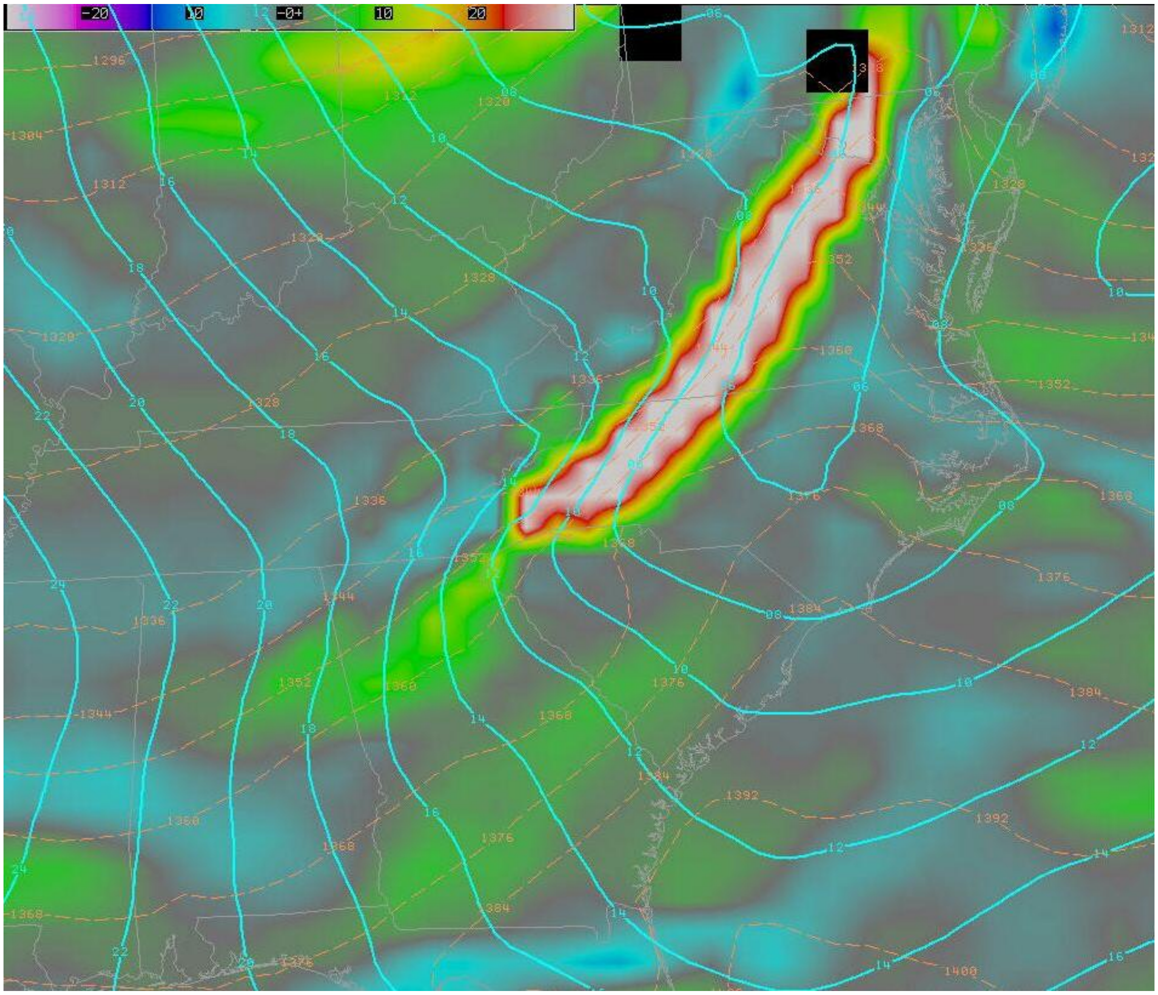

Figure 6: 6-hour Eta forecast of mean sea level pressure (solid, hPa), 1000 to 850 hPa thickness (dashed, m), and 850 hPa horizontal frontogenesis (image, FGU) valid at 0000 UTC 8 March 2004. (Note: 1 FGU = 10 K (100 km)$^{-1}$ (3 h)$^{-1}$)

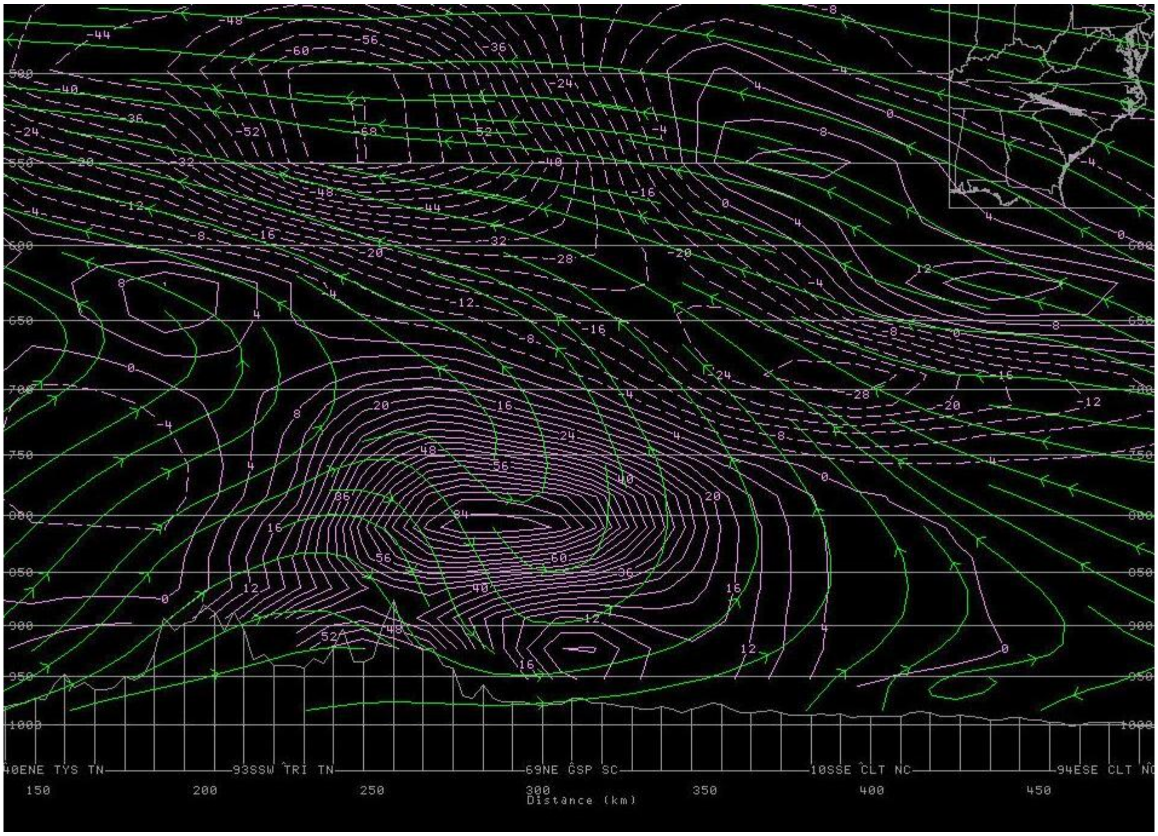

Figure 7: WNW to ESE cross section of the western Carolinas showing 6-hour Eta forecast of horizontal frontogenesis (contours, FGU), and ageostrophic vertical circulation (streamlines) valid at 0000 UTC 8 March 2004.

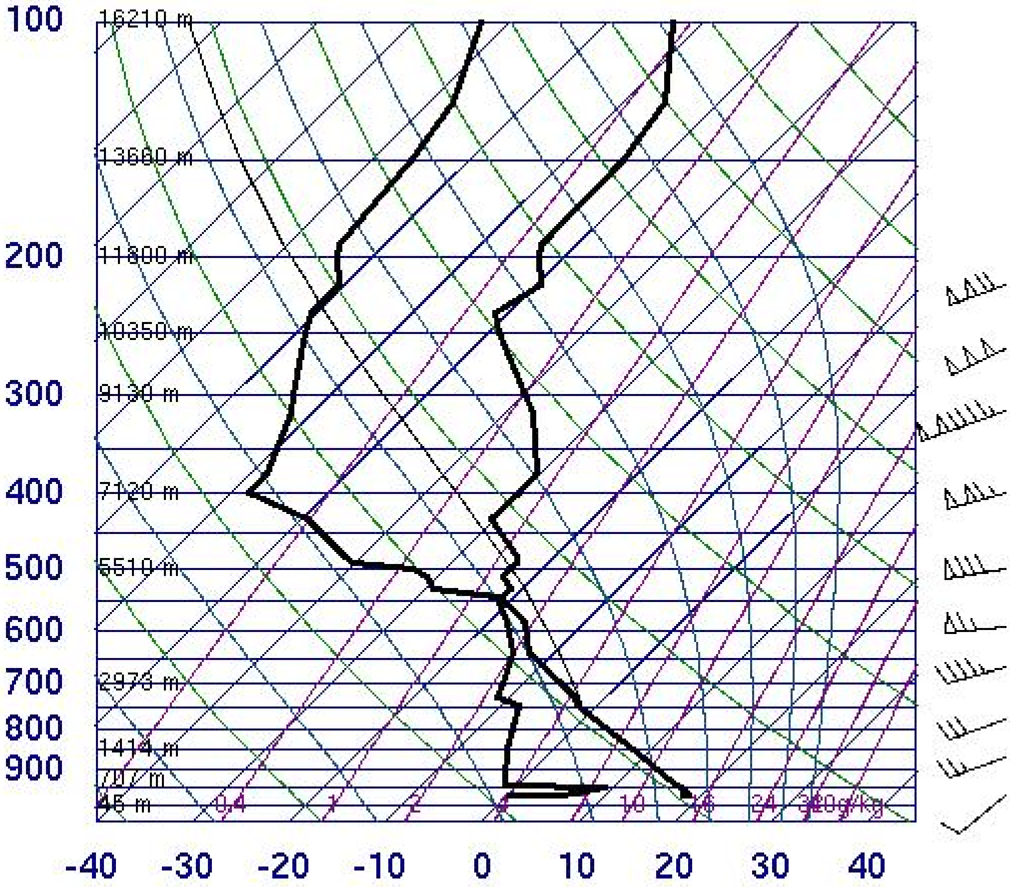

Figure 8: 0000 UTC 8 March 2004 RAOB sounding from Greensboro, NC (GSO) (Source: University of Wyoming)

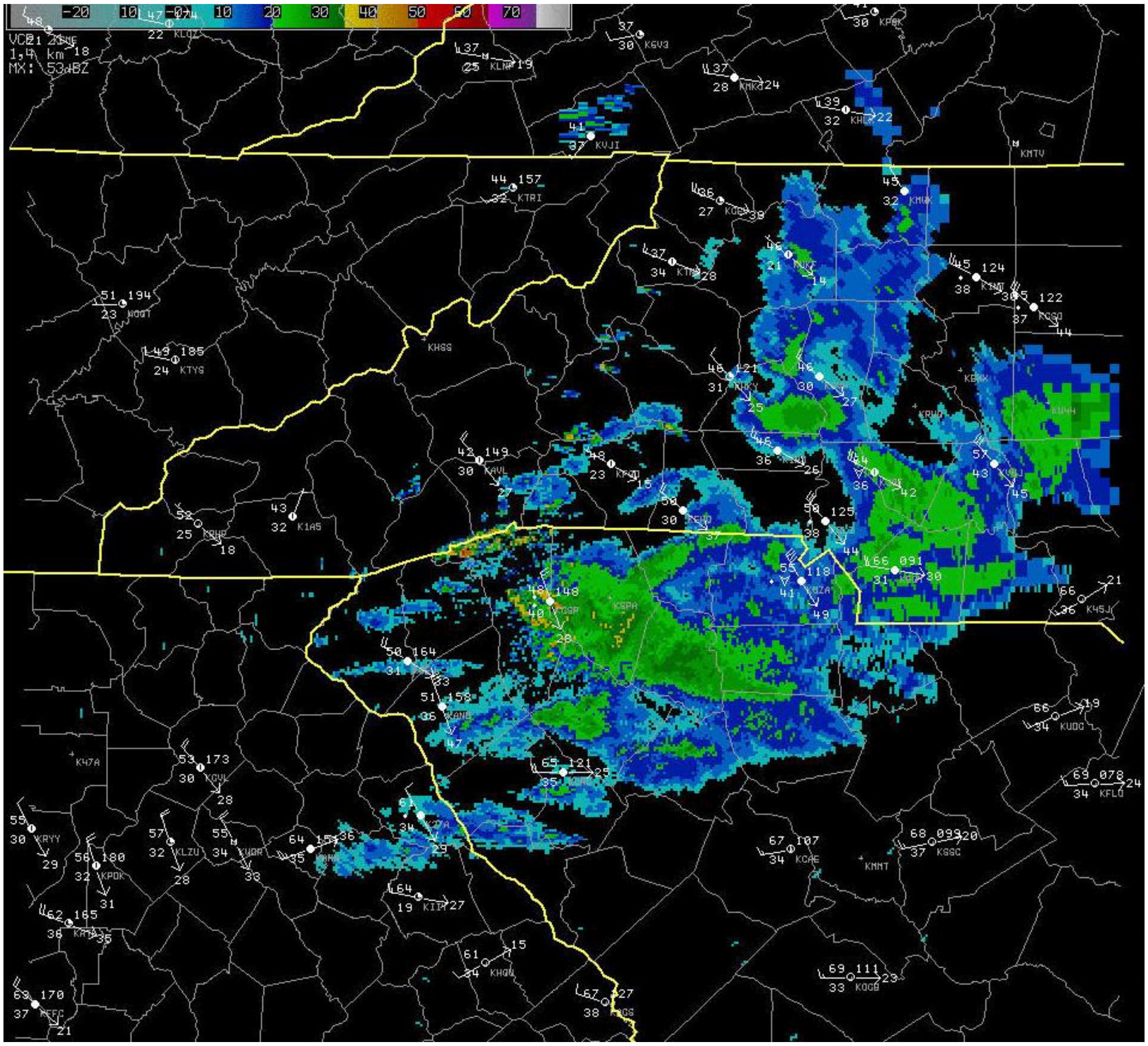

Figure 9: 0100 UTC 8 March 2004 KGSP composite reflectivity (dBZ) (Note that the higher reflectivities in the South Carolina mountains are anomalous propagation into the higher terrain.)

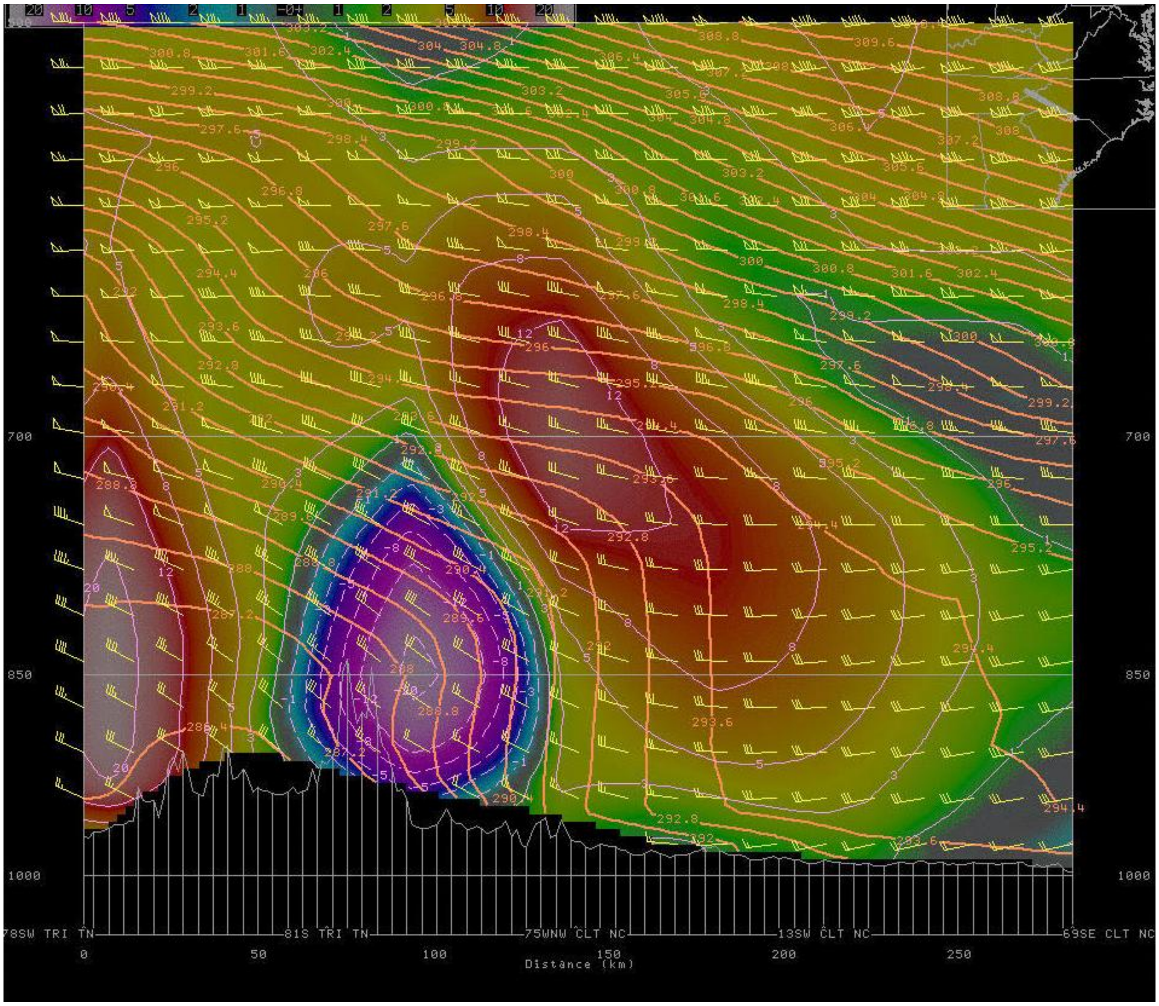

Figure 10: WNW to ESE cross section of the western Carolinas showing 6-hour Eta forecast of omega (dashed and image, microbars/second), potential temperatures (solid, °K), and wind barbs (kt) valid at 0000 UTC 8 March 2004.

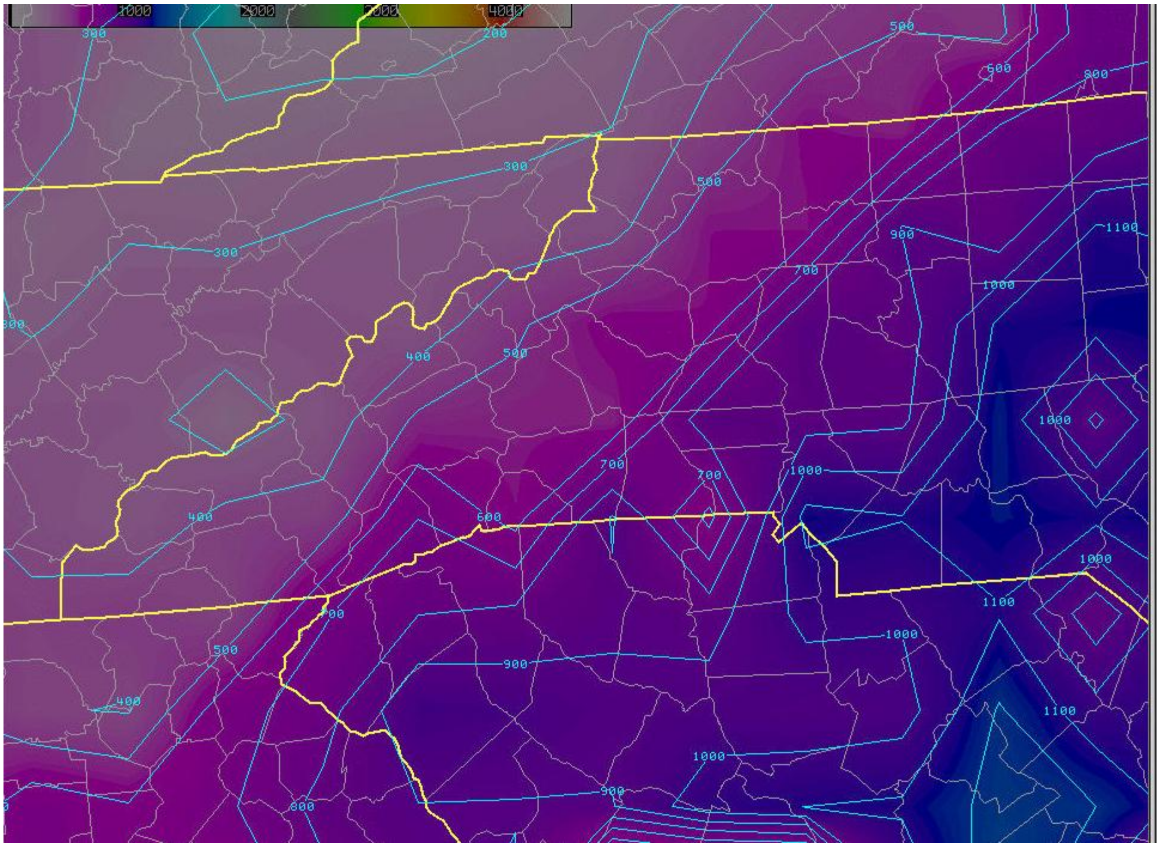

Figure 11: 3-hr Eta Forecast of DCAPE (J/kg) at 2100 UTC 7 March 2004

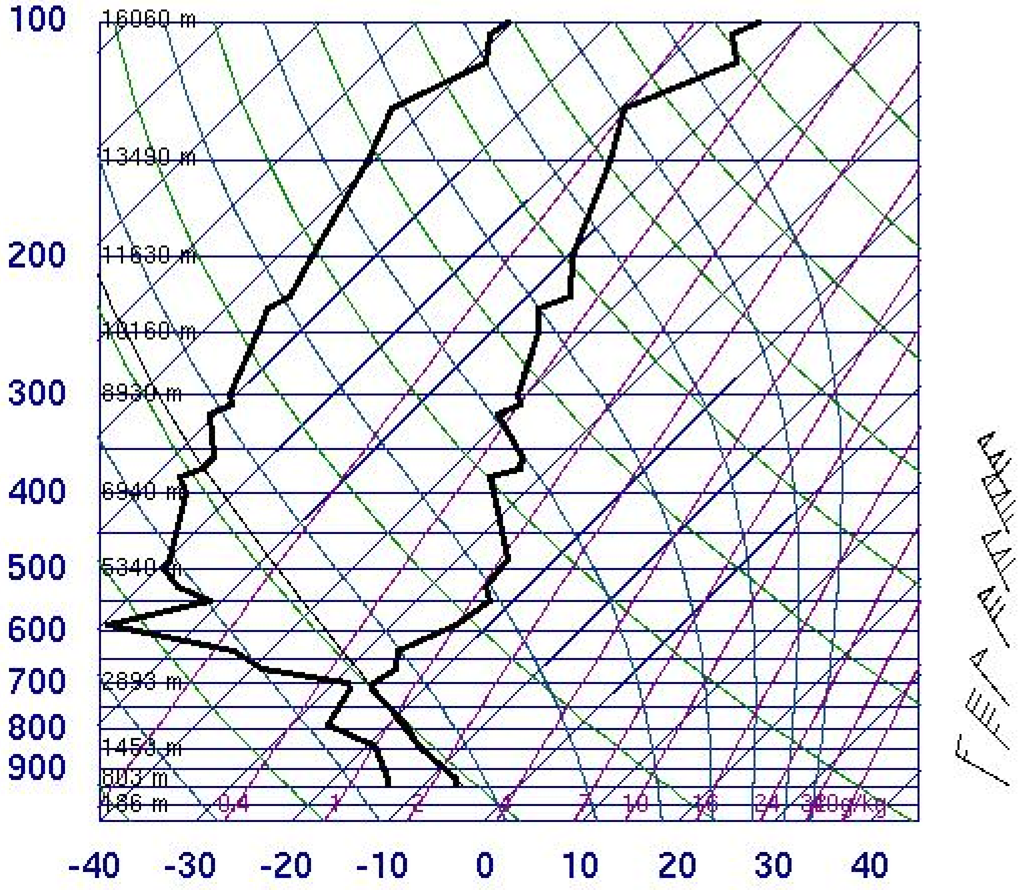

Figure 12: 0000 UTC 5 February 2002 RAOB sounding from Blacksburg, Virginia (RNK) (Source: University of Wyoming)

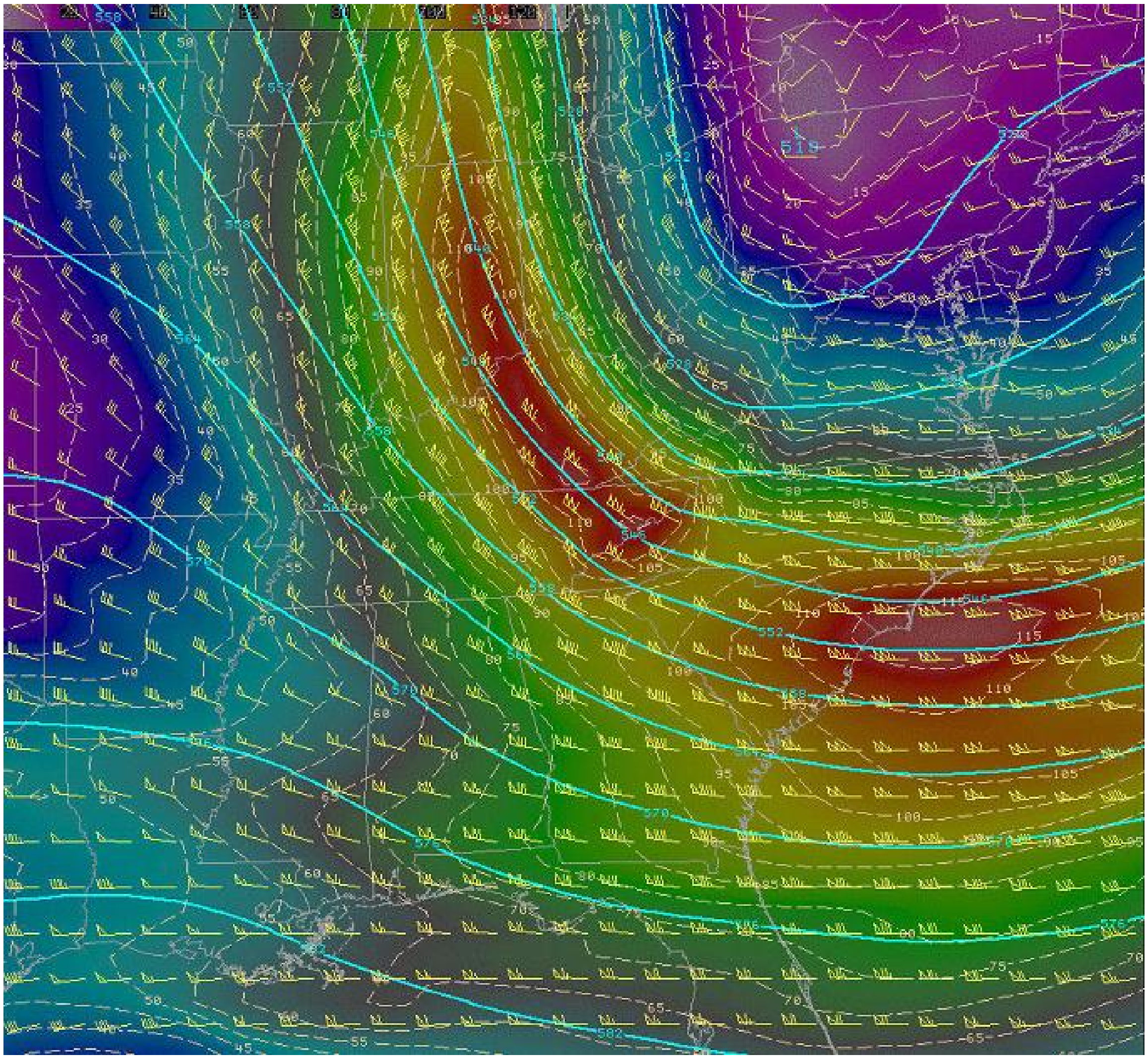

Figure 13: Initialization of 500 hPa heights (solid, dm), winds (barbs, kt), and isotachs (dashed and image, kt) from 1800 UTC 4 February 2002 Eta.

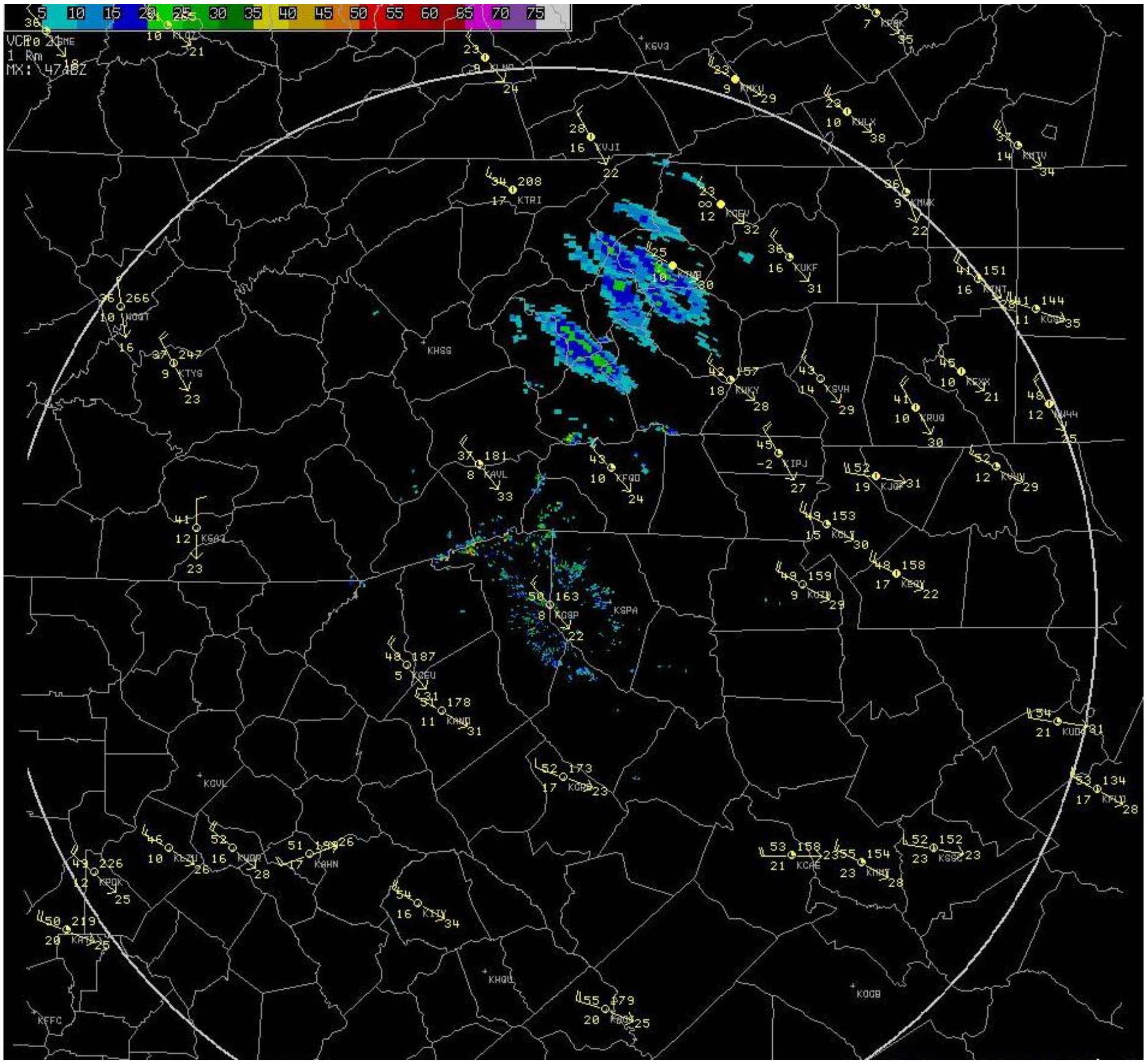

Figure 14: 1900 UTC 4 February 2002 KGSP 0.5 degree base reflectivity (dBZ).

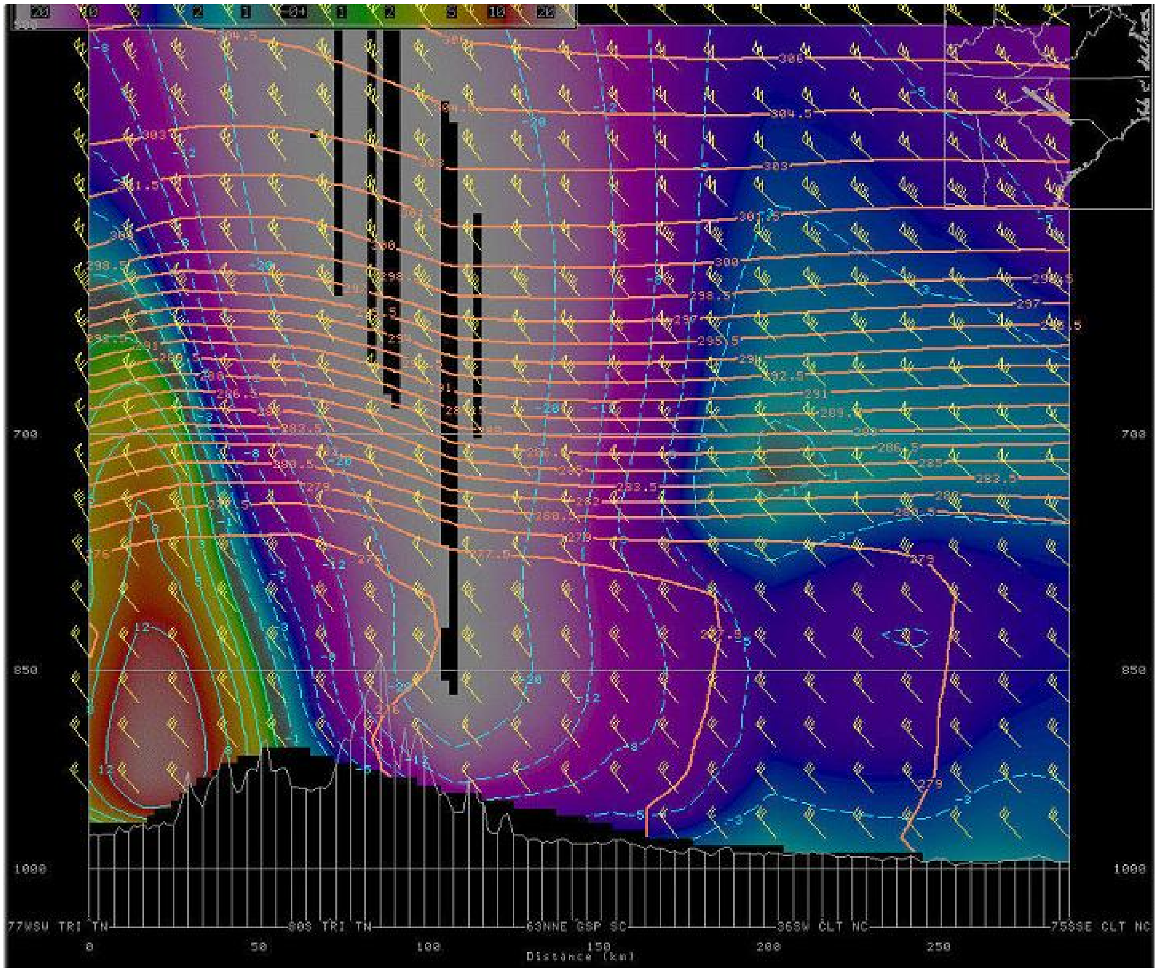

Figure 15: WNW to ESE cross section of the western Carolinas showing 3-hour Eta forecast of omega (dashed and image, microbars/second), potential temperatures (solid, °K), and wind barbs (kt) valid at 2100 UTC 4 February 2002.

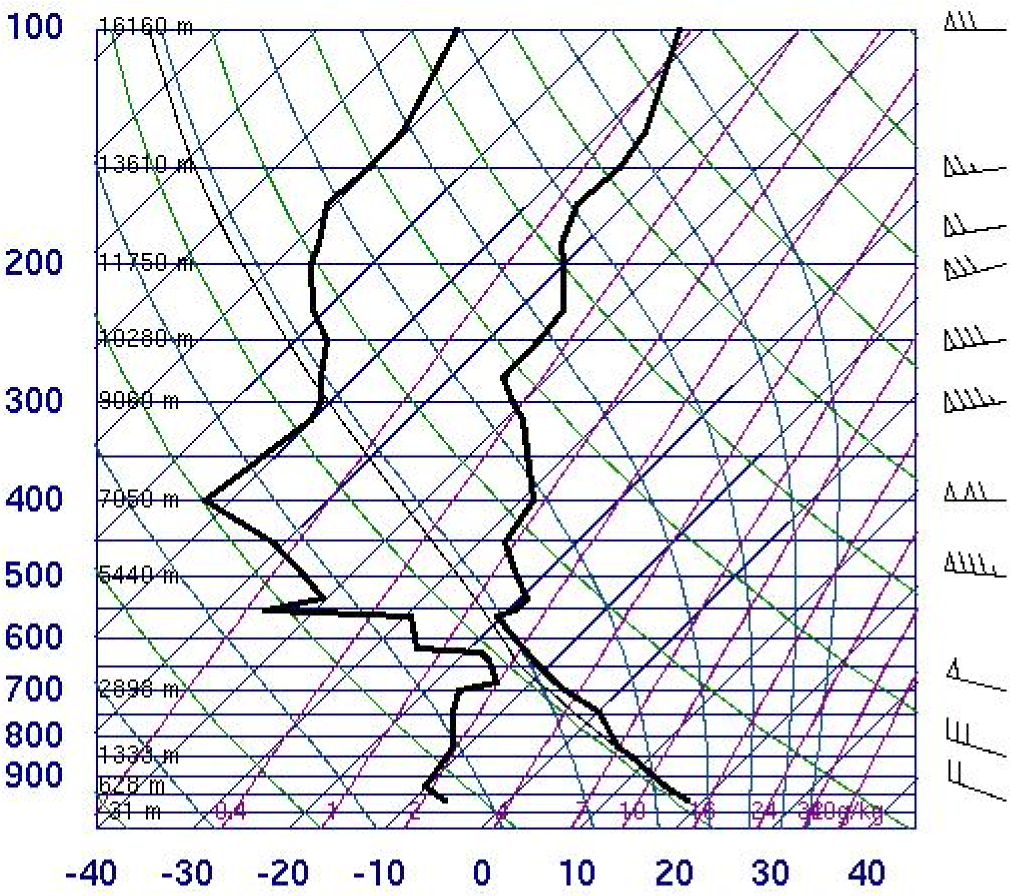

Figure 16: 0000 UTC 29 March 2000 GSO RAOB sounding (Source: University of Wyoming)

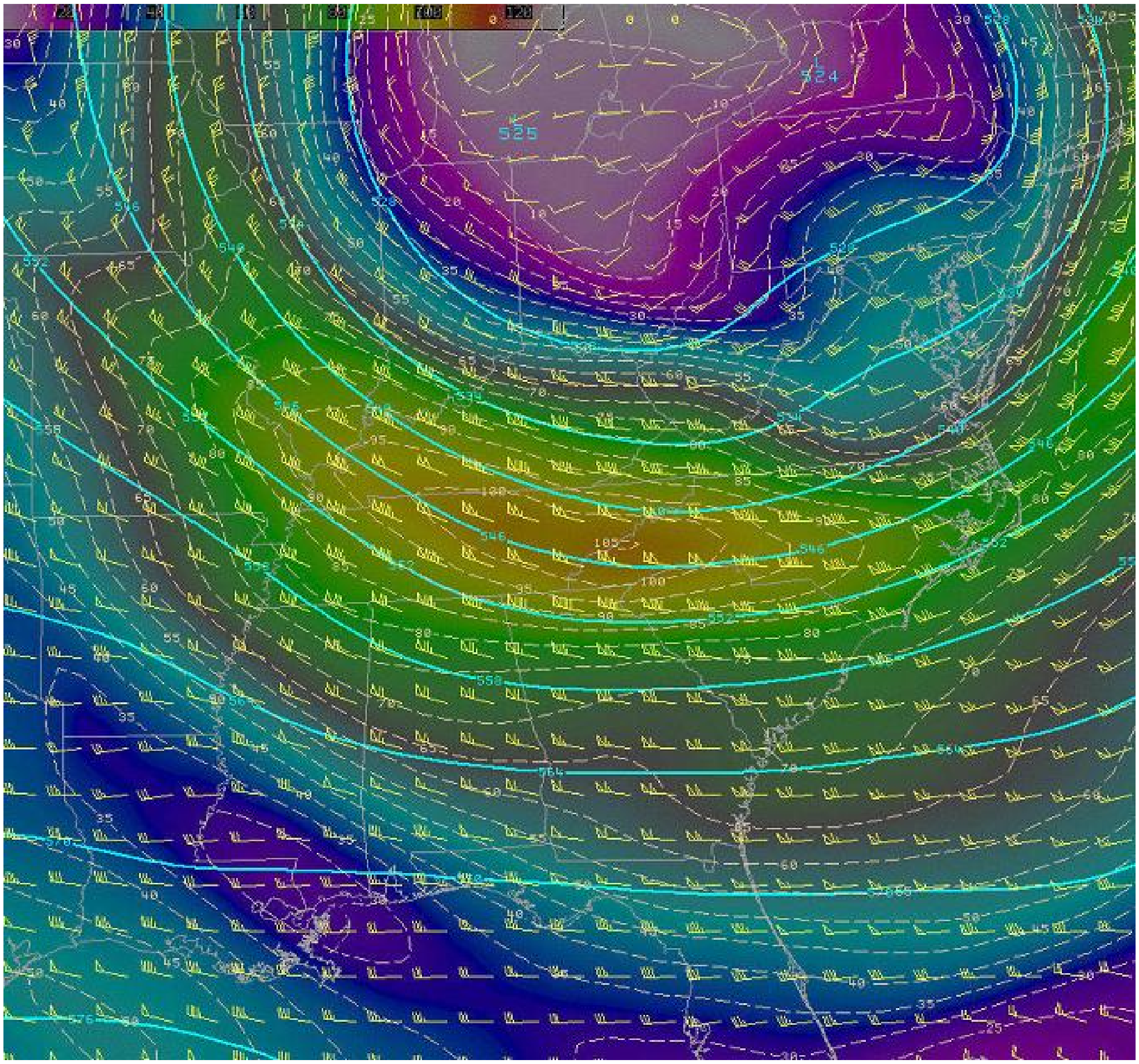

Figure 17: Initialization of 500 hPa heights (solid, dm), winds (barbs, kt), and isotachs (dashed and image, kt) from the 1800 UTC 28 March 2000 Eta.

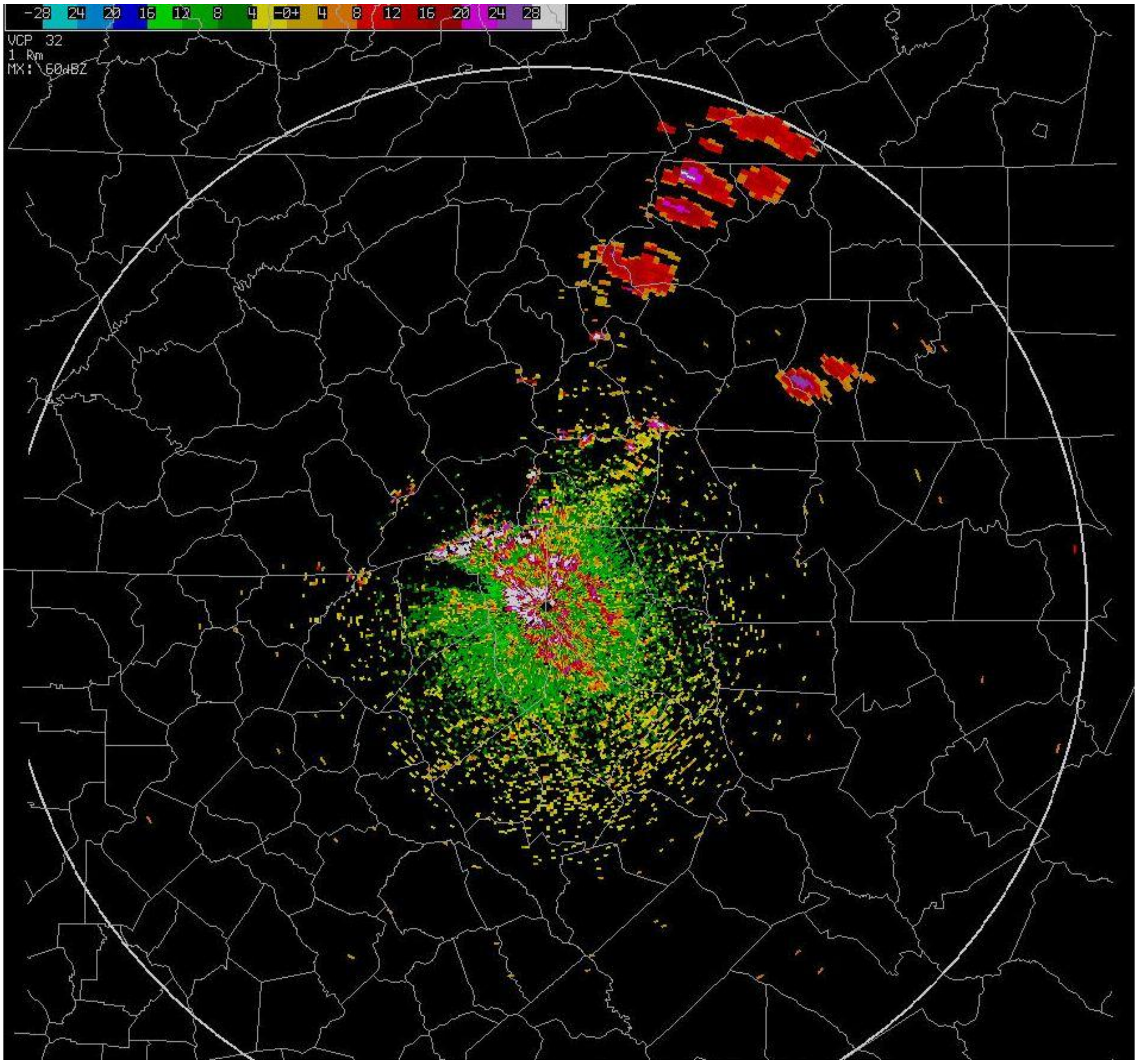

Figure 18: 1835 UTC 28 March 2000 KGSP 0.5 degree base reflectivity (dBZ).

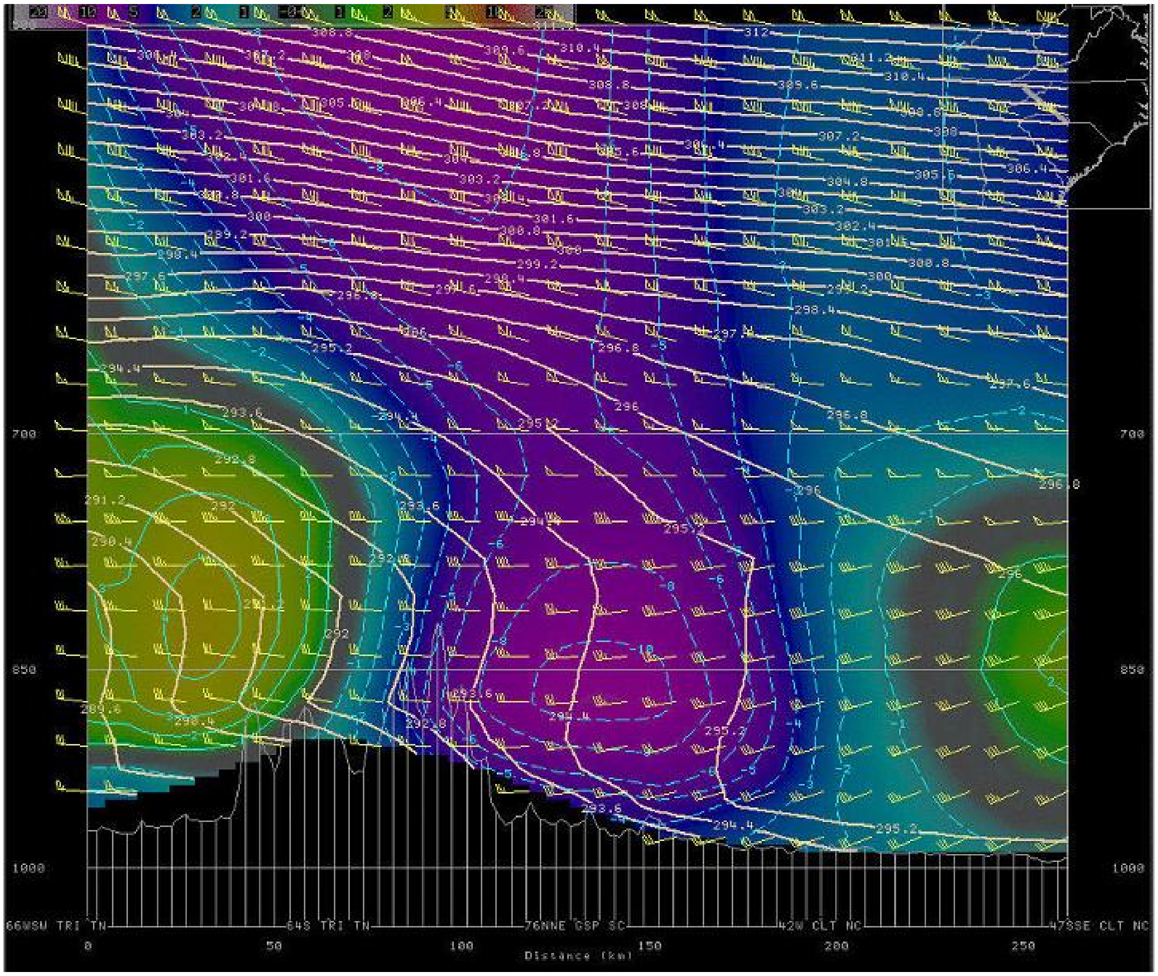

Figure 19: WNW to ESE cross section of 3-hour Eta forecast of omega (dashed and image, microbars/second), wind (barbs, kt), and potential temperature (solid, degrees K) valid at 2100 UTC 28 March 2000.