NOTES AND CORRESPONDENCE

Comments on ‘‘Numerical Simulations of an Observed Narrow Cold-Frontal Rainband’’

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1. Introduction

In a recent paper, Chen et al. (1997, hereafter C97) presented a detailed mesoscale model simulation of the intense cold front event of 28 December 1988 in Maryland studied by Koch and Kocin (1991, hereafter KK91). Although the findings of C97 are interesting, there are several issues that are of concern. In order to put these matters into proper perspective, it is first necessary to understand that the observational synthesis conducted by KK91 suggested that the frontal-scale contraction process culminating in the generation of this narrow cold-frontal rainband (NCFR) was the result of a complex *series* of interactions between phenomena on *several* scales. First of all, the NCFR developed following merger of an arctic front with a stalled cold front over the Appalachian Mountains. The merged frontal system displayed a pressure jump at its leading edge, which appeared to be dynamically linked to a deep tropopause fold. An ageostrophic momentum surge associated with this isallobaric feature appeared to have initiated rapid frontogenesis over the lee slopes of the Appalachians. KK91 hypothesized that the subsequent descent of the merged frontal system down the lee slopes and evaporative cooling of intense precipitation that developed within the NCFR led to the formation of a *new* microscale pressure jump of 8-mb amplitude and a gravity current–like microstructure at the leading edge of the front. They explained the intensity and maintenance of the NCFR on the basis of a balance between the solenoidally forced vorticity within the gravity current and the vorticity produced by strong vertical wind shear associated with a prefrontal low-level jet, in a manner described by Rotunno et al. (1988).

The fundamental issue that was raised by the KK91 study—but could not be answered—is what processes are necessary to produce such gravity current structures along cold fronts. Controversy continues to surround this issue. Observational studies of both precipitating and nonprecipitating fronts in which gravity current structures have been alluded to have rarely exhibited a strong ‘‘feeder flow’’ in the cold air that is required of a gravity current system (Smith and Reeder 1988), yet simulated fronts subjected to intense cross-frontal differences in sensible heating may exhibit gravity current structures (e.g., Koch et al. 1995; Koch et al. 1997). But what about situations in which sensible heating is not a major factor, such as the late December case studied by KK91? A strong 9 m s^{-1} feeder flow was diagnosed 50 km into the cold air in this case. Unfortunately, the available observations and numerical model guidance did not permit them to determine the relative importance of adiabatic frontal collapse, evaporative cooling, low-level shear, and ageostrophic accelerations caused by orography in the frontal contraction process leading to a gravity current structure.

KK91 suggested that a high-resolution model with comprehensive microphysics should be used to examine this multiple-scale hypothesis. Regrettably, because of deficiencies in the Mesoscale Model version 5 (MM5) simulations performed by C97, these numerical experiments are not adequate for testing the relative importance of the various scale contraction processes leading to the formation of a gravity current. As is explained below, these experiments fail to test the scale contraction hypothesis, because the results are inconclusive as a consequence both of these deficiencies and the experimental design.

2. Deficiencies in simulating the gravity current

The MM5 model was run by C97 on a 5-km-resolution nested grid with an explicit microphysical scheme, a multilevel planetary boundary layer (PBL) scheme, and four-dimensional data assimilation, all at-

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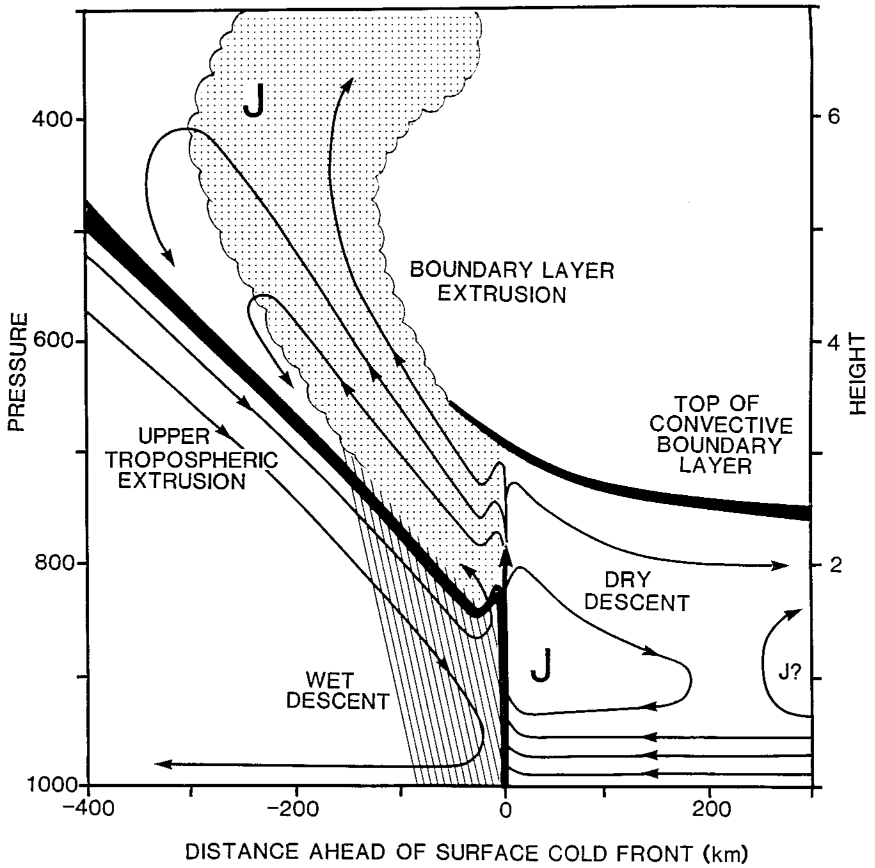

FIG. 1. Circulation and precipitation systems composing a narrow cold-frontal rainband (NCFR) according to the schematic model of Browning and Pardoe (1973). Thick lines represent the cold frontal zone and the top of the convective boundary layer. Front-relative circulation system, low-level jet(s), and regions of intense rainfall and of saturated slantwise ascent are all depicted.

tributes shared by or similar to typical research mesoscale models currently in use. The model successfully produced an intense, narrow rainband in the correct place at the right time. However, the MM5-predicted rainfall rates within the rainband of 10 mm h^{-1} are a small fraction of the 114–180 mm h^{-1} rates determined by KK91 from the radar reflectivity within the core of the NCFR. While this failure was acknowledged by C97 and is easily attributable to the grid resolution, they did not mention the negative effects that this would have on the development of a gravity current structure in the model simulation due to its poor representation of evaporative cooling. The microphysics scheme developed by Dudhia (1989) for the MM5 model produces evaporation when precipitation falls into a layer that is subsaturated with respect to water, as long as the evaporation of cloud water is insufficient to remove the subsaturation. The evaporation parameterization is based essentially on the work of Kessler (1969), according to which the evaporation is assumed to be nearly proportional to a product of the saturation deficit and a power of the rainwater mixing ratio, which is related to the precipitation content. Thus, an order-of-magnitude error in the forecast precipitation rate will result in a very large underestimate of the evaporative cooling rate. This error seriously limited the ability of the MM5 model to produce a true gravity current.

This problem was compounded by the fact that the model failed to produce the observed slantwise ascent that was necessary to generate a strong cold pool. The schematic model of the NCFR circulation system shown in Fig. 1 (Browning and Pardoe 1973) depicts strong vertical ascent within the NCFR updraft, though it is the hydrometeors produced by the slantwise ascent rearward of the front that are essential for maintaining the evaporational cooling as the precipitation falls into dry postfrontal air. This precipitation system is not unlike that of a mature mesoscale convective system containing a trailing stratiform anvil (Houze 1993), in which frozen hydrometeors provided by the leading convective line are supplied to the mesoscale ascent region to the rear. By contrast, the simulated frontal circulation reported by C97 shows an erect NCFR convective structure with no significant postfrontal precipitation (Fig. 2). As noted by the authors, the simulated evaporative cooling was unimportant, since the hydrometeors fell into the moist

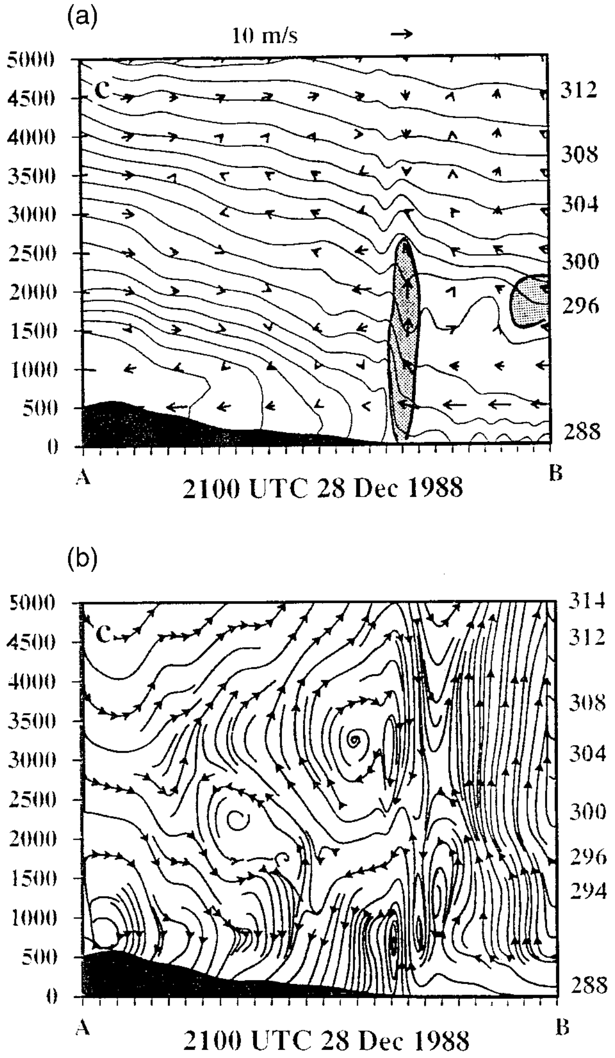

FIG. 2. Vertical cross sections normal to simulated front at 2100 UTC, the time of most pronounced "gravity current–like structure": (a) contours of potential temperature (K) and cloud mixing ratio (shaded ≥ 0.5 g kg^{-1}), and (b) streamlines. The profile of terrain is shown by dark shading near the bottom boundary. The dimensions of the cross section are 480 km in the horizontal direction (tick marks at 17-km spacing) and 5 km in the vertical. [Cross sections (a) and (b) are adopted from Figs. 10c and 12c of C97, respectively.]

air at and ahead of the front. Even if the model *had* produced the detrainment of ice particles in a slantwise ascent region, it would still have been necessary to account for the Bergeron–Findeisen process. By allowing supercooled water to exist in the presence of ice particles, vapor depositional processes could be handled correctly, and the particles would sublimate as they fell into the very dry postfrontal air mass. Recent versions of the MM5 model contain the option for such mixed-phase processes, but it would appear that C97 chose the simpler option that excluded the Bergeron–Findeisen process [i.e., the original Dudhia (1989) approximation].

The net result of these deficiencies and poor experimental design choices is that the model underforecast the observed rate of cooling and failed to produce a clear manifestation of a gravity current. The observed rate of cooling was 12°C 60 min^{-1} at Baltimore, which corresponds to a temperature gradient of 17°C 100 km^{-1} given the frontal speed of 19.4 m s^{-1}; the gradient was as large as 69°C 100 km^{-1} at Salisbury, Maryland. By comparison, the maximum temperature gradient attained in the MM5 simulation is estimated from Fig. 2a to be only 7°C 100 km^{-1}. The actual cross-frontal temperature gradient produced pressure jumps of >5 mb 15 min^{-1} at Salisbury, followed by a short period of nearly stationary pressure before the resumption of a pressure rise associated with the synoptic-scale cold front. Thus, the displacement between the gravity current and the cold front was quite distinct, not "speculation" as suggested by C97. Such a feature in the MM5 simulated fields was never discussed by them, so it is unknown whether this important feature was successfully modeled. The observed cross-frontal pressure gradient resulted in an ageostrophic momentum surge manifested as a strong feeder flow over a depth of 1.8 km, with front-relative speeds as large as 9 m s^{-1}. However, the MM5 produced only a weak, elevated patch of positive front-relative flow over a small region behind the front. The authors admit (p. 1036) that "for this reason, we cannot conclude that the system is a pure gravity current."

3. Deficiencies in treatment of orography

KK91 suggested that orographic effects also may possibly have been important in the scale contraction process. The impact of mountains upon airflow and precipitation has been studied by many investigators [e.g., see review by Smith (1989)]. These studies have shown that standing mountain waves, internal hydraulic jumps, severe downslope winds, upstream blocking, and wave breaking may occur in low Froude number (U/NH_M), where U is the cross-mountain wind component, N is the Brunt–Väisälä frequency (or static stability), and H_M is the mountain height. Idealized primitive equation modeling studies of frontal interactions with symmetric mountains have revealed the importance of these same phenomena on frontal structure and propagation (Williams et al. 1992; Gross 1994), including the development of leeside acceleration in response to the upslope high pressure under conditions of upstream blocking, frontogenesis on the lee slopes, and hydraulic jumps for narrow (nonsemigeostrophic) mountains.

The influence of the terrain on promoting the development of the NCFR finescale structure was claimed to have been studied by C97 by running a model simulation in the absence of terrain. Relatively minor effects are evident on the low-level flow and the cloud fields (although a pronounced "rain shadow" effect only appears in the presence of terrain); moreover, a weak "gravity current–like structure" structure still develops by 2100 UTC. The rotor that appears in the no-terrain run, which they speculated was an upstream-propagating bore, is also apparent in the control run. Hence, it is perplexing how C97 could conclude that ‘‘orographic features are important in shaping the cloud band structure’’ (p. 1043).

The authors seem to have ignored the results of previous idealized studies showing that the mesoscale effects of mountains on fronts are only important when the mountains are narrow. The terrain used by C97 in the MM5 control run (Fig. 2) is much too smooth to examine these orographic effects on leeside frontal-scale contraction. A comparison is presented in Fig. 3 between two runs of the Chen (1991) nonhydrostatic two-dimensional model initialized with the 0000 UTC 29 December sounding from Huntington, West Virginia (representative of the upstream conditions near the time of frontal collapse). The top panel shows the results of running the model with a smooth envelope representation of the terrain similar to that used in the MM5 experiments (mountain half-width $a \sim 100$ km). Only a weak stationary mountain wave develops, with a horizontal wavelength of 50 km. This result is consistent with the predictions from two-layer hydraulic theory (Houghton and Kasahara 1968) based on the soundings available in the region (Fig. 4); in all cases, only a weak stationary jump (or no jump) develops. In other words, use of such a smooth terrain should have *very little effect* upon frontal-scale contraction. On the other hand, use of a much more representative Appalachian mountain profile in the region (Fig. 3b), which includes numerous valleys and ridges, produces a large-amplitude hydrostatic mountain wave with a horizontal scale of $<$20 km directly downwind of the largest mountain in the chain.

The nonhydrostatic MM5 model can handle complex terrain with large slopes without becoming unstable (Dudhia 1995). Use of much more detailed terrain in the simulations would have provided a ‘‘crucial test’’ of the hypothesis that orography played a significant role in frontal scale contraction. The decision by C97 to compare a no-terrain to a smooth terrain simulation means that the real importance of orography on frontal-scale contraction remains ambiguous.

4. The importance of multiscale processes in frontal contraction

The authors entirely neglected the multiple-scale contraction processes leading up to the events on the lee slopes of the mountains *prior* to precipitation formation that were discussed by KK91 and that formed the basis for tentative hypotheses that should have been tested with the MM5 model. This is most unfortunate, since these are important issues that current-generation mesoscale models are well equipped to address, including the following.

- To what extent did the tropopause fold produce the pressure gradient responsible for the strong ageostrophic winds observed over the windward slopes of the Appalachians? Although the Nested Grid Model (NGM) did represent the fold, it badly underforecast the pressure gradient; the MM5 model could have been used for detailed investigation of this process.
- Does the merger of two fronts near a mountain crest result in strengthening and acceleration of the merged frontal system over the lee slope, similar to that seen in laboratory studies of gravity currents (Simpson and Linden 1989)? It is unknown whether the dual-front system was even produced by the MM5.
- What is the importance of adiabatic frontal contraction and frontal merger on the windward slopes relative to that of diabatic precipitation processes and leeside orographic enhancement in the frontal-scale contraction process? These are important issues, about which analysis of the MM5 simulation could have provided insight, but only if the deficiencies in the treatment of microphysics and terrain were removed.
- What roles are played by the following processes in driving the NCFR frontogenetical circulation system (Fig. 1): evaporation and sublimation of falling precipitation, latent heat release within the line convection, warm advection by the southerly low-level jet, and compensatory subsidence warming? These processes have all been suggested as helping to create the strong horizontal temperature differences and vertical circulations in other NCFR studies (Carbone 1982; Parsons et al. 1987; Dudhia 1993).
- To what extent did nonhydrostatic vertical pressure gradient forces maintain the strong frontal updraft within the NCFR (Parsons et al. 1987), instead of hydrostatic effects as postulated by C97? The relative roles of hydrostatic and nonhydrostatic dynamics were never elucidated by the authors, though the importance in doing so is clear.

5. Summary

These model deficiencies and experimental design failures precluded the testing of falsifiable hypotheses concerning the relative importance of microphysical, orographic, and adiabatic frontal-scale contraction processes. Nevertheless, C97 came to the conclusion that low-level wind shear played *a key role* in the generation of the gravity current–like structure. Their proposed process goes like this: the wind shear steepens the frontal slope and depth, resulting in a hydrostatic pressure buildup and enhanced cross-frontal pressure gradient, which intensifies the ageostrophic circulation, leading to the observed structure. While there is no contention that this process may be an important one, this study cannot assess its *relative* importance, nor refute alternative hypotheses.

In a broader context, this paper raises important issues for the use of mesoscale modeling in testing tentative hypotheses concerning complex interactions between

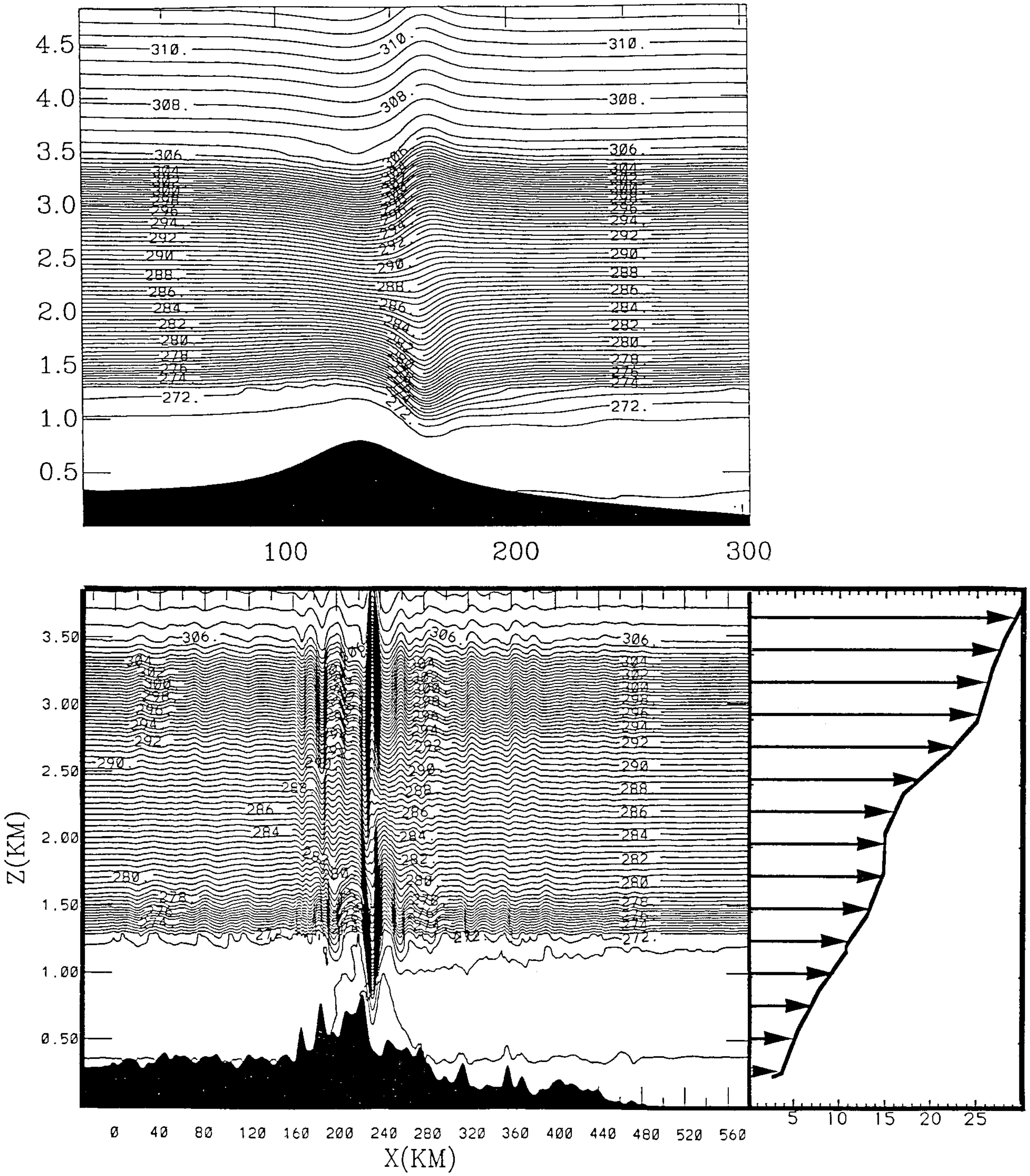

FIG. 3. Airflow across two different representations of the Appalachian Mountains in the vicinity of Maryland (the cross-sectional plane is roughly the same one used in the MM5 simulations by C97; e.g., Fig. 2). The top figure shows a smooth envelope, with a mountain half-width of 100 km, similar to that used in the MM5 simulations. The bottom figure shows a much more detailed representation of reality, which is that the Appalachians are composed of numerous parallel ridges and valleys. The airflow is represented by the isentropic structures (1 K intervals), and the initial cross-mountain wind profile used in both simulations is depicted on the bottom panel.

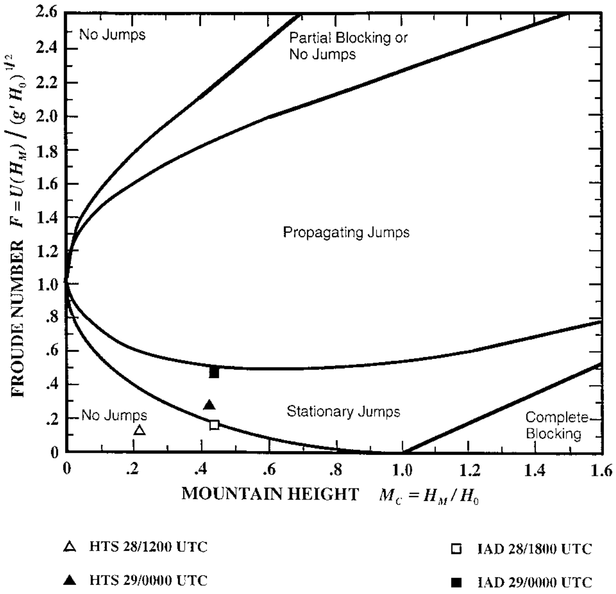

FIG. 4. Predictions from two-layer hydraulic theory (Houghton and Kasahara 1968) of hydraulic jumps as a function of the Froude number and the nondimensional mountain height (see text). Four predictions are shown based upon the soundings taken at Huntington, West Virginia (HTS), at 1200 UTC 28 December (28/1200) and 29/0000, and Dulles, Virginia (IAD), at 29/0000 and 28/1800 (the latter sounding represents a subjective reconstruction of the atmosphere at the time of the NCFR development). Inversion height is H_0.

processes that operate over a wide range of scales. In this case, the model configuration was ill equipped to account for the actual influence of cloud microphysics, the possible influence of topographically forced hydraulic jumps, and the interactions between the frontal updraft and the slantwise convection that occurred to the rear of the front. In particular, the use of a 5-km-resolution grid resulted in ''pseudoconvection,'' in which the updraft width and intensity contained within the NCFR were poorly resolved. This hurt any attempt to estimate the role played by the evaporation of precipitation in the generation of a gravity current. The sensitivity of microphysical processes to model grid resolution has been highlighted in other recent studies in which very high resolution mesoscale models have been used to study the initiation of deep convection along fronts (e.g., Dudhia 1993; Ziegler et al. 1997). These studies indicate that 1-km grid resolutions are necessary to produce the narrow convergence bands (<10 km wide) that provide the lift for initiating deep convection. Thus, it would seem that such cloud-scale grid resolutions are necessary to fully examine scale-interactive processes.

Finally, it is worth noting that this study is typical of those that employ model sensitivity experiments, in which one or another process (e.g., diabatic processes or terrain forcing) is eliminated to attempt to determine which processes are most important for the evolution of a phenomenon. These studies fall short of providing a conceptual framework based on general dynamical principles governing the step-by-step interactions and feedbacks among various scale-interactive processes, a criticism made a decade ago by Keyser and Uccellini (1987) in their review arguing that mesoscale models would become new tools for research (an excellent prediction). Much greater attention must be paid by the mesoscale modeling community to this need to investigate the atmosphere from more than a single perspective.

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