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NUMERICAL PREDICTIONS AND NOWCASTING OF DOWNSLOPE WINDSTORMS ALONG THE COLORADO FRONT RANGE

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1. INTRODUCTION

Strong downslope winds are relatively infrequent, but significant weather phenomena which occur during the winter months along the Colorado Front Range (see Figure 1). However, until recently the mechanisms responsible for the onset of severe downslope windstorms have not been well understood. Recent work (e.g. Smith, 1985, 1989) has clarified the process somewhat. The generalized hydraulic jump theory has shown that the presence of a critical layer, which can act like a rigid lid or free surface, is fundamental to the onset of these events. This critical layer can either pre-exist in the environment, or be generated through wave breaking. In idealized numerical experiments, (Clark and Peltier, 1984; Durran, 1986; Durran and Klemp, 1987; Bacmeister and Pierrehumbert, 1988), such a layer is required to reflect the upward propagating wave energy back downward to create the strong downslope wind. Using this knowledge, it is possible to improve the forecast of such events by means of a mesoscale meteorological model.

One stumbling block exists to such numerical forecasts. Due to the non-linear lower boundary condition (Lilly and Klemp, 1979) a high resolution numerical model is necessary to resolve the processes involved in downslope windstorms. This makes it practically impossible to run the model on a routine basis. Fortunately, certain synoptic conditions are also required for such an event to occur (Brown, 1986; Lee *et al.*, 1989). Therefore, we do not need to make a decision to perform a numerical prediction until these conditions are present. Numerical results can then be used, on an "as needed" basis, to provide more detailed guidance to weather forecasters.

In this study, the Colorado State University Regional Atmospheric Modeling System, known as CSU RAMS (Tremback *et al.*, 1986), is used to recreate an actual downslope wind event which occurred on 17 Jan 1982 in Boulder, Colorado (location B, Figure 1). The model utilizes available rawinsonde data to "predict" such parameters as time of onset, wind speed, behavior of moisture fields, etc. The model predicted cloud field is compared to GOES satellite imagery.

2. ATMOSPHERIC CONDITIONS

On the late afternoon of 16 Jan 1982 (0000 UTC, 17 Jan 1982), upper air analyses found the western United States under a ridge of high pressure. Flow aloft, from 70 kpa to 30 kpa was from the northwest, and strong. At the surface, cold air had "backed" into Colorado (CO) from the east, forcing a pressure trough, and cold front, to be situated right along the front range. While these condition are not particularly favorable for severe downslope winds at Fort Collins (see Lee *et al.*, 1989), they do represent pre-cursor conditions for other front range cities, such as Boulder (Brown, 1986).

The upwind rawinsonde data from Grand Junction, CO (location G, Figure 1) is shown in Figure 2. The data find a stable layer near the surface which is capped by a relatively neutral layer between 70 and 80 kpa. The Scorer parameter, l (where $l^2 = \frac{N^2}{\bar{u}^2} - \frac{\bar{u}_{zz}}{\bar{u}}$) is plotted as a function of height in the right panel of Figure 2. The Scorer parameter also shows a discontinuity at this interface. It has been shown (e.g., Smith, 1985) that this upper layer of less stable air can behave like a critical layer in the generalized hydraulic jump theory. In such cases, the wave energy will be trapped in the more stable layer below.

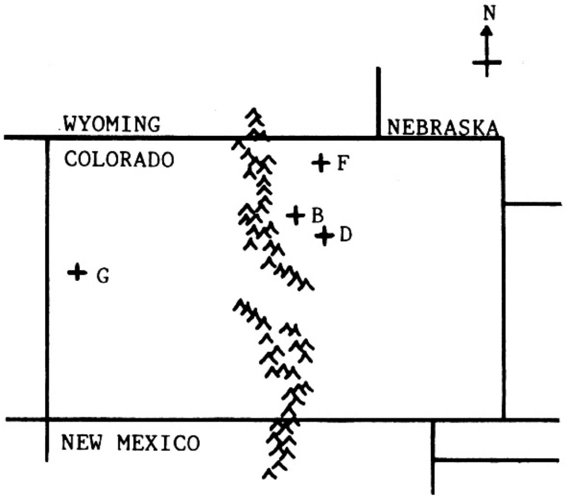

Figure 1. Map of some of the key geographical features referred to in this paper. Line of carats represents the approximate position of the "Front Range" of the Rocky Mountains. Locations of four cities are indicated by letters. F = Fort Collins, B = Boulder, D = Denver, and G = Grand Junction.

3. THE MODEL SETUP

The horizontal resolution chosen for this simulation was 10

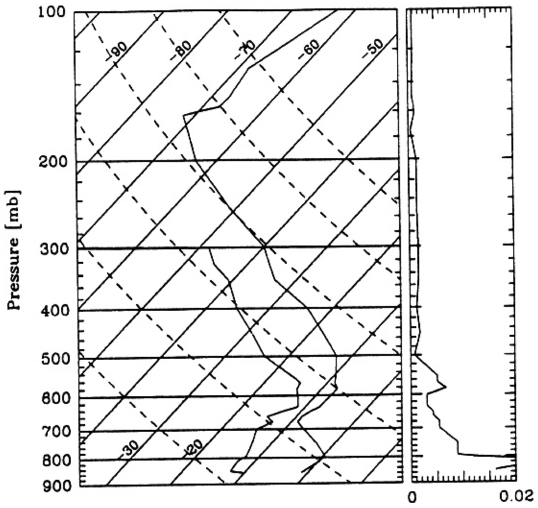

Figure 2. Rawinsonde data from Grand Junction, Colorado at 0000 UTC, 17 January 1982. The square of the Scorer parameter is shown in the right panel.

km, with an array of 90 grid points. The NCAR-archived, five minutes terrain data with $2\Delta x$ waves removed was used for the lower boundary. An east-west cross-section with Boulder at the center of the domain was selected.

The model top is located at 20 km. Vertical resolution varies, with a stretch ratio of 1.1; from 100m near the surface to a maximum of 500 m aloft. The Klemp and Durran (1982) radiative upper boundary condition coupled with 3 km of viscous damping layer (Durran, 1982) is used. For the lateral boundary, the Klemp and Lilly (1978) radiative condition is used. A non-slip lower boundary condition is used with a surface roughness length of 1 cm. Cloudiness is diagnosed from the moisture field with super saturation condensed.

The Grand Junction upper-air sounding was used to initialize the model for this case. The moisture profile in the sounding was modified to have 100% relative humidity in the cloud layer. This was done because the actual upwind direction from Boulder was west-northwest. Satellite imagery showed this region to be more cloudy than that over Grand Junction. The model was then integrated for 12 hours, which is intended to cover the gap between the upper-air observations.

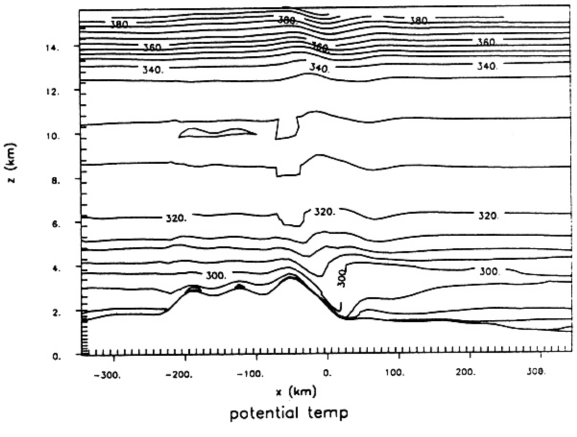

Figure 3. Potential temperature at 2300 LST. Contour interval is 5°K.

4. RESULTS

Figure 3, shows a vertical cross-section of potential temperature 6 hours into the model run (2300 LST). The analysis at this time finds strong evidence that a hydraulic jump pattern has developed. Notice that the wave amplitude above 70 kpa is relatively small, indicating that only a small amount of wave energy has penetrated into the less stable layer aloft. Most of this energy has become trapped below 70 kpa, causing the hydraulic jump to form.

The evolution of the horizontal velocity field is quite consistent with observations at Boulder. The model suggests that strong westerly winds on the upshear side of the hydraulic jump should reach Boulder sometime between 5h and 6h into the run. Wind speeds at this time were "predicted" to be 43 ms^{-1} (Figure 4). Indeed, the downslope event evolved very close to what the model suggested. Figure 5 is the windspeed trace from the Boulder anemometer. Notice that the winds actually do begin gusting at around 0000 LST. Also, notice that while the maximum recorded gust was 136 mph (61 ms^{-1}), **most** of the max gust were around the 112 mph (50 ms^{-1}) mark. This seems reasonably close to what was predicted.

The condensed water field (Figure 6) shows that a fairly uniform cloud field has become more irregular with time. Vertical motions associated with the developing wave have caused large clear (subsiding) regions to form between smaller cloudy regions (in the upward moving locations). Along the Front

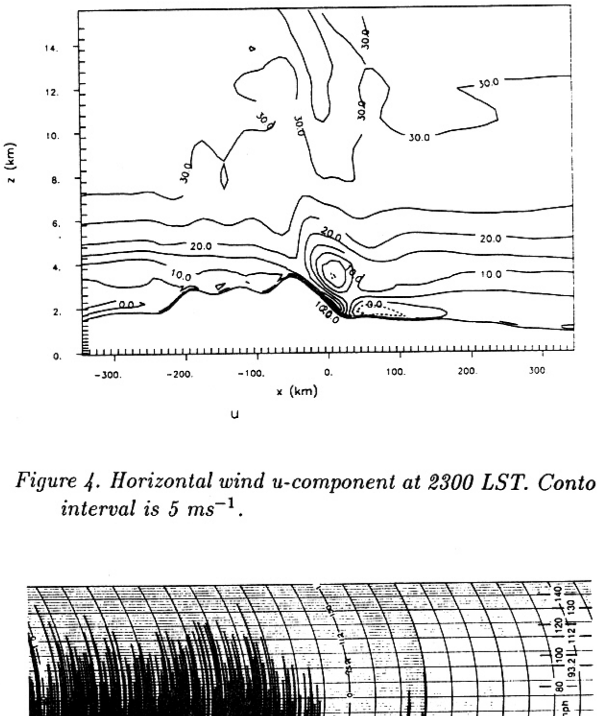

Figure 4. Horizontal wind u-component at 2300 LST. Contour interval is 5 ms^{-1}.

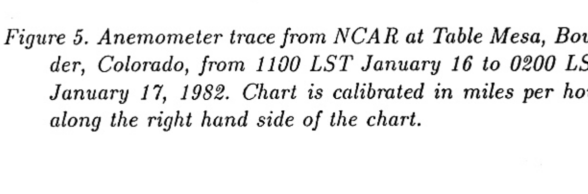

Figure 5. Anemometer trace from NCAR at Table Mesa, Boulder, Colorado, from 1100 LST January 16 to 0200 LST January 17, 1982. Chart is calibrated in miles per hour along the right hand side of the chart.

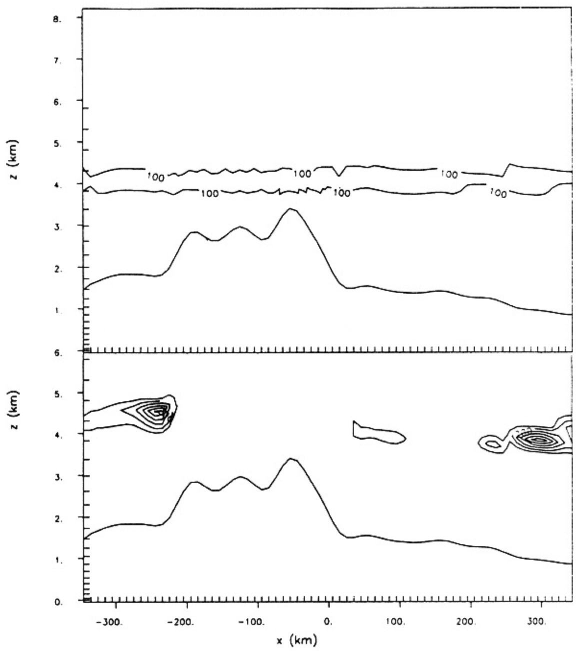

Figure 6. Condensate mixing ratio at 2300 LST. Contour interval is 0.1 g kg^{-1}. Labels have been multiplied by 100. The top panel shows the initial field.

Range, a clear slot, or "Foehn Gap", had developed. This clear slot occurs frequently in downslope wind events, and has been identified as a downslope "signature" in satellite imagery (Ellrod, 1987). The GOES-IR satellite image from 0430 UTC (Figure 7) shows essentially the same sort of behavior in the clouds over extreme northern Colorado as occur in the model. Note the narrow, north-northwest, south-southeast bands of cloudiness interspersed with large, suppressed areas in between.

5. CONCLUDING REMARKS AND PLANS FOR FUTURE RESEARCH

One of the primary goals of this ongoing research is to learn to utilize the CSU RAMS model to accurately reproduce the key attributes of severe downslope wind outbreaks in Colorado. Thus far, reasonably accurate simulations have been carried out for three outbreaks, including the one described above. Although we did not show the evolution of the model predicted fields, results seem to closely match observations. The intensity of the downslope wind gust, and the timing are roughly correct. The "Foehn Gap" associated with the descending region of the mountain wave is explicitly simulated.

Figure 7. GOES-IR satellite image from 0430 UTC, 17 January 1982. Temperatures are contoured and shaded. Dark topped clouds to the west of Colorado are -55 to -60 °C. Most of Colorado is cloud free. Cloud top temperatures in the small cloud bands in extreme northern Colorado range from -32 to -43 °C.

Plans for the near future include simulating several historical cases in which mesoscale variations in storm development brought severe winds to one location, and only moderate winds to another. It is hoped that, through this process, we can get a better handle on the role of terrain shaping and orientation. This factor, and the non-linearity of the downslope event (which causes model initialization to be extremely critical), represent the most difficult problems that need to be solved.

Once several events have been properly simulated in terms of storm onset, strength of outbreak, evolution of cloud field, etc., we hope to utilize the results to search out pre-cursor "signatures", on satellite and elsewhere, which might give the forecaster a short-range (1h-6h) tool to use in recognizing the incipient outbreaks. Such pre-cursor signatures would be welcome supplements to other forecast methods, including any future capability of performing mesoscale model runs in real-time.

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