Meteorol. Atmos. Phys. 37, 1–10 (1987)

Meteorology and Atmospheric Physics

551.578.45

CIRA and Department of Atmospheric Science, Colorado State University, Ft. Collins, CO

Numerical Simulations of Orographic Effects on NE Colorado Snowstorms

D. J. Abbs* and **R. A. Pielke**

With 15 Figures

Received October 29, 1986
Revised November 4, 1986

Summary

In this paper we show using a three-dimensional mesoscale model that terrain forcing has a major effect on the observed snowfall distribution under upslope conditions in northeast Colorado. Two upslope snowstorms (in 1982 and in 1985) were simulated. The effects are strongly dependent on the orientation of the prevailing wind with respect to terrain orientation.

It is suggested that an approach such as discussed in this paper could be used in a forecasting mode, combined with traditional tools such as the NWS Limited Fine Mesh Model (LFM) or Nested Grid Model (NGM). In both of these cases the LFM correctly predicted the development of these storms. However, due to its much coarser resolution it was unable to resolve the terrain-forced variation evident in the simulations presented here.

1. Introduction

On Christmas eve 1982, a severe blizzard with winds gusting to 30 ms^{-1} dumped 0.5 to 1.0 meters of snow on Denver and the nearby Front Range region. An interesting aspect of this blizzard was the manner in which the surrounding orography modulated the snowfall distribution. For example, in Fort Collins (see Fig. 1) only 2.5 cm of snow was recorded, while at Denver and regions to the south and west, 60 cm to over 1 m were recorded. This variation occurred over a horizontal distance of 100 km and could be related to the way in which the surrounding orography affected the prevailing northeasterly synoptic flow. The evolution of this storm is detailed in Schlatter et al. (1983).

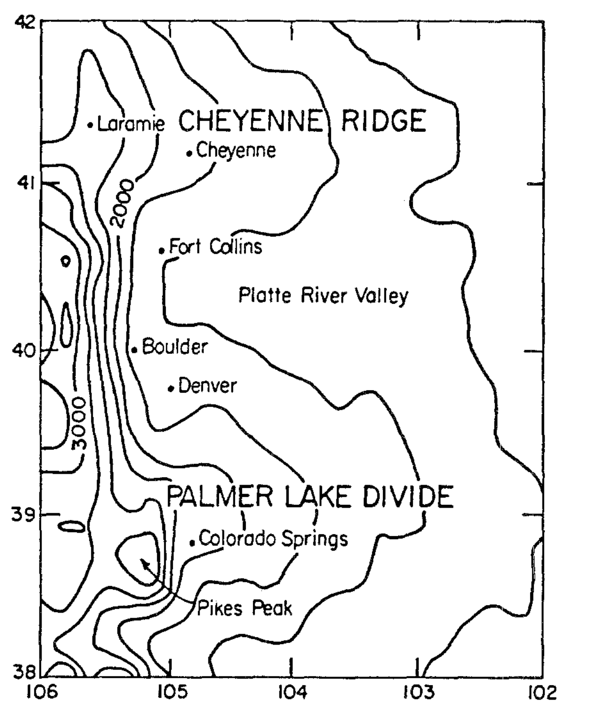

Fig. 1. Topography of NE Colorado. The Continental Divide lies along the western border of Fig. 1. The Front Range is the region between 1750 m and 1500 m and includes the cities of Fort Collins, Boulder, and Denver

* Present Affiliation: CSIRO Division of Atmospheric Research, Aspendale, Vic., Australia.

In a similar manner, the orography modulated the snowfall distribution in the snowstorm of 9–10 December, 1985. On these days a southeasterly synoptic flow prevailed and Fort Collins and the nearby Front Range region received up to 40 cm of snow.

In the present paper we use a numerical mesoscale model to investigate the way in which the orography modulates the prevailing synoptic flow and we compare these simulations to observations from the snowstorms discussed above.

2. Case Studies

a) *Case 1*: 24 December, 1982—A Northeasterly Synoptic Flow

The 850 mb analysis for this event is presented in Fig. 2. The location of Colorado is indicated on this diagram. The main feature to note is the cut-off low centered over the Oklahoma panhandle. This low resulted in strong northeasterly flow over Colorado. These northeasterlies are also evident in the Denver upper air sounding for 5.00 MST (Fig. 3). The winds veer with height and upslope easterly flow is recorded at all levels to the tropopause. This upslope flow, coupled with a nearly saturated atmosphere from the surface to 400 mb, resulted in the heavy snowfalls that were recorded over the Front Range area.

Schlatter et al. (1983) point out that "although the synoptic-scale lifting associated with this storm was considerable (Denver was in the northwest quadrant of the circulation), the modulating effect of terrain on snowfall amounts is easy to demonstrate". Fig. 4 is a map of snow depths (in centimeters) as measured on Christmas morning 1982. The features to note are the band of heavy snow which stretches east and northeast from the continental divide, and the areas of light snowfall (in some cases less than 2.5 cm) on the southern slopes of both the Cheyenne Ridge and the Palmer Lake divide. These regions received much less snow than the northern slopes, as the strong northerly winds were forced downslope in these areas.

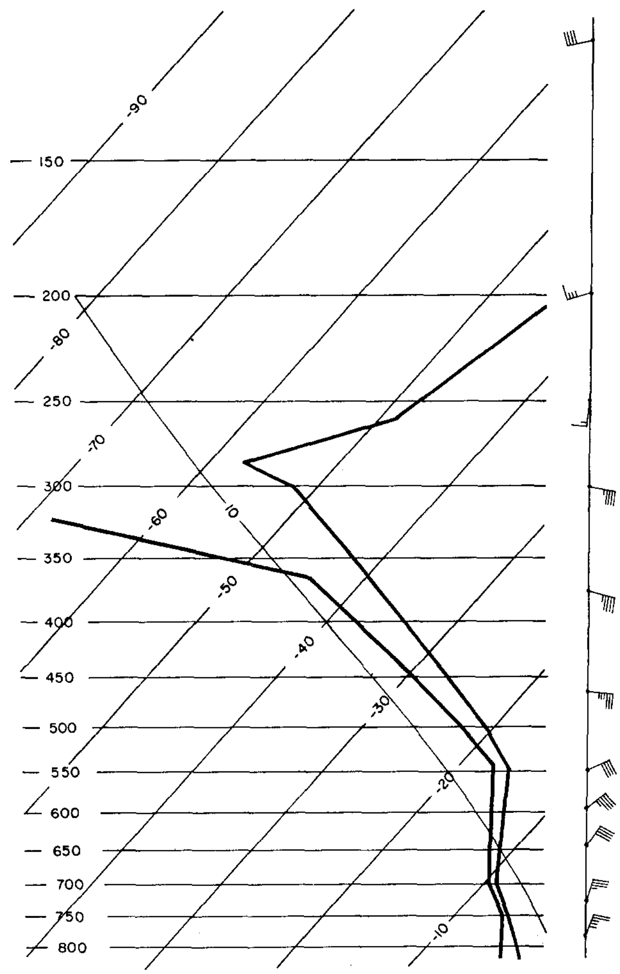

Fig. 3. Denver upper air sounding for 5.00 MST, 24 December 1982

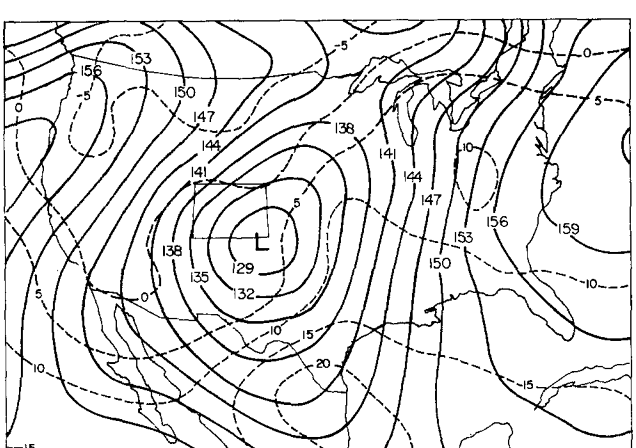

Fig. 2. NWS 850 mb analysis for 5.00 MST, 24 December 1982

Surface winds from the PROFS (Program for Regional Observing and Forecasting Services) surface mesonetwork are presented in Fig. 5. These data show a strong, generally northerly flow over the Front Range. Stations nearest the foothills were protected from the strong, northerly winds, while those to the lee of the Cheyenne

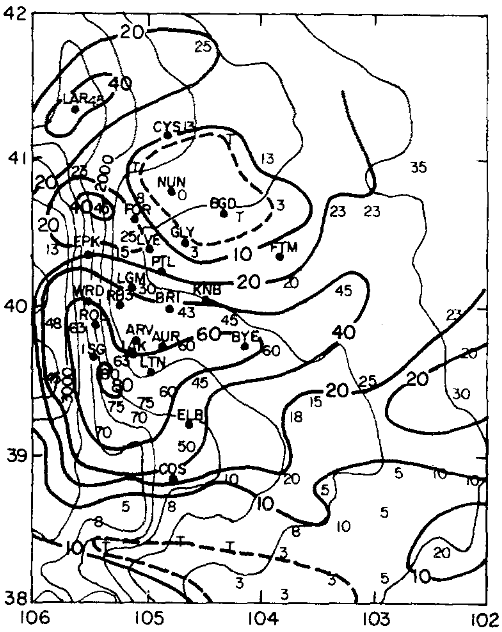

Fig. 4. Maximum observed snowdepth, or increase in snowdepth, resulting from the blizzard of 23–25 December, 1982. Figures are in centimeters

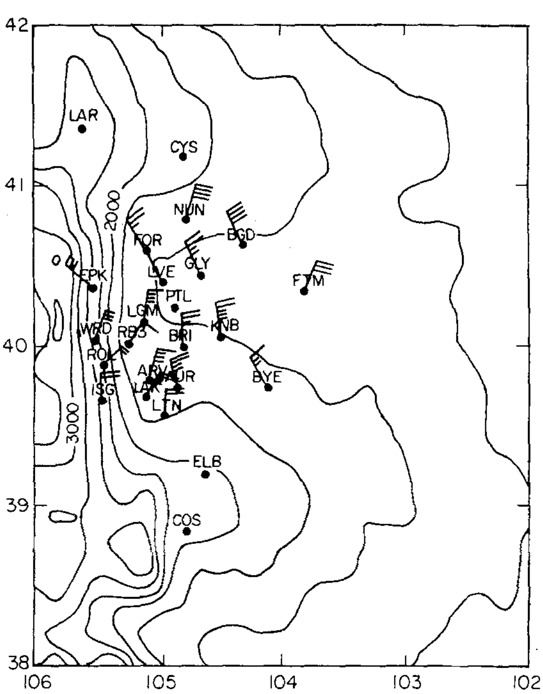

Fig. 5. Surface winds from the PROFS mesonet for 1300 MST, 24 December 1982. Long barbs: $5\,\mathrm{ms}^{-1}$, short barbs: $1\,\mathrm{ms}^{-1}$

Ridge received stronger winds as the flow accelerated on its downslope trajectory.

As mentioned earlier, this case is discussed in detail in Schlatter et al. (1983).

b) *Case 2*: 9 December, 1985—A Southeasterly Synoptic Flow

The 850 mb analysis for Case 2 is presented in Fig. 6. As before, the location of Colorado is indicated on this diagram. In this case, a closed low centered over southwestern Colorado produced moderate southeasterly flow along the Front Range region of Colorado. In this case, however, upslope flow was not recorded through the depth of the troposphere as the winds veer with height and southwesterly winds were recorded at 700 mb. This turning is illustrated in Fig. 7—the Denver upper air sounding for 17.00 MST on 8 December, 1985. Through the layer of southeasterly flow the atmosphere is almost saturated and very stable.

Once again this upslope flow, coupled with the nearly saturated atmosphere to 670 mb, resulted in the heavy snowfalls that were recorded over parts of the Front Range region. In a similar manner to Case 1, the terrain appears to have had a modulating effect on the snowfall distribution even though there was significant synoptic-scale lifting associated with the storm.

Fig. 8 is a map of snow depths as measured on the morning of 9 December 1985. Most snow fell during the evening of the eighth and early morning hours of the ninth. The maximum snowfalls recorded from this storm fell on the windward side (southern slopes) of the Cheyenne Ridge and along the eastern slopes of the continental divide. Snowfalls were lighter to the lee of both the Palmer Lake Divide and Cheyenne Ridge as the southeasterly flow was downslope in these areas. An interesting aspect of the snowfall distribution on this day was the area of very light snowfall (less

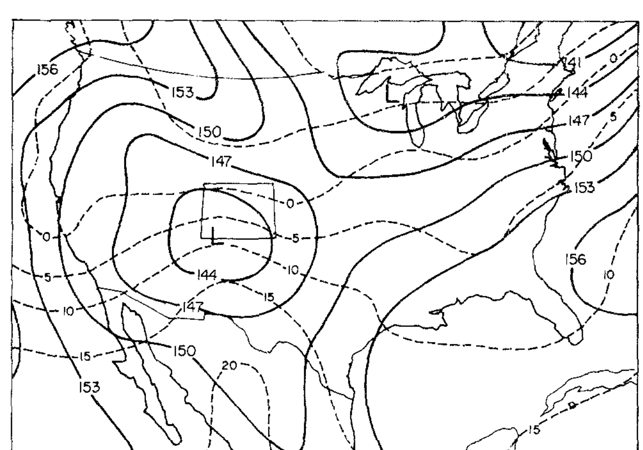

Fig. 6. NWS 850 mb analysis for 1700 MST, 8 December 1985

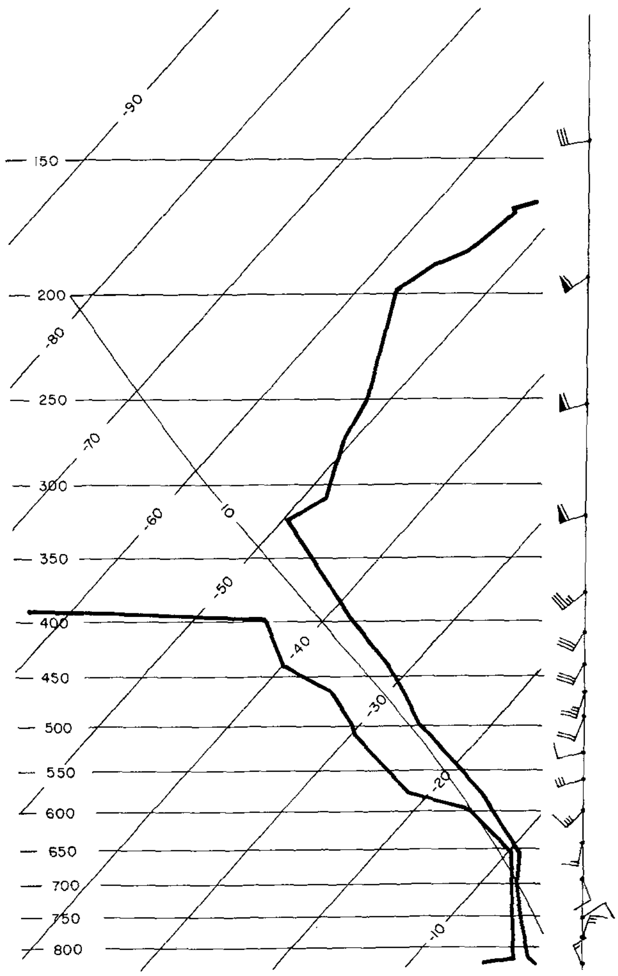

Fig. 7. Denver upper air sounding for 1700 MST, 9 December 1985

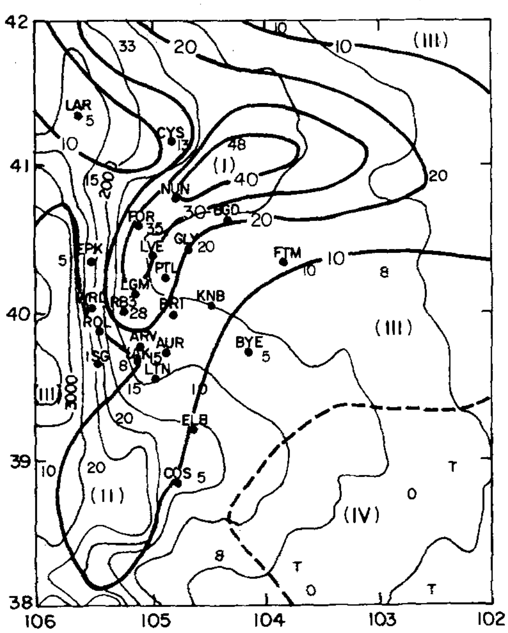

Fig. 8. Maximum observed snowdepth, or increase in snow-depth, resulting from the snowstorm of 8–9 December 1982. Figs. are in centimeters

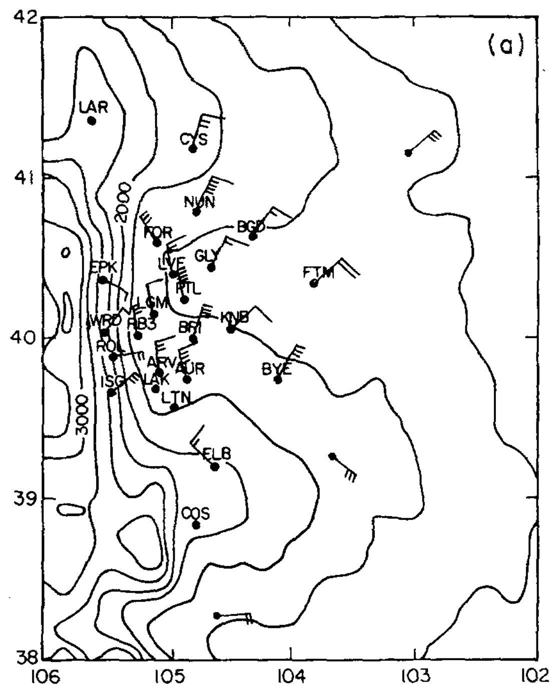

Fig. 9a. Surface winds from the PROFS mesonet for 5.00 MST, 9 December 1982. Long barbs: $5\,\mathrm{ms^{-1}}$, short barbs: $1\,\mathrm{ms^{-1}}$

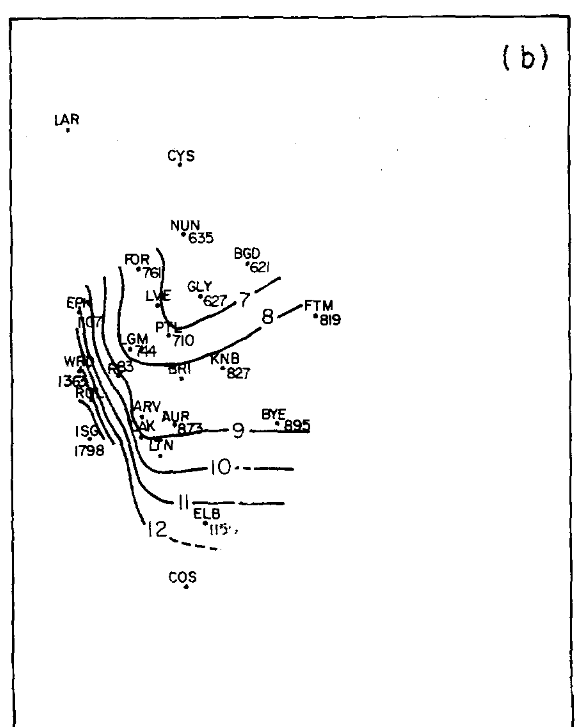

Fig. 9b. Surface potential temperatures for 5.00 MST, 9 December 1982

than 2.5 cm) east of Colorado Springs. Since this is in a region of upslope flow, heavier snowfalls would have been expected here.

Surface winds from the PROFS surface mesonetwork are presented in Fig. 9 a. These indicate a general north to northeasterly flow across the network. Potential temperatures are presented in Fig. 9 b. The surface winds are likely to be related to the passage of a trough through the network. This trough was indicated on the surface charts, to the north of the network, at 00 Z. The passage of the trough is evident in the potential temperature field, with the crowding of isentropes against the eastern slope of the Continental Divide and the north-south gradient in the potential temperature field.

3. The Model

The CSU mesoscale model (Pielke 1974, Mahrer and Pielke 1977, McNider and Pielke 1981) was used to predict regions of terrain-forced convergence and divergence. The model was run without thermal forcing so that any vertical motions initiated are solely the result of orographic lifting or subsidence.

The model atmosphere had 26 vertical levels with greatest resolution near the surface. An absorbing layer (Klemp and Lilly 1978, Mahrer and Pielke 1978) was included in the upper levels to control the reflection of vertically propagating wave energy. The orography used in this study were 20 minute averages calculated from the Defense Mapping Agency's 30 second grid point data. The horizontal grid interval was approximately 15 km on a 32 × 29 domain. At the lateral boundaries the grid spacing was expanded and a zero-gradient condition was applied to the orography. The parameters used to initialize the model are presented in Table 1.

Table 1. *Input Parameters Used to Initialize the Model*

Horizontal grid interval	15 km
Horizontal grid size (x) × (y)	32 × 29
Vertical levels	26
Time step	90 s
Mean latitude	40 N
Roughness length	3 cm
Initial PBL height	2 000 m
Initial surface pressure	830 mb
Free atmospheric lapse rate of potential temperature	8.5 K km^{-1}
Soil characteristics:	
a) Density	1.5 g cm^{-3}
b) Specific heat	0.3 cal g^{-1} K^{-1}
c) Diffusivity	0.0025 cm^2 s^{-1}
d) Wetness	4%

Models levels for u, v, and π (the Exner function):

10, 20, 30, 50, 90, 150, 250, 500, 750, 1 000, 1 350, 1 750, 2 250, 2 750, 3 250, 3 750, 4 250, 4 750, 5 500, 6 500, 7 500, 8 500, 9 500, 10 500, 11 500, 13 500

θ and q are staggered halfway between these levels

The results from the model are presented in the form of horizontal cross sections of the winds and vertical velocity. Only the interior of the domain is presented in these sections. Winds are presented for the 10 m level and vertical velocities for a height of 250 m. The results presented are after 8 hours of simulation, by which time the model had reached a steady solution.

4. Model Results

a) *Run 1*: A Northeasterly Synoptic Flow

In this simulation the model was initialized using the sounding for 5.00 MST, 24 December 1982 (Fig. 3). It was assumed that the deep layer of northeasterly winds could be represented by a geostrophic wind of 16 ms^{-1} from the northeast. The initial meteorological fields were assumed horizontally uniform over the model domain. Computer resources prevented the stronger winds aloft from being correctly represented. It will be shown, however, that this inaccuracy does not appear to significantly detract from the simulation.

Surface winds predicted by the model are presented in Fig. 10. As with the observations, the predicted winds indicate a general northerly flow with a tendency toward northeasterly flow along the eastern slopes of the Continental Divide. The speeds predicted by the model are in qualitative agreement with those in the observations. For example, along the southern slope of the Cheyenne Ridge there has been an increase in the speed of the flow compared with that in the S. Platte River Valley. The model, however, has been unable to reproduce the magnitude of windspeed strengthening evident in the observations, with a model predicted windspeed of 14 ms^{-1} compared to 20 ms^{-1} in the observations. Similarly, the

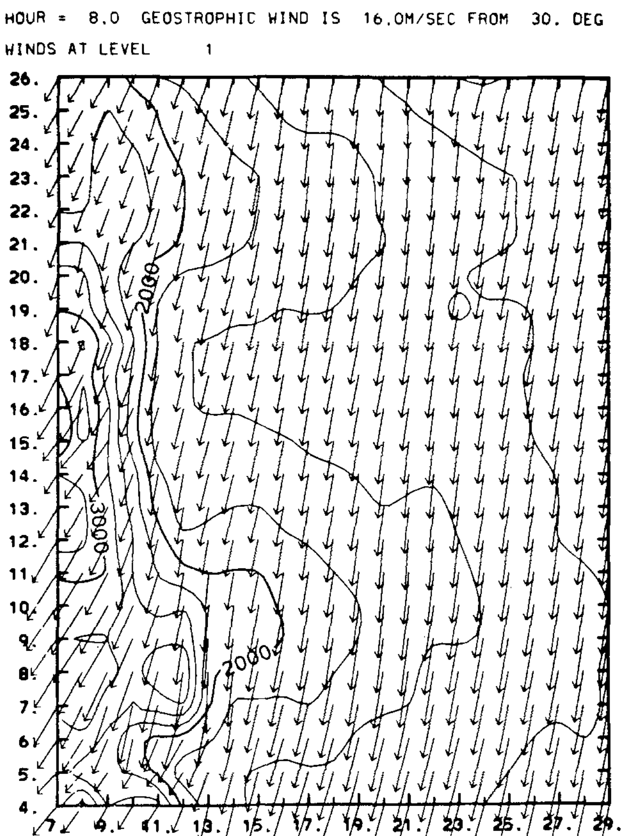

Fig. 10. Model predicted 10 m winds after 8 hours of integration—Run 1

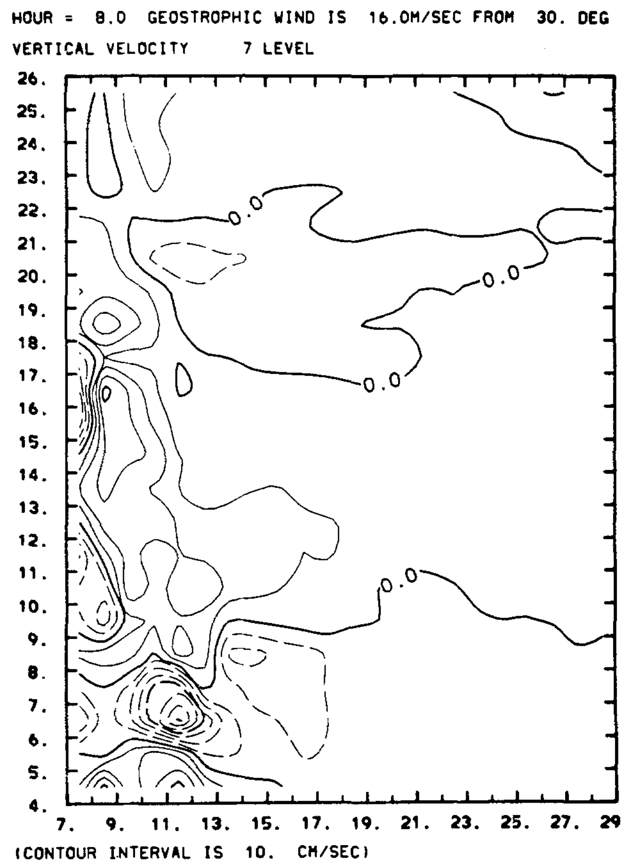

Fig. 11. Vertical velocity field at 250 m for Run 1 after 8 hours of integration

reduction in windspeeds along the eastern slope of the continental divide has been modelled, but not to the extent observed. For example, the minimum speeds observed along this slope are 3 ms^{-1} compared to 7 ms^{-1} in the model results. These discrepancies can, perhaps be related to the model's inability to resolve the small scale terrain features in these regions. In the S. Platte River Valley the agreement between the model and observations is much better, with both showing northerly winds of 10 to 15 ms^{-1}.

The vertical velocity field (Fig. 11) can be directly related to the snowdepths, with subsidence regions corresponding to areas of little or no snow and strong ascent corresponding to the regions of heaviest snow. Comparison of Figs. 4 and 11 shows very good agreement between the observed and predicted fields. Subsidence is evident to the south of both the Cheyenne Ridge and the Palmer Lake divide, in the regions where only small amounts of snow were reported. Along the eastern slope of the continental divide and along the northern slopes of the Palmer Lake divide, strong ascent was predicted by the model and coincides with the area of heaviest snowfall. This ascent extends eastwards onto the plains, as does the band of snow.

b) *Run 2*: A Southeasterly Synoptic Flow

The sounding for 17.00 MST, 8 December 1985 (Fig. 7) was used to initialize the model for this simulation. It was assumed that the imposed synoptic flow was 5.5 ms^{-1} from the southeast. As with Run 1, the initial meteorological fields were assumed horizontally uniform throughout the model domain. Vertical shear was included such that aloft the winds were 15 ms^{-1} from the southwest. It was considered that, unlike Run 1, a correct representation of the winds aloft was important for a successful simulation.

The surface winds predicted by the model are presented in Fig. 12. The agreement between these and the observed winds is poor, except over the

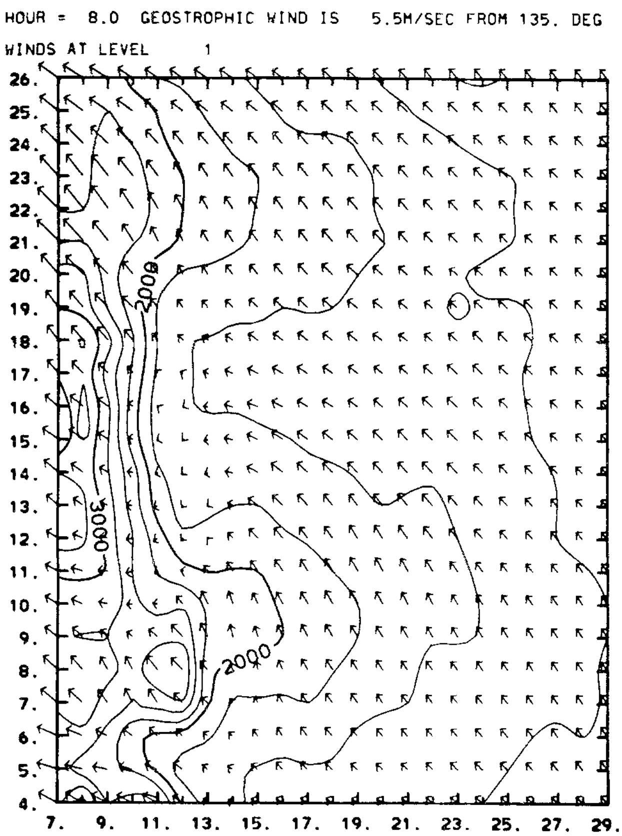

Fig. 12. Model predicted 10 m winds after 8 hours of integration—Run 2

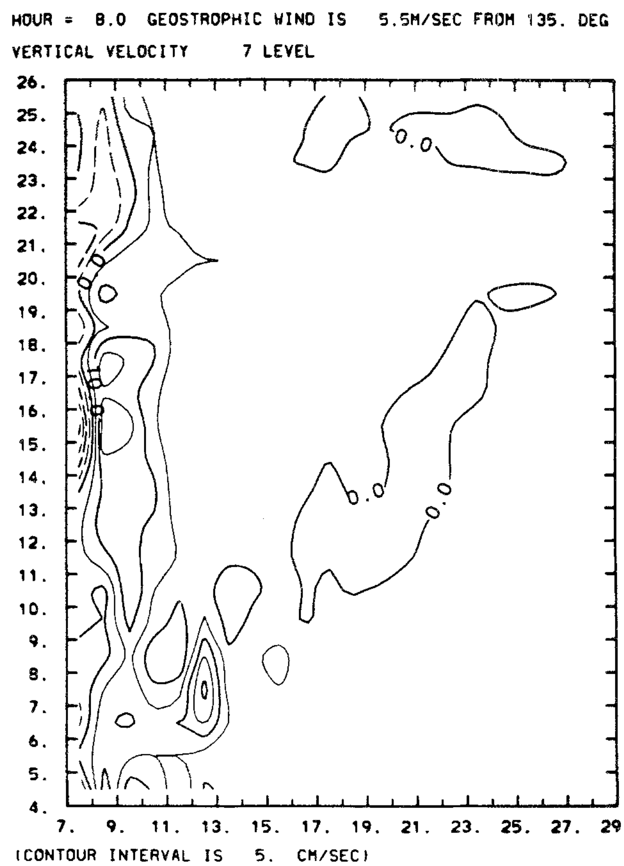

Fig. 13. Vertical velocity field at 250 m for Run 2 after 8 hours of integration

southern section of the domain and along the eastern slopes of the continental divide. Over the southern section of the domain, both the observations and the model show light southeasterly winds, while along the eastern slopes of the continental divide both show very light easterly flow. However, over the northern portion of the domain and over the plains there is little agreement between the model and the observations, with the model predicting moderate southeasterly flow and the observations indicating quite strong northeasterly flow. This discrepancy reinforces the assumption that other important processes are occurring over the model domain, particularly the passage of a trough southward through the domain.

As would be expected, the predicted vertical velocity field (Fig. 13) does not correspond with the observed snowfall distribution as well as in Run 1. Some correlations are evident, however. Subsidence to the lee of both the Palmer Lake divide and the Cheyenne Ridge corresponds with lighter snowfalls in these regions. The ascent along the eastern slopes of the continental divide can be associated with the higher snowfalls along these slopes. There is also some indication of slightly stronger ascent along the southern slopes of the Cheyenne Ridge and the heavy snowfalls there could be partly attributed to this. The major discrepancy occurs in the southeast corner of the domain where the lightest snowfalls occurred in a region of predicted ascent.

Thermodynamic indices were plotted for the domain to determine if processes, such as convection, were possible over particular regions and could help explain the observed snowfall distribution. The indices examined were the lifted index, the average moisture deficiency $(\theta_{e_s} - \theta_e)$ to 3 000 m and the average relative humidity. Despite the disagreements in the observed and predicted wind fields, the composites of these indices appear to be related to the snowfall distribution of Fig. 8 in the manner described as follows (see Fig. 8 for the locations of the areas referred to below).

I. This is the region of heaviest snowfall. This was a region of ascent in which the air was near saturation.

II. This region has very similar characteristics to (I.) but the atmosphere was less moist.

III. These are regions of light snowfall and correspond with modelled areas of subsidence and dried air.

IV. Little or no snow fell in this area even though it was in a region of ascent. The thermodynamic indices show that here the atmosphere was both stable and drier, characteristics not conducive to heavy snowfall.

It should be noted that over the entire domain the atmosphere was very stable.

c) *Run 3*: A Southeasterly Synoptic Flow with a Cold Pool to the North

As mentioned in 2 b, the passage of a cold pool into the domain was evident on close examination of the observations. In this section we will show that this feature modified the pattern which would be expected from a uniform southeasterly flow. It was assumed that this trough could be considered a gravity current (Young and Johnson, 1984) and hence be easily represented by the model.

The technique used was based on that of Garrett and Physick (1986). In this simulation, a cold-air source was produced from the surface to 1 000 m height over the three grid points adjacent to the northern boundary. This cold-air source was introduced to that part of the domain east of the Front Range (i.e.: from grid points 12 to 32). Cooling was applied in 0.5 K increments at every time step until a cold air source of $\theta = 279$ K was obtained. This gives a reservoir of cold air 8 K colder than the environmental air. The model was integrated for 4 hours of simulation time before the cold air source was introduced. In this way, the density current was moving southwards into an environment in steady state.

The model output presented in this section is after 13 hours of simulation—9 hours after the introduction of the cold air source. Fig. 14 shows the model predicted 10 m winds at this time. Vertical velocities at a height of 250 m and 1 350 m are shown in Figs. 15 a and b respectively. Comparison of Figs. 14 and 9 a shows that the model predicted winds are now in much better agreement in this simulation than those of Run 2. The model

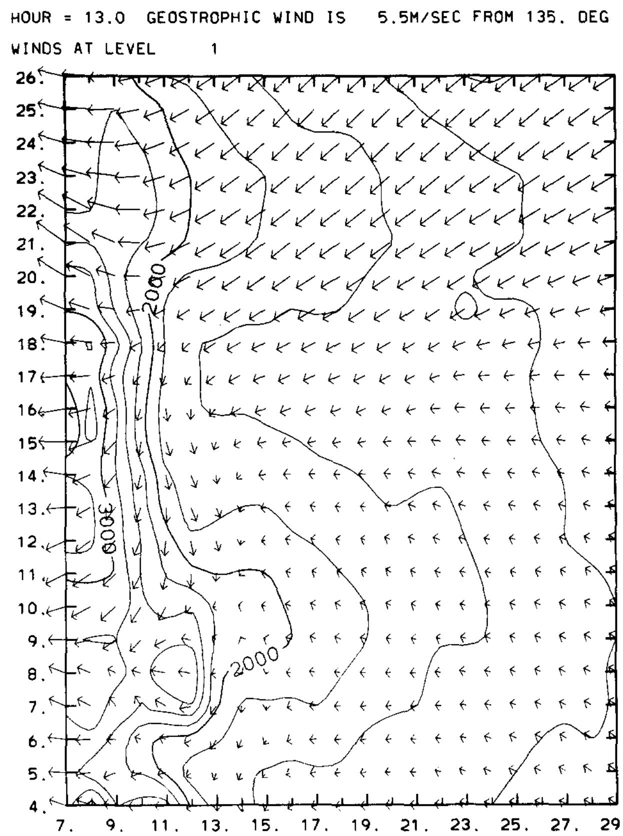

Fig. 14. Model predicted 10 m winds after 13 hours of integration—Run 3

has successfully simulated the northeasterly flow over the northern part of the domain. This flow can be directly attributed to the density current. Along the Front Range the density current has been blocked by the terrain and northerly flow is evident there. Light southeasterly winds are still present over the southern section of the domain.

Fig. 15 a shows that convergence along the southern slopes of the Cheyenne Ridge is concentrated along the eastern slopes of the continental divide. The ascent from the density current is evident at a height of 750 m and is at maximum strength at 1350 m. In Fig. 15 b it is evident that the zone of ascent now extends eastwards along the southern slopes of the Cheyenne Ridge. Using this field it is possible to explain the snowfall distribution. Basically, the formation mechanisms are unchanged from those described at the end of section 4 b. In this case, however, the density current has had the effect of amplifying these effects. For example, in region I, the effect of the density current was to decrease the values of the moisture deficiency. Consequently, the at-

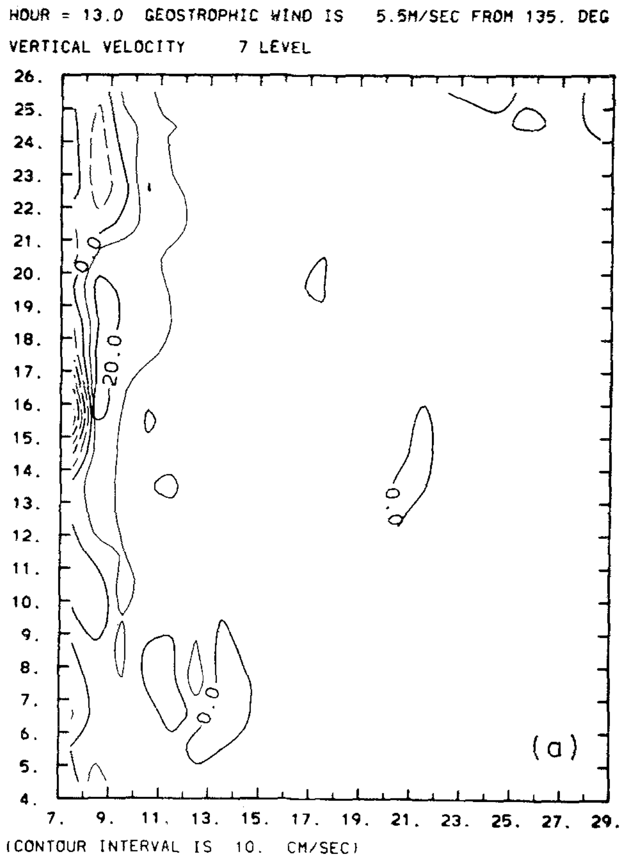

Fig. 15a. Vertical velocity field at 250 m for Run 3 after 13 hours of integration

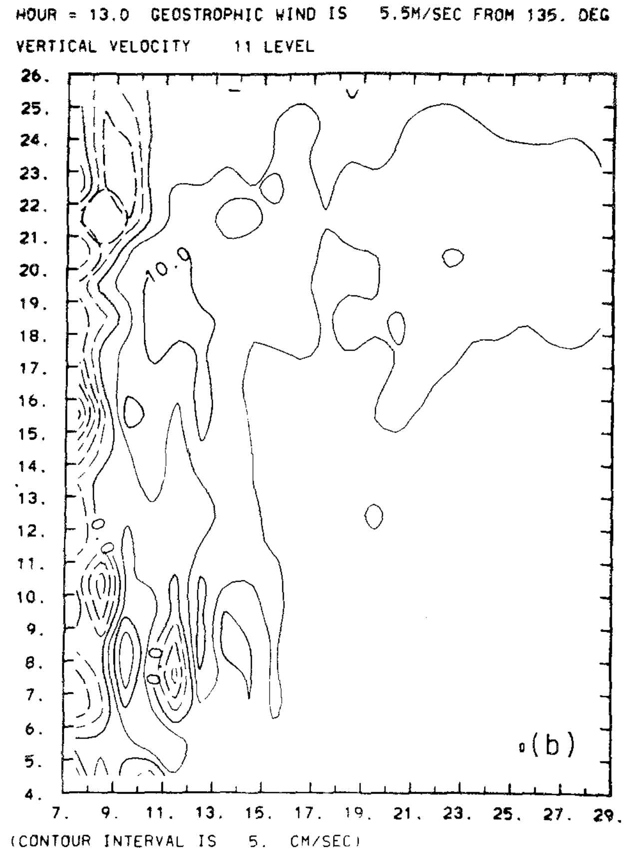

Fig. 15b. Vertical velocity field at 1350 for Run 3 after 13 hours of integration

mosphere is closer to saturation here than elsewhere. This, combined with the stronger ascent in this region, appears to have caused the observed high snowfall.

It also appears from the modelling results that blocking of the very stable cold pool by the Palmer Lake divide prevented the continued southern propagation of the density current. This had the effect of maintaining the ascent on the southern slope of the Cheyenne Ridge rather than it moving south. This also helped to concentrate the snowfall in this region.

5. Discussion

Several criticisms can be made at such a simple treatment of a phenomenon as complex as a major snowstorm. For instance, microphysical properties are likely to be an important aspect in such storms. Although this is true, we have shown that a dry model can be used to predict the regions of heaviest snowfall in complex terrain. We are not suggesting, of course, that the snowfall amount can be predicted using this approach.

Secondly, it could be suggested that with such strong winds involved as those in Run 1, the snowfall distribution should be displaced downstream of the predicted ascent/descent regions. In some situations this may be true, however, in the cases presented here the lower atmosphere was saturated and so the snow was falling out of clouds from a level close to the surface. Under these conditions the snow is not blown long distances before it settles. In situations where this was not the case, it is possible to use the model fields and the free-fall velocity of snow to diagnose the snowfall distribution.

6. Conclusions

In this paper we have shown that terrain forcing has a major effect on the observed snowfall distribution under upslope conditions in northeast Colorado. These effects are strongly dependent on the orientation of the prevailing wind with respect to the terrain orientation.

It is suggested that an approach such as this could be used in a forecasting mode, combined with traditional tools such as the NWS Limited Fine Mesh Model (LFM) or Nested Grid Model (NGM). In both of these cases the LFM correctly predicted the development of these storms. However, due to its much coarser resolution it was unable to resolve the terrain-forced variation evident in the simulations presented here.

Acknowledgements

This study was supported by the NSF under grant ATM-8414181. The computations were carried out by the NCAR CRAY computer. NCAR is sponsored by the National Science Foundation. While completing this research the first author was supported by a CIRA Visiting Fellowship under NOAA grant NA 81 RA-H-00001. We would like to thank Bobbie Schwinger for typing the manuscript and Judy Sorbie for drafting the figures.

References

Garratt, J. R., Physick, W. L., 1986: Numerical study of atmospheric gravity currents I: Simulations and Observations of Cold Fronts. *Beitr. Phys. Atmosph.*, **59**, 282–300.

Klemp, J. B., Lilly, D. K., 1978: Numerical simulation of hydrostatic mountain waves. *J. Atmos. Sci.*, **35**, 78–107.

McNider, R. T., Pielke, R. A., 1981: Diurnal boundary layer development over sloping terrain. *J. Atmos. Sci.*, **38**, 2198–2212.

Mahrer, Y., Pielke, R. A., 1977: A numerical study of the airflow over irregular terrain. *Beitr. Phys. Atmosph.*, **50**, 98–113.

Mahrer, Y., Pielke, R. A., 1978: A test of an upstream spline interpolation technique for the advective terms in a numerical mesoscale model. *Mon. Wea. Rev.*, **106**, 818–830.

Pielke, R. A., 1974: A three dimensional numerical model of the sea breeze over south Florida. *Mon. Wea. Rev.*, **102**, 115–139.

Schlatter, T. W., Baker, D. V., Henz, J. F., 1983: Profiling Colorado's Christmas Eve Blizzard. *Weatherwise*, **36**, 60–66.

Young, G. S., Johnson, R. H., 1984: Meso and microscale features of a Colorado Cold Front. *J. Climate Appl. Meteor.*, **23**, 1315–1325.

Authors' addresses: Prof. Dr. Roger A. Pielke, Department of Atmospheric Science, Colorado State University, Ft. Collins, CO 80523, U.S.A.; Ms. Deborah J. Abbs, CSIRO Division of Atmospheric Research, Aspendale, Victoria, 3195, Australia.