JP4J.3 MESOSCALE STRUCTURE IN A COASTAL FRONT: A CASE STUDY

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1. INTRODUCTION

Between 31 March and 03 April 2004, a heavy rainstorm moved through the southern part of the northeast United States, extending from Connecticut eastward into Rhode Island and northward into Massachusetts, Vermont, and New Hampshire. This event caused extreme precipitation totals of over three inches throughout the region, with some areas receiving in excess of seven inches of precipitation as shown in Figure 1.

The heaviest precipitation fell along the leading edge of the interior highlands of southeast New Hampshire and northeast Massachusetts east of the Merrimack Valley extending southward into the Blue Hill region just southwest of Boston, Massachusetts. Precipitation was primarily the result of a coastal low pressure area located over the Delmarva Peninsula, but was enhanced by the local orography and a coastal warm front.

Cold air damming was initially present along the New England coast, and extending southward toward the Delmarva Peninsula. As time passed, the damming became less intense, but the cold air remained in place along the coastal plain of Massachusetts, New Hampshire, and Maine. As the coastal low pressure center advanced towards the northeast, the warmer air from over the ocean was unable to intrude into the interior of Massachusetts and New Hampshire, and a weak coastal front formed on 01 April. Over the next 24 hours, heavy rain fell along the coast, and just inland, suggesting that the presence of the strong temperature gradient at low levels contributed to the upward motion, and hence, to the precipitation rate.

Preliminary examination of the radar data suggests that banding occurred along the east-facing hills of Massachusetts and New Hampshire where the upward vertical motion and precipitation were the greatest, extending along a strong baroclinic zone just above the lower 50 hPa. Additionally, synoptic scale calculations have already shown that on the large scale, differential vorticity advection dominated the production of upward vertical motion, but this forcing was concentrated in the 850 – 1000 hPa layer, rather than above 500 hPa. Low level temperature advection was also strongest at low levels. Altogether there were three separate banding episodes visible in the Level II radar data from Boston/Taunton, MA, with a variety of widths and orientations. Most of the bands were oriented northwest to southeast, were between 300 and 500 km long, and between 30 and 50 km wide.

In this paper, we will examine one pair of bands which formed between 16 and 18 UTC on the 1st of April, 2004, and lasted until 00 UTC on the 2nd of April. We will present imagery from the Level II radar data from the Boston/Taunton, Massachusetts radar site (KBOX), as well as output from a mesoscale model run initiated at 00 UTC, 01 April 2001. Section 2 will describe the model configuration, section 3 will give a synoptic overview of the storm, section 4 will present a brief comparison between the model output, and the KBOX images, section 5 will show observations and model-derived cross-sections through the coastal front, and some rain bands, while section 6 will draw some preliminary conclusions.

2. MODEL CONFIGURATION

The Fifth Version of the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) was run for 48 hours of simulated time beginning at 00 UTC, 01 April, 2004, using Eta Model, 90-km gridded output for boundary and initial conditions. The model was set up with 3 grids, as shown in Figs. 2a, b and c. The outer grid had a 36 km grid size, and two-way interaction was used for the nested 12 km and 4 km grids. Simple ice physics (Dudhia, 1989) was employed, the MRF boundary layer parameterization (Hong and Pan, 1996) produced the boundary layer fluxes, and the Grell convective scheme (Grell, 1993) was applied in the 36 and 12 km grids, while no convective parameterization was used in the 4 km grid. The model was run with 34 sigma levels in the vertical, twelve of which were below 1.5 km.

The model output was produced at one-hour intervals, and processed into GrADS (Grid Analysis and Display System – see http://grads.iges.org/grads for more details) format using a Unix script.

3. SYNOPTIC OVERVIEW

3.1 *Surface Patterns*

At 00 UTC 1 April 2004 shown in Figure 3a, an organized low pressure area formed east of the Virginia and North Carolina coastlines from three low pressure areas that were present in the region 12 hours prior. Cyclonic flow broadened over the Atlantic coastline inland to western Kentucky as this area of low pressure continued to deepen and organize. Cold air damming over the Northeast, ceased as high pressure had moved east over the

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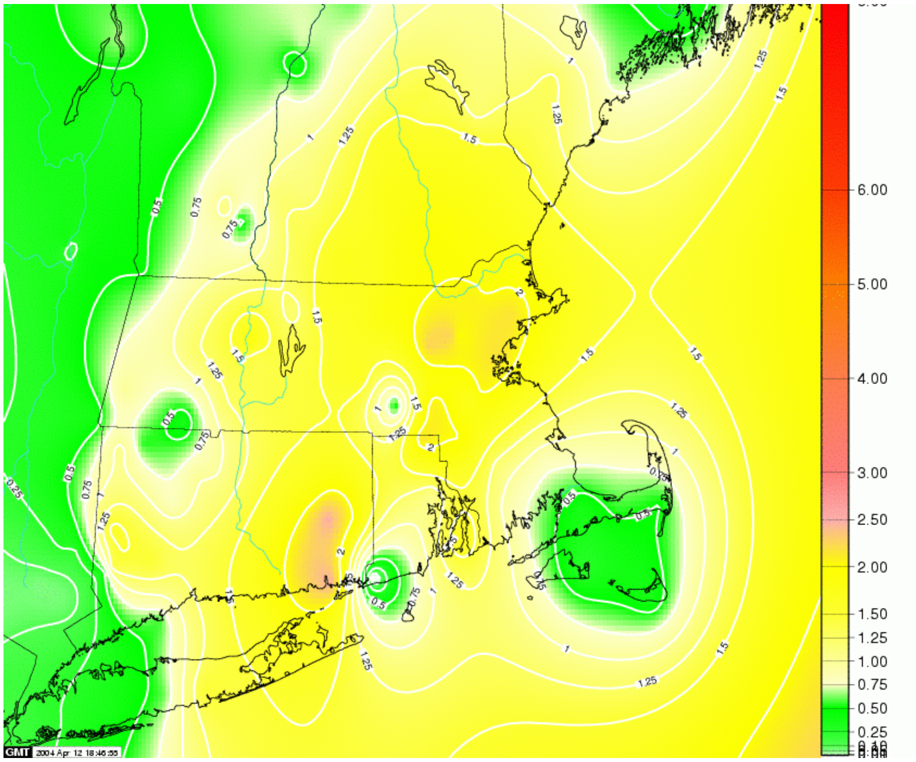


Figure 1a. 24 hour precipitation between 12 UTC, 31 March and 12 UTC, 01 April 2004 in inches, from the National Weather Service office at Taunton, MA.

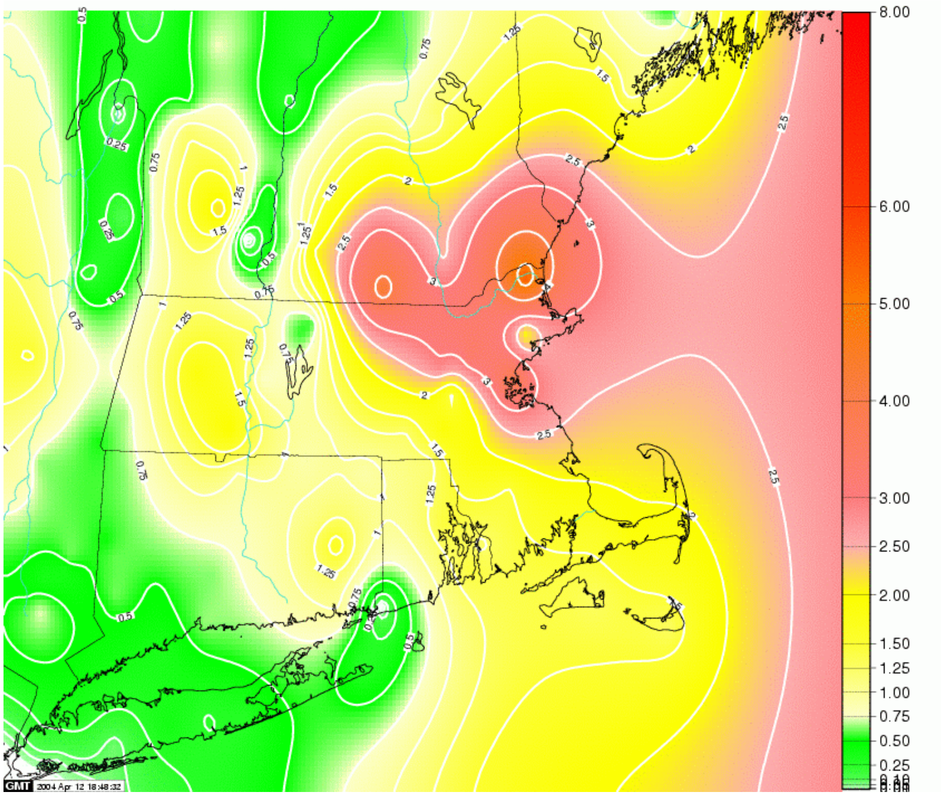


Figure 1b. As in Fig. 1a, except for the period 12 UTC, 01 April – 12 UTC, 02 April, 2004.

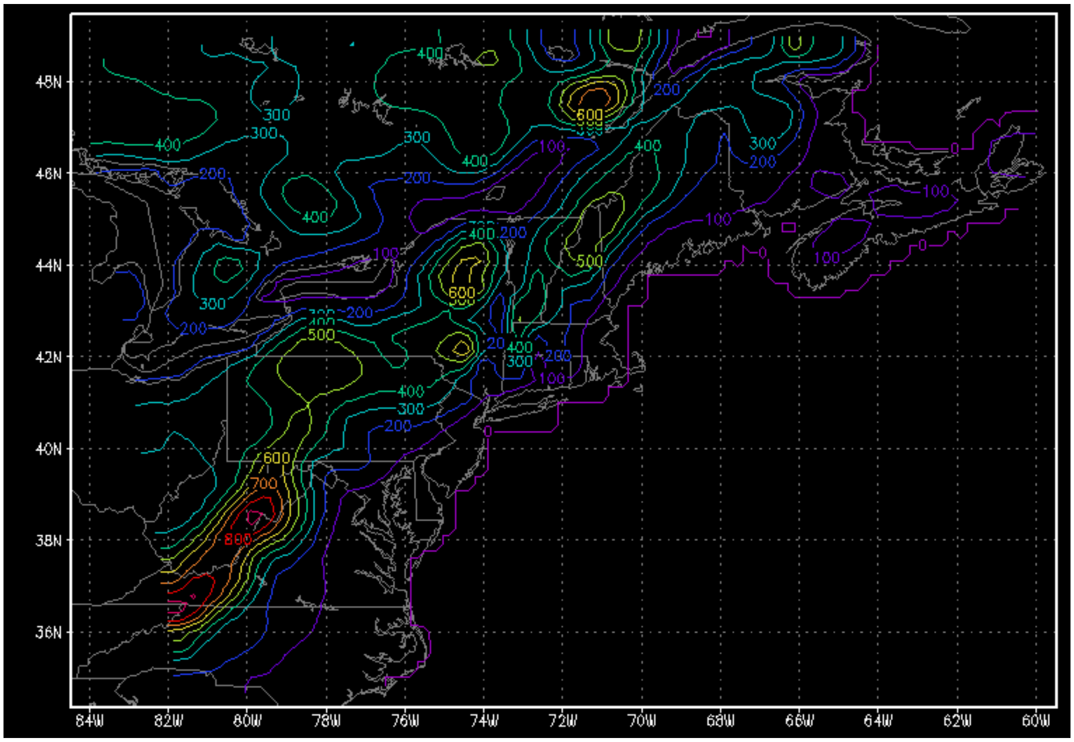


Figure 2a. 36 km grid for MM5 model run, with terrain in meters.

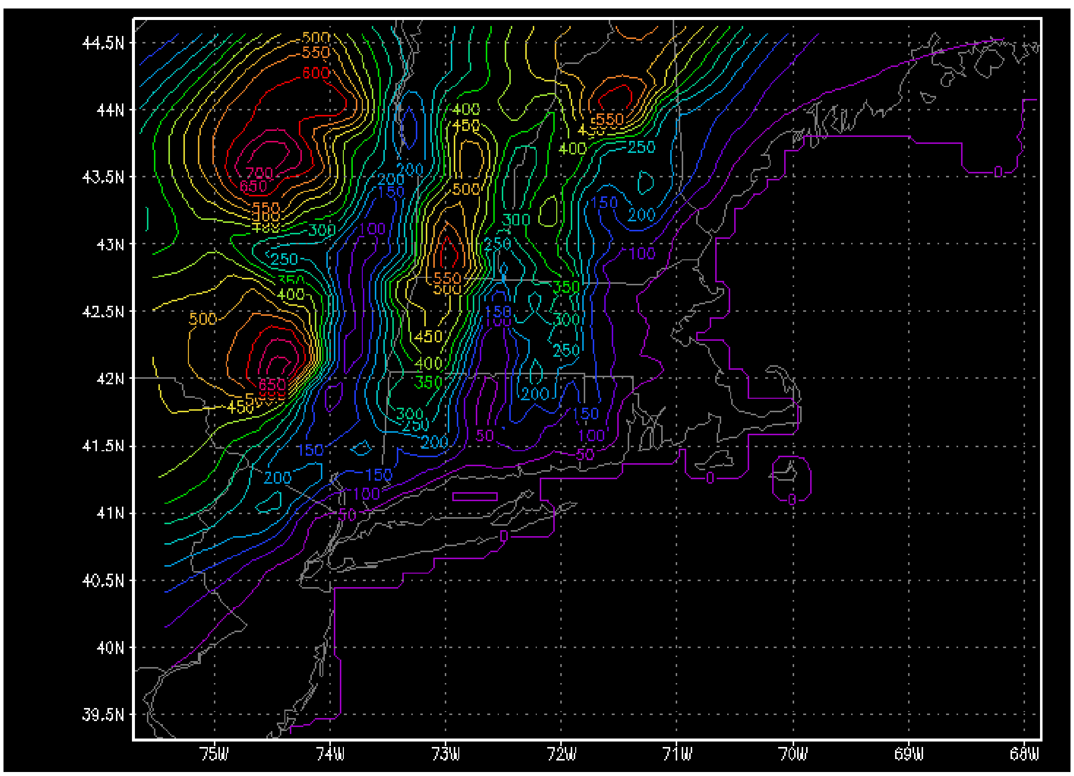


Figure 2b. 12 km grid for MM5 model run, with terrain in meters.

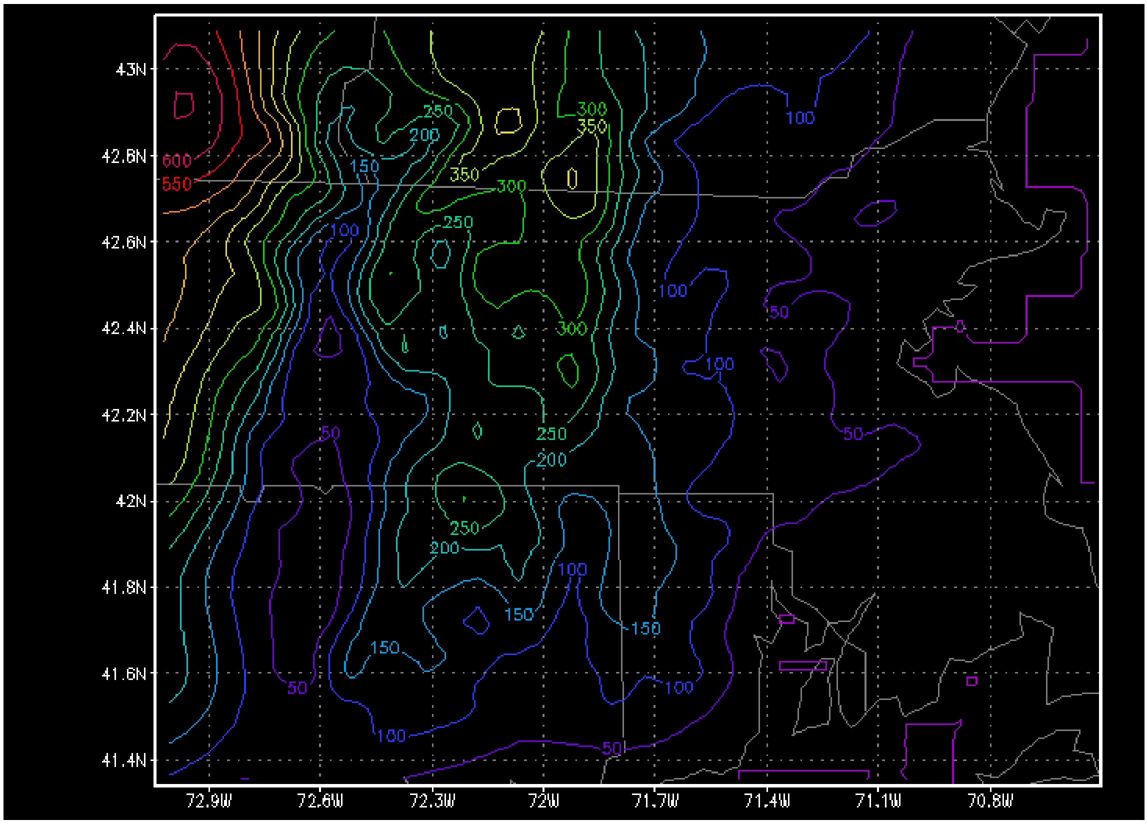


Figure 2c. 4 km grid for MM5 model run, with terrain in meters.

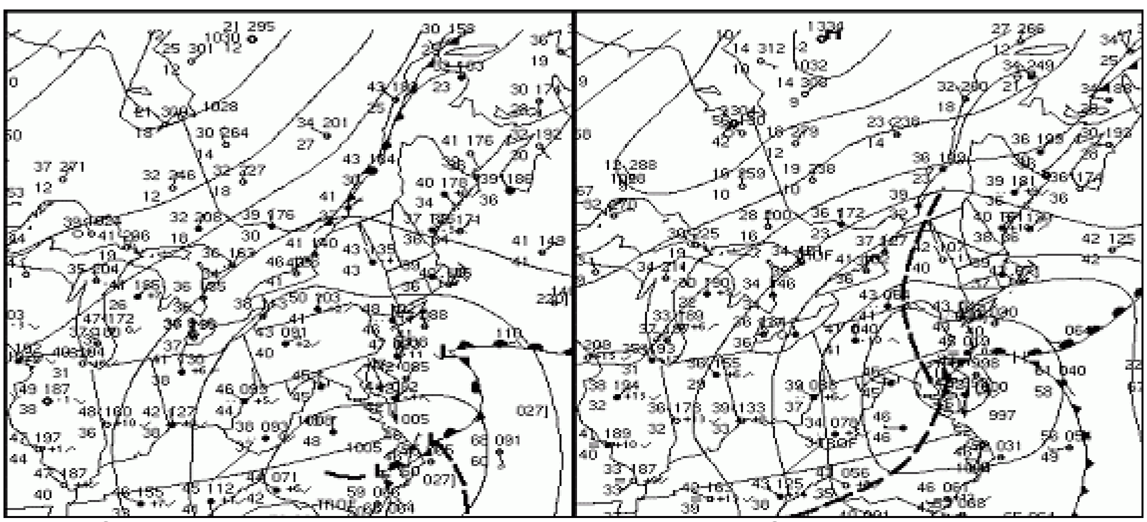

a) 00 UTC 1 April 2004 b) 00 UTC 2 April 2004

Figure 3. National Weather Service sea-level pressure analysis at the labeled times. Observations plotted in conventional manner.

previous 12 hours (not shown); however, cyclonic flow around the low pressure area over the mid-Atlantic coastline created onshore flow and temperatures remained near 5 ºC throughout much of southern New England. By 00 UTC 1 April 2004, cloud heights dropped below 500 ft in most areas of southern New England, precipitation began over the south coastal areas and quickly worked northward toward inland sections.

At 00 UTC 2 April 2004 shown in Figure 3b, low pressure cyclogenesis continued with pressure falls of

12 hPa in the 24-hour period of 1 April near Washington/Dulles, VA (KIAD). The low pressure center had become positioned over the Delmarva Peninsula along the Atlantic coastline with a cold front draped south of the low, a warm front extending east of the low and trough-like features extending in multiple directions from the low as denoted in the isobaric patterns.

Due to a stronger pressure gradient, wind speeds over southern New England increased from 5 to 20 kt out of the east-northeast providing a greater maritime influence that allowed daytime high temperatures to reach 5 °C for the duration of the precipitation event. Warm temperature advection commenced east of the low pressure area along various inverted trough features that moved north toward New England during the precipitation event. This allowed for baroclinic conditions to exist near 900 hPa over south coastal portions of Rhode Island and Massachusetts, which was integral in the creation of upward motion and heavy precipitation over the Northeast United States from 31 March through 3 April.

2 April 2004 (not shown) was characterized by little change in the overall synoptic surface pattern although the central low pressure area over the Delmarva region showed signs of weakening in response to weakening upper level features with a 24-hour central pressure rise of 6 hPa. Due to weakening of the low pressure area, warm temperature advection east and north of the low decreased and baroclinic conditions lessened in the lower troposphere over southern New England, which allowed for the decrease in upward motion and precipitation by late on 2 April.

3.2 Upper Level Patterns

At 00 UTC 1 April 2004 (Figure 4), a closed vortex was positioned over the Appalachian Mountains in Tennessee, Kentucky, and North Carolina. Observed winds around the vortex were nearly 100 kt in the jet core at the 300 hPa (not shown) and 500 hPa levels while a lower level jet at 700 hPa had strengthened to speeds of 50 kt. Positive vorticity advection (not shown) continued to become stronger in the jet core region at 500 hPa as the surface low continued to strengthen.

A local height maximum over Nova Scotia at this time continued to weaken and move northeast; thus, falling heights and increasing wind speeds were observed over the Northeast at all pressure levels. By 12 UTC 1 April 2004 (not shown) the closed vortex and synoptic scale trough feature moved eastward across the Appalachian Mountains toward the Atlantic coastline, and the closed vortex had become vertically coupled at the 300, 500, and 700 hPa pressure levels. The closed vortex continued to deepen to heights of 291 dam at 700 hPa and temperatures within the vortex were generally around –8 °C along with saturated air. At 500 hPa, strong positive vorticity advection was observed in the region of the jet core and in the region of the rapidly intensifying surface low pressure area. Figure 5 depicts the 500 hPa absolute positive vorticity advection by the observed wind along with 500 hPa heights, which shows that the region of positive vorticity advection was greatest over the Delmarva Peninsula northward into Maryland, Delaware, and New Jersey. Synoptic scale calculations show that absolute positive vorticity advection was the chief contributor for the development and intensification of the surface low in the Delmarva region. Over the next 24 hours, there was very little movement of the large vortex and synoptic scale trough over the Atlantic Coastline although there was slight deepening of the vortex at 700 hPa where heights fell to around 888 dam. Positive vorticity advection decreased significantly in the direction of the low pressure area at 00 UTC and 12 UTC 2 April (not shown), which indicated that development of the surface low pressure due to positive vorticity advection had nearly ceased. Therefore, the surface low weakened after 2 April.

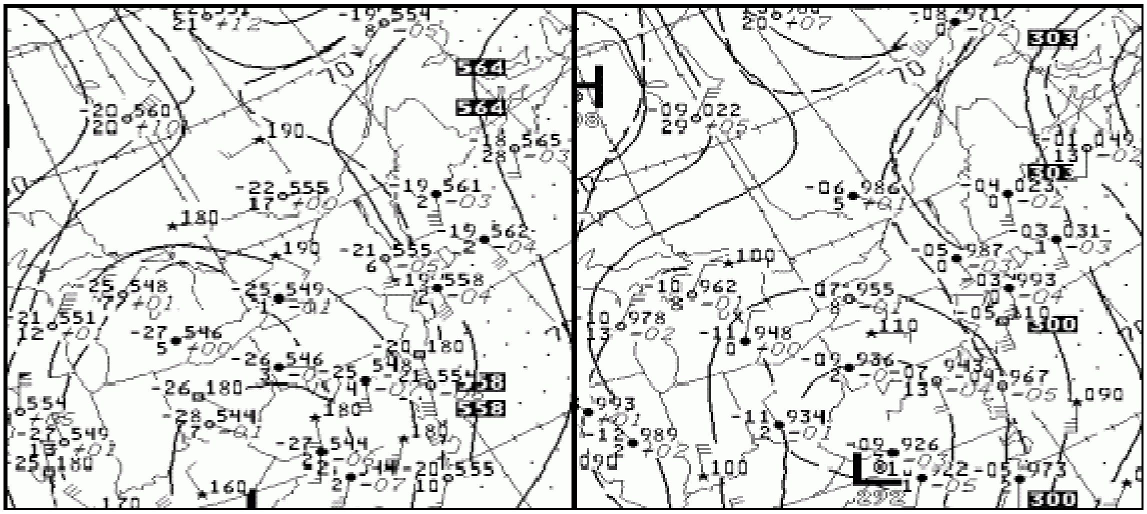
4 MODEL VALIDATION

Before relying on the MM5 output as a proxy for the real atmosphere, we wanted to be able to confirm that the model produced structures that resembled what actually happened. Once this validation process is complete, we can feel more confident in using the detailed model output to try to understand the behavior of the atmosphere.

The MM5 model run produced four distinct banded precipitation structures that lasted for more than two hours. Of these four, three had analogues in the Level II radar data. The fourth band was very weak in the model simulation, and may have been too weak to show up on radar.

The first band that shows up in the MM5 run is the weak band with no apparent similar structure in the radar data. Figure 6 shows the integrated rain water from the 12 km MM5 grid at 06 UTC, 01 April 2004, and the corresponding radar image. The weak band that stretches down the coastline in the MM5 run does not have a counterpart in the radar data, although the location of the band is reasonable based on the onshore flow that exists at this time.

By 12 UTC, as shown in Fig. 7, a series of rain cores is oriented in a line stretching approximately from New York City, NY, northeast to the New Hampshire coastline. The corresponding radar image from 1129 UTC shows a very similar pattern. By 16 UTC, a series of bands oriented southeast to northwest appears in the MM5 simulation. Figure 8a shows three such bands. By 18 UTC, Fig. 8c, there are two strong bands, as in the radar imagery for this time.



a) 500 hPa b) 700 hPa

Figure 4. National Weather Service constant pressure level analysis on 00 UTC 1 April 2004.

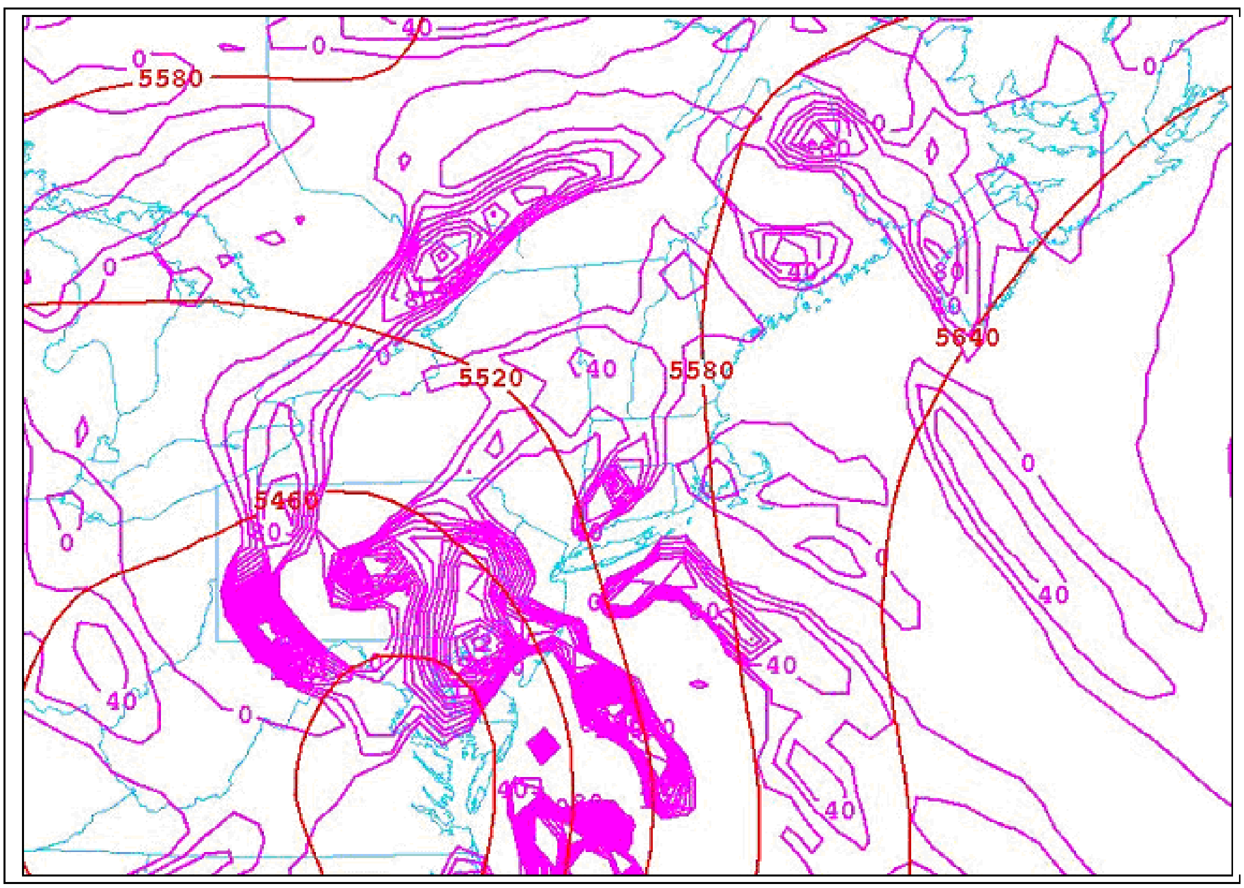


Figure 5. Absolute positive vorticity advection by the observed wind at 500 hPa and 500 hPa heights at 12 UTC, 01 April 2004. Lines of constant absolute positive vorticity advection are contoured at every 10^{-14} s^{-2} and lines of constant height are plotted in (m).

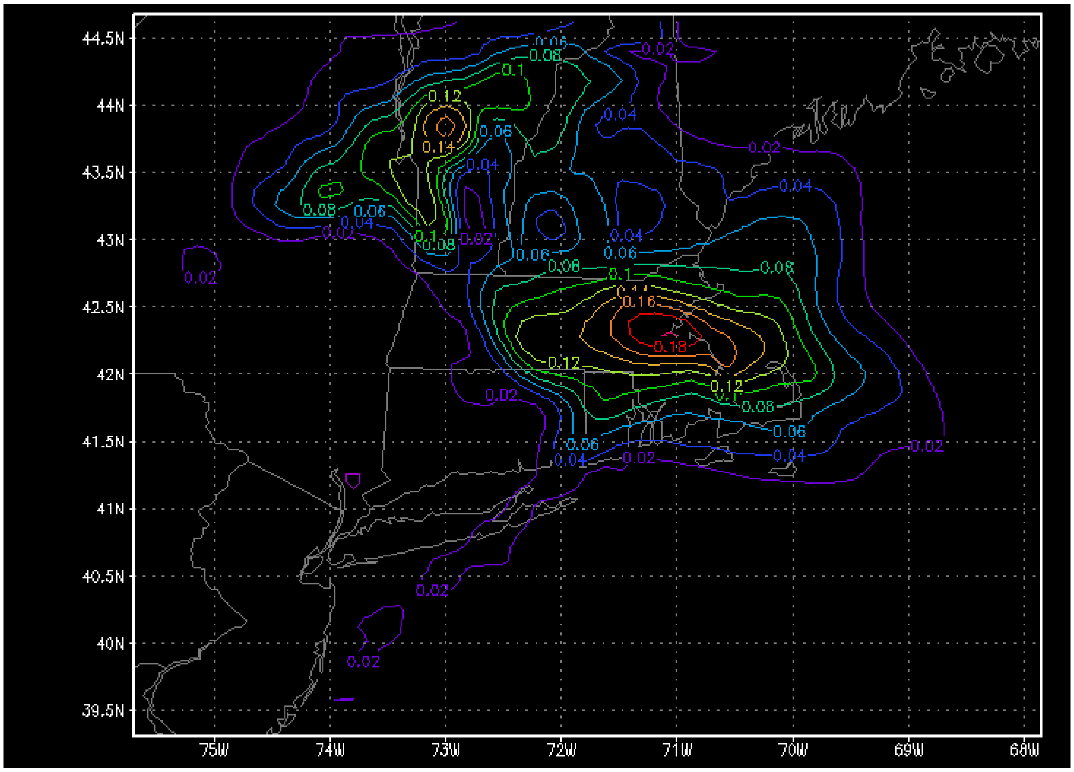


Figure 6a. Integrated rain water from 12 km MM5 output grid, contoured in cm, for 06 UTC, 01 April 2004.

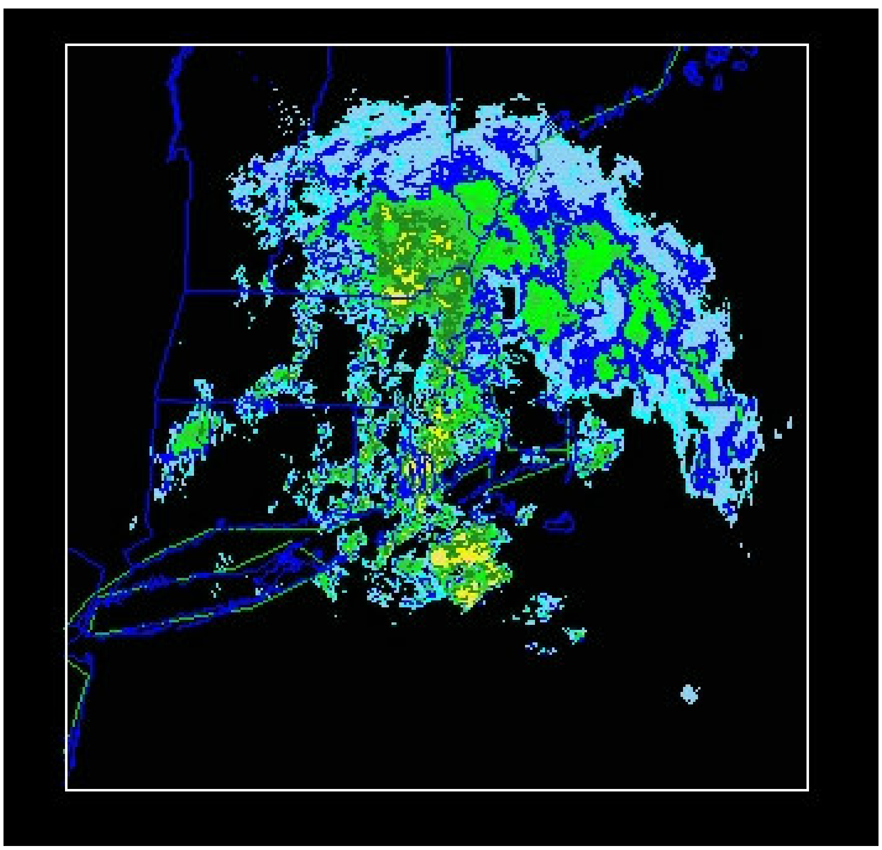


Figure 6b. Reflectivity from Boston/Taunton, MA WSR88-D, Level II radar data for 0557 UTC, 01 April 2004. Blue colors show 5 – 19 DbZ, green 20 – 34 DbZ, yellow 35 – 49 DbZ, and red 50 DbZ or more.

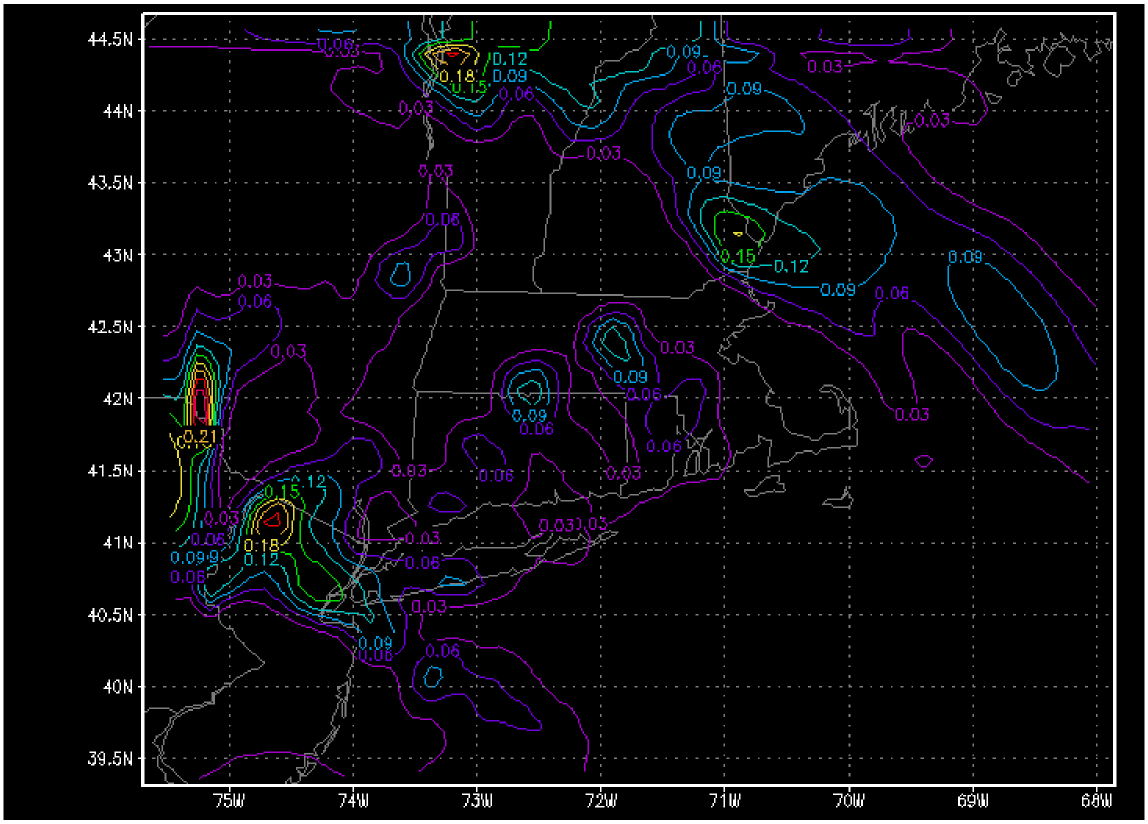


Figure 7a. As in Fig. 6a, except for 12 UTC.

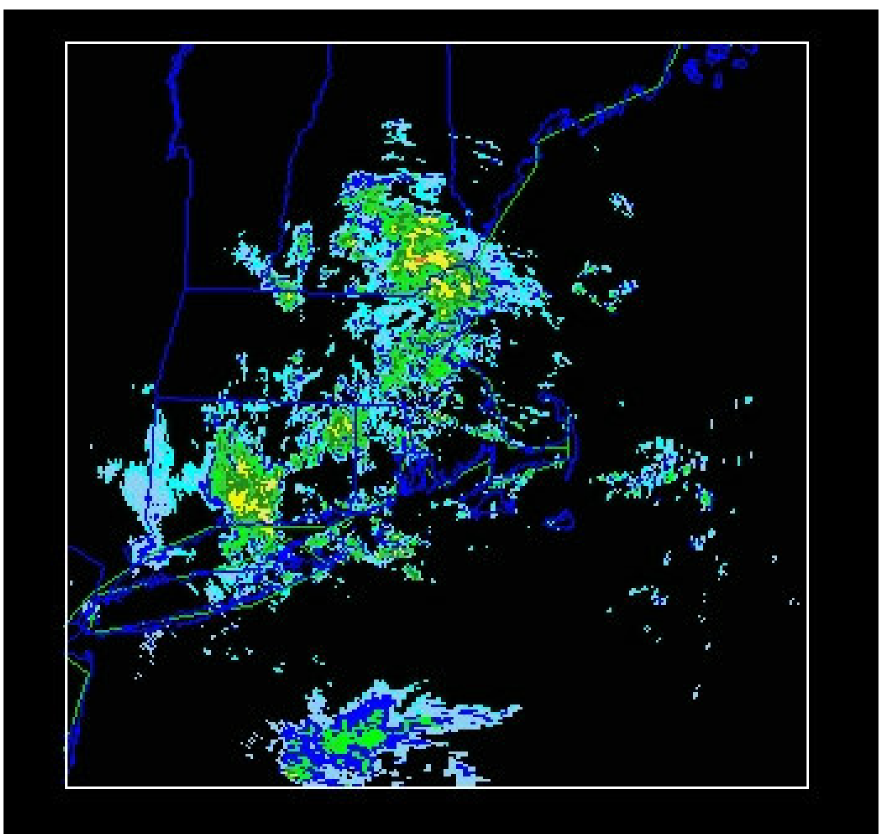


Figure 7b. As in Fig. 6b, except for 1100 UTC.

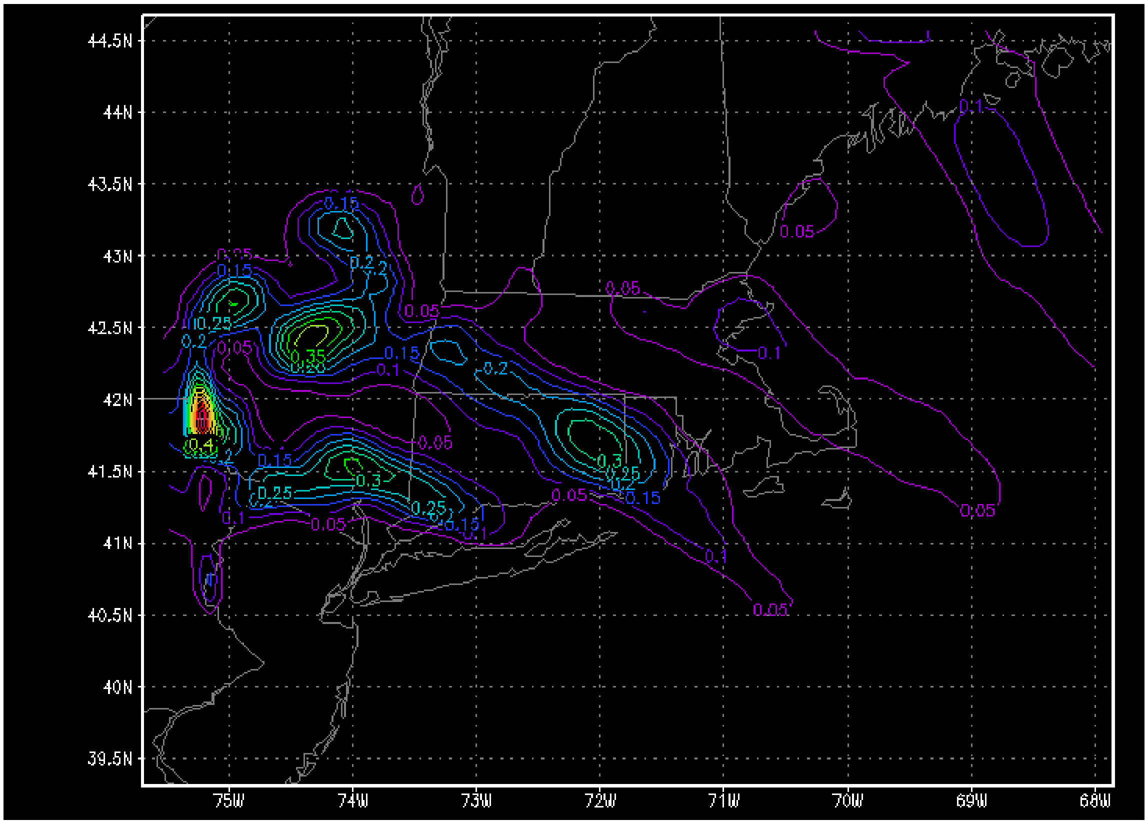


Figure 8a. As in Fig. 6a, except for 16 UTC.

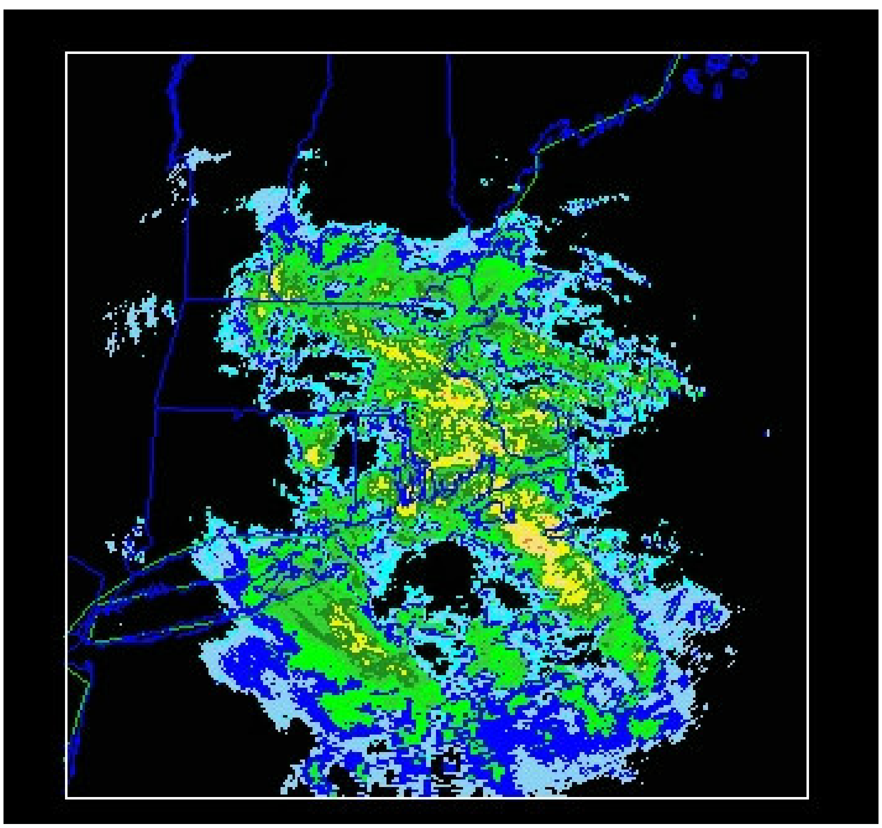


Figure 8b. As in Fig. 6b, except for 1700 UTC.

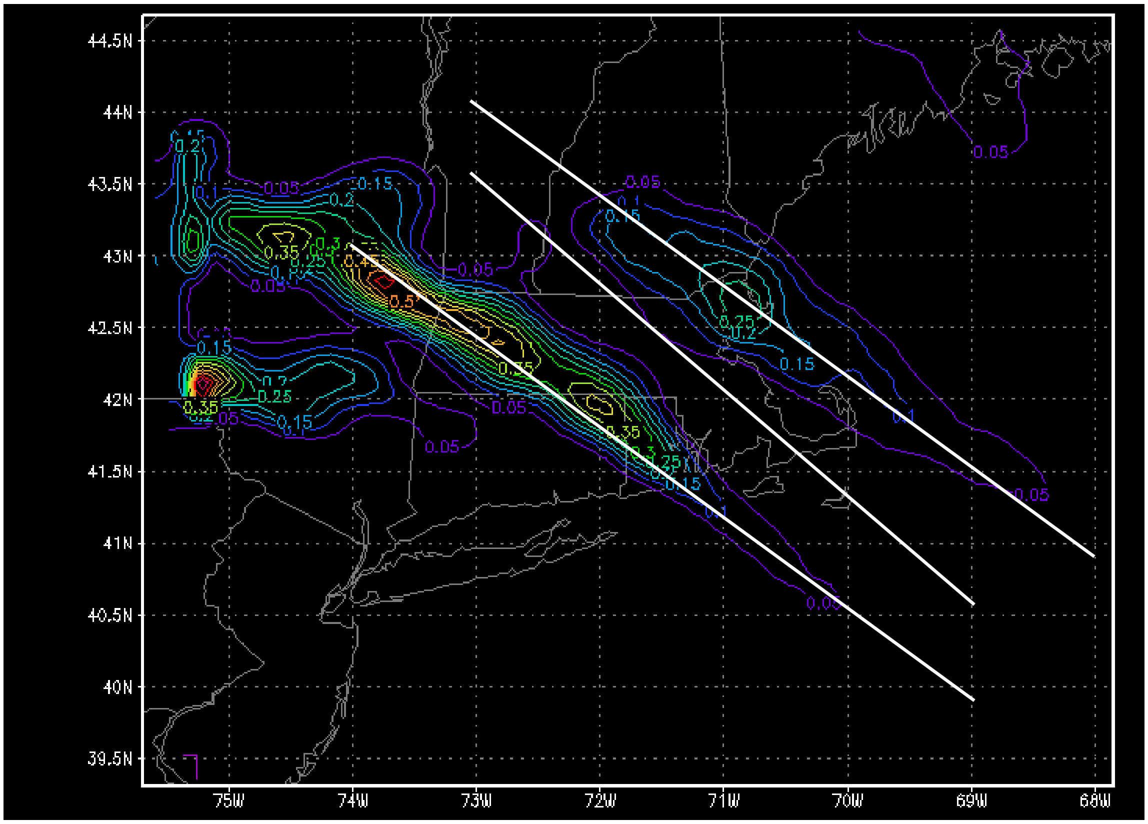


Figure 8c. As in Fig. 6a, except for 18 UTC.

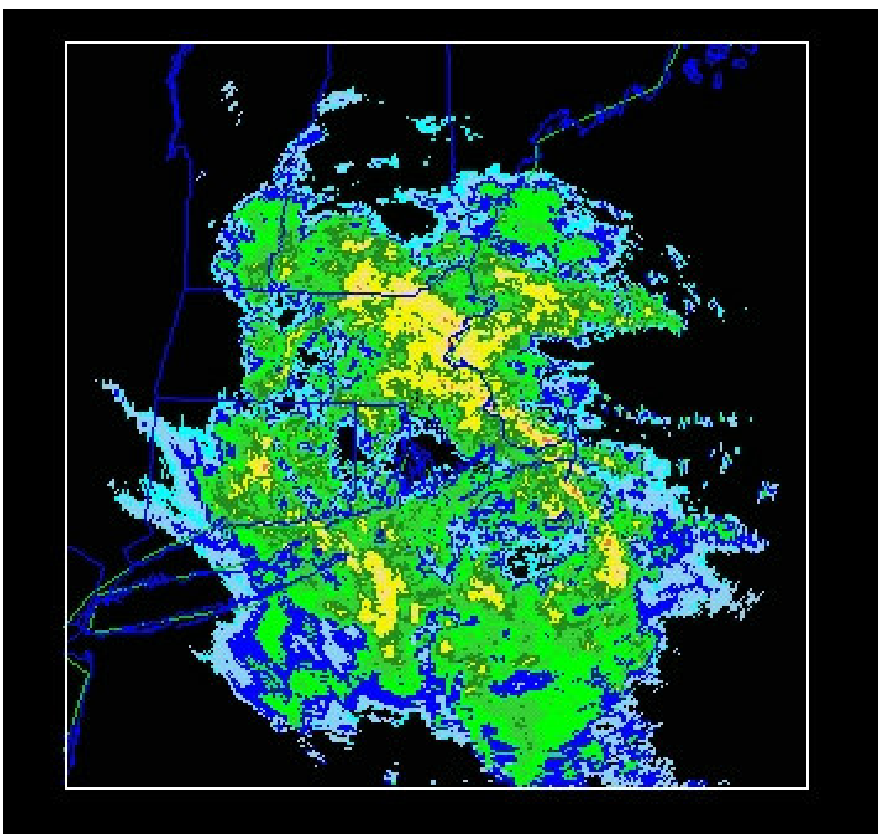


Figure 8d. As in Fig. 6b, except for 1758 UTC.

(Fig. 8d). These bands remain intact and nearly stationary for the next six hours in both the MM5 simulation and the radar data. Figure 9a shows these bands at 23 UTC, by which time the northern band has become dominant. The corresponding radar image (Fig. 9b) for 0004 UTC shows a similar pattern

Finally, by 06 UTC, 02 April 2004, the northern band becomes the only band, and the southern band dissipates. Figure 9 shows the model simulation for 06 UTC on the 2^{nd}, as well as the radar data for 0402 UTC. Notice the similarities between the two images, including the orientation of the band.

In all of these pairs of images, the radar data is much noisier than the model output, and as is often the case, the timing of the various bands is not necessarily the same. This last pair is particularly noteworthy for the timing issue. If one looks at the radar data for 06 UTC, the band is still there, but is located well north and east of the 0402 UTC image. This seems to be a general behavior when looking at mesoscale structures in model output. That is, we have seen a number of instances in which the model is able to simulate the meteorology, but the timing and/or location is not exactly correct.

In our case, given the correspondence between the various bands in the radar data, and the bands produced by the MM5, we are comfortable using the MM5 output to provide insight into the behavior of the atmosphere.

5. Coastal Front and Mesoscale Bands

The presence of the coastal front is best seen by looking at cross sections through it. Figure 10 shows a plan view of the near-surface temperature field superimposed with the vertical motion at about 940 hPa. In this figure, the presence of the topographically influenced flow in central and western Massachusetts shows up very well, but the upward motion along the coast, where the low-level temperature gradient is strong, is also prominent. This coastal front was present for much of the period of precipitation.

One very interesting twist on the coastal front is that the bands that formed were generally oriented perpendicular to the front. For instance, the dual bands that showed up in the model simulation around 16 UTC, and lasted beyond 00 UTC, 02 April (see Figs. 8a, 8c, and 9a) cross the coastal front at right angles.

Figure 11 shows cross sections that run parallel to the bands, as shown in Fig. 8a. Notice the transition from south to north, as the intensity of the inversion between the warm marine air and the cold continental air becomes more pronounced. The vertical motion is very strong right at the boundary between the marine air and the continental air, where the horizontal temperature gradient is strongest.

6. SUMMARY

What isn't clear from the imagery is why the two bands formed, rather than one wider band, as happened later on (see Fig. 9). Further work with the shear profile is underway, in an attempt to find instabilities that might cause the banding. The tendency to form bands showed up early in the storm's history, as shown in Fig. 7a, so there is something fundamental causing this banding. Additional images and discussion of these issues can be found on the website, http://storm.uml.edu/~colby/coastalfront.htm.

7. References

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.,* ***46,*** *3077–3107.*

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.,* **121,** 764-787.

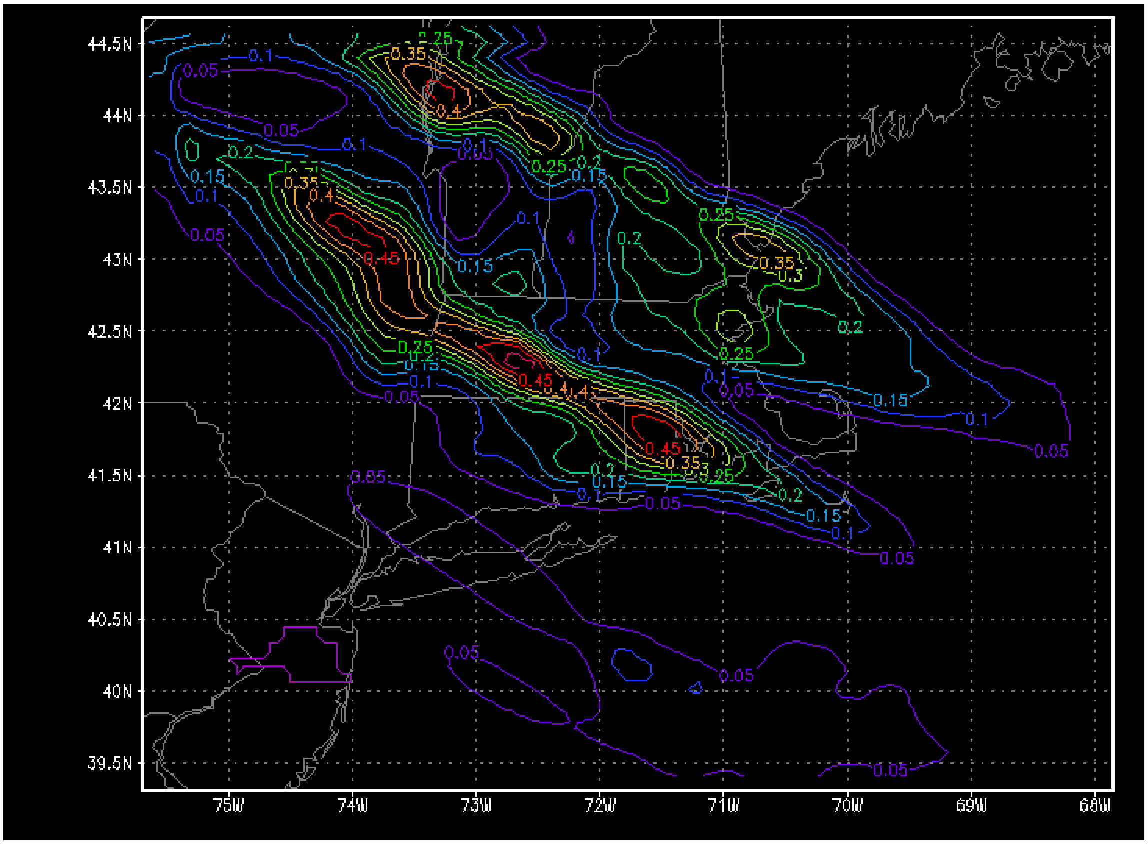


Figure 9a. As in Fig. 5a, except for 23 UTC.

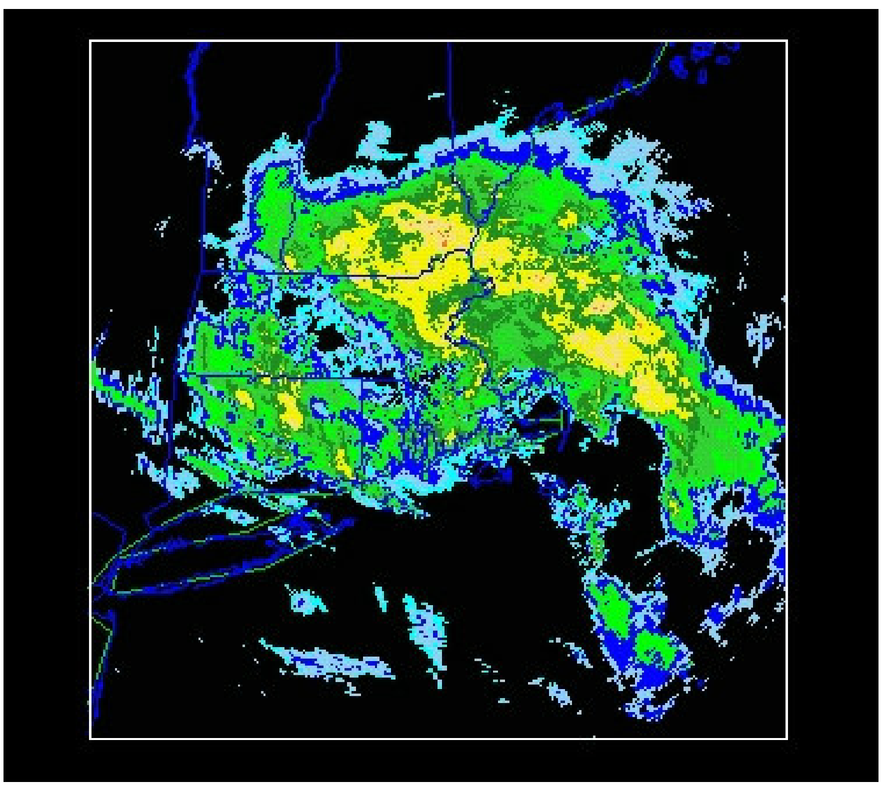


Figure 9b. As in Fig. 5b, except for 0004 UTC.

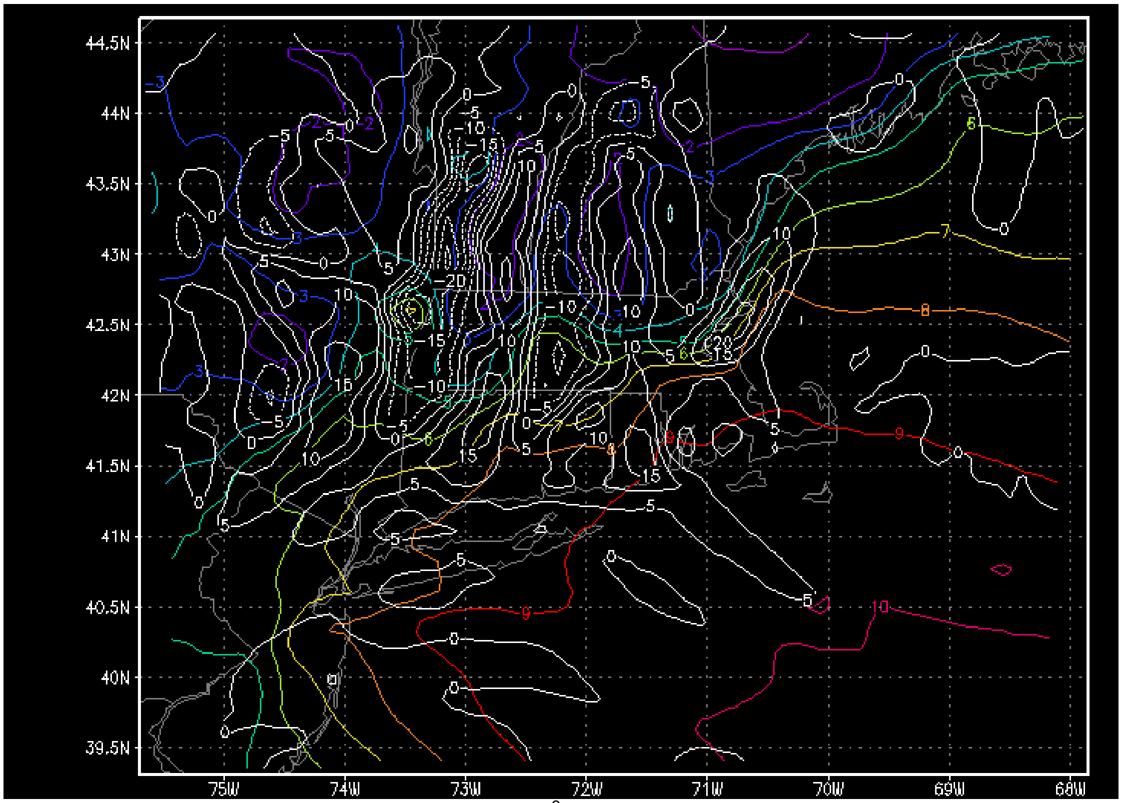


Figure 10. Temperatures from lowest model layer (^{o}C) in color, and vertical motion at 940 hPa (cm/s) in white.

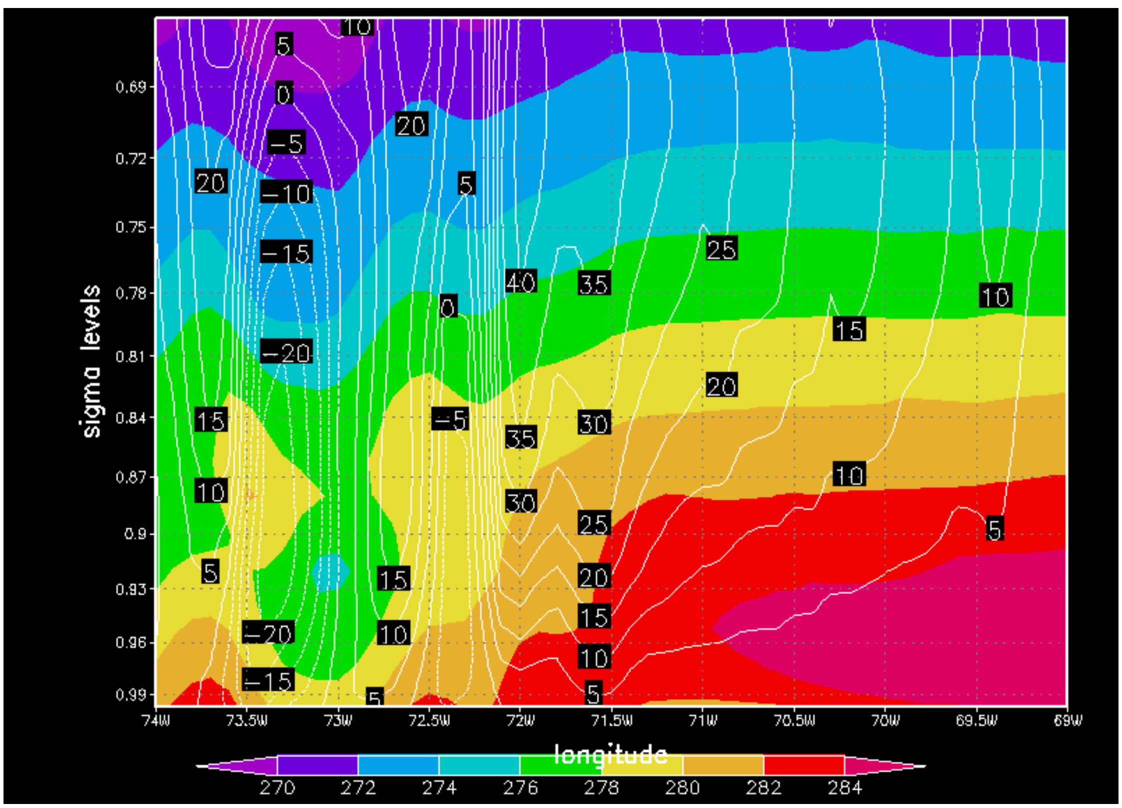


Figure 11a. Cross section along southern-most line in Fig. 8a. Temperature in color (K) and vertical motion (cm/s) in white.

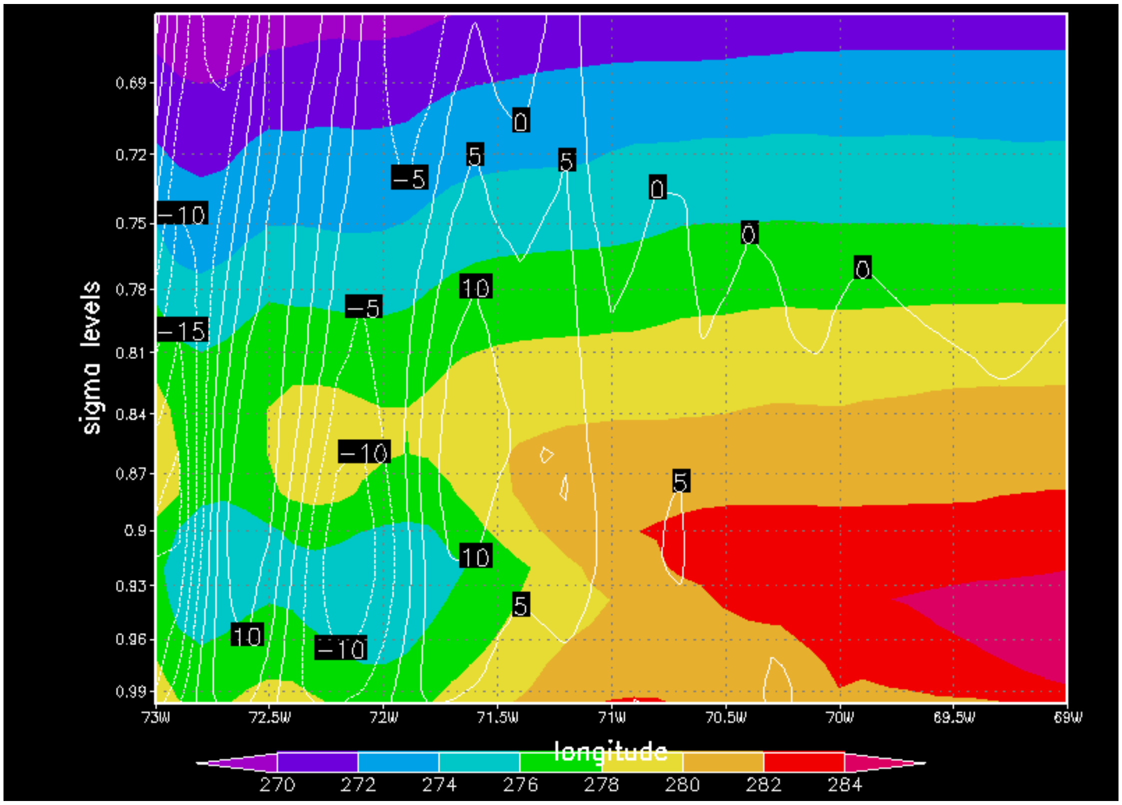


Figure 11b. As in Fig. 11a, except for middle line in Fig. 8a.

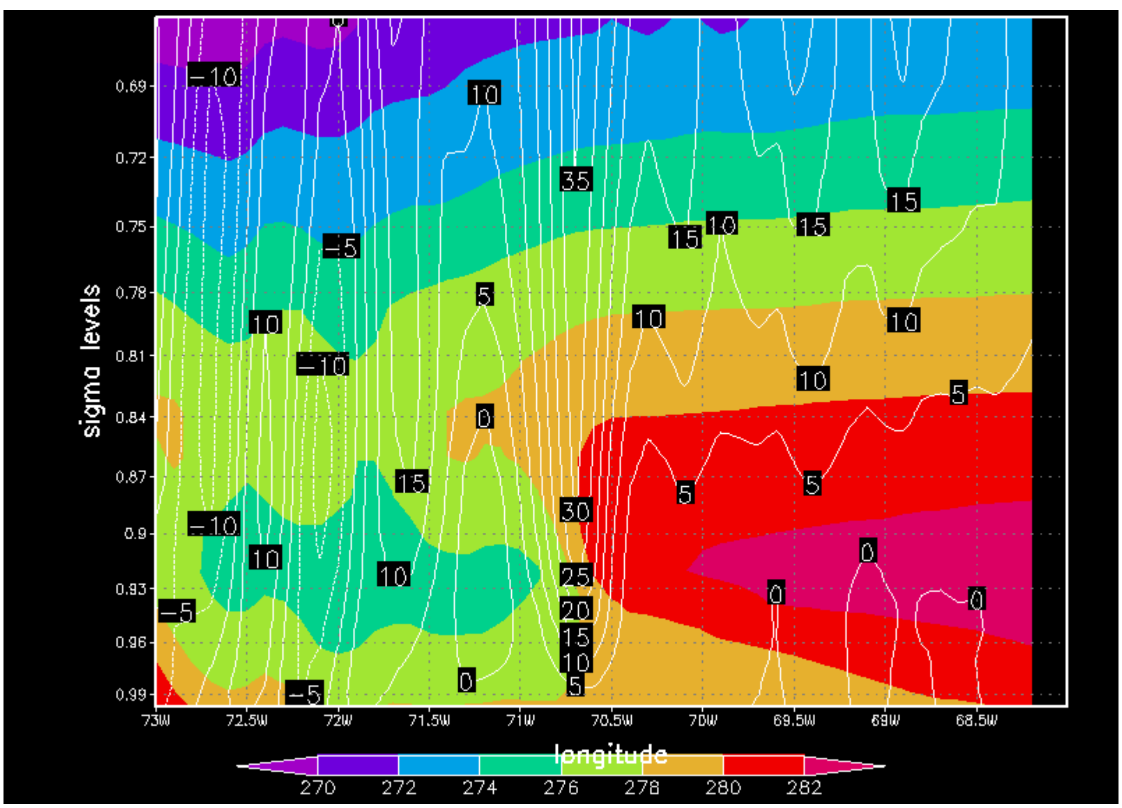


Figure 11c. As in Fig. 11a, except for northern-most line in Fig. 8a.