

NOTES AND CORRESPONDENCE

**An Unusual Summertime Downslope Wind Event
in Fort Collins, Colorado, on 3 July 1993**

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ABSTRACT

An unseasonal, severe downslope windstorm along the eastern foothills of the Colorado Rocky Mountains is described. The storm, which occurred on 3 July 1993, produced wind gusts in Fort Collins, Colorado, over 40 m s^{-1} and resulted in extensive tree and roof damage. The synoptic pattern preceding the wind event resembled a pattern typical of that for a Front Range late fall or wintertime wind storm, including a strong south-southwest-oriented height gradient at 700 mb and a strong west to east sea level pressure gradient across the Front Range. A particularly interesting facet of the event was that one small geographical area in and near Fort Collins experienced wind gusts nearly 40% stronger than any other location involved in the event.

The mesoscale forecast version of the Regional Atmospheric Modeling System (RAMS) with 16-km grid spacing over Colorado was run for the storm. Consistent severe winds were not predicted by the model in this configuration. Increasing resolution in postanalysis to a 4-km grid spacing along the Front Range resulted in severe downslope winds but of too strong a magnitude. The addition of explicit, bulk microphysics moderated the forecast wind strengths to observed magnitudes. That is, both a grid spacing of $\sim 4 \text{ km}$ and the use of explicit bulk microphysics were required to produce an accurate representation of the downslope winds observed.

1. Introduction

Strong downslope windstorms occur occasionally along the eastern foothills of the Colorado Rocky Mountains. When downslope windstorms do occur, it is most often during the fall and winter months (e.g., Lee et al. 1989, 1990), as shown in Fig. 1. On 3 July 1993, the Front Range area of northern Colorado experienced an unseasonal severe downslope windstorm event during which wind gusts in Fort Collins, Colorado, reached 82 kt ($\sim 40 \text{ m s}^{-1}$). Tree and roof damage was extensive since all the trees had full foliage, unlike during late fall or winter outbreaks.

This paper describes the synoptic and mesoscale environment associated with this event. The results of running a mesoscale forecast model initialized with

standard National Weather Service observations are presented along with sensitivity experiments, which identify the physical and dynamical factors important to numerical prediction of this type of downslope windstorm.

2. Synoptic situation

The 1200 UTC morning analyses (Fig. 2) showed the polar jet much farther south than is typical for summertime patterns in Colorado. At 300 mb, a strong jet maximum was just entering western Colorado, with winds in the core exceeding 100 kt ($\sim 51 \text{ m s}^{-1}$). The associated shortwave trough was similarly intense, as illustrated by the strong cold-air advection from the surface up through 500 mb and the strong wind shear over eastern Utah at 500 mb. The 12-h NGM forecast for northeast Colorado (Fig. 3) suggested that by late afternoon a strong, south-southwest-oriented height gradient would develop at 700 mb and that subsidence

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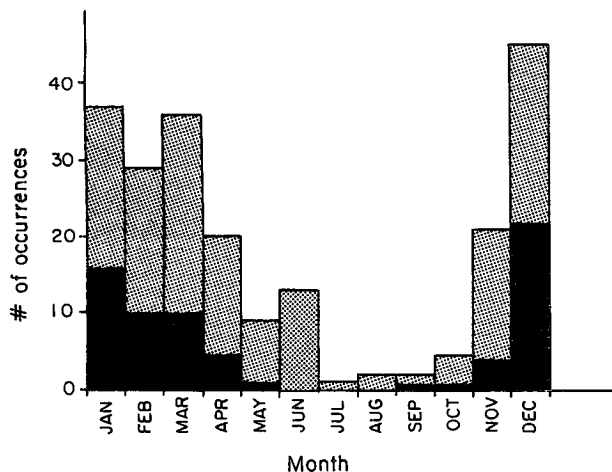


FIG. 1. Examples of the seasonal tendencies for downslope wind events in Fort Collins, Colorado. Monthly episodes from the larger sample are given by the values at the top of the stippled bars. These statistics are from a dataset collected during the 10-yr period 1968–1977. There were a total of 221 events selected by the following criteria: (a) windspeeds > 20 kt, (b) surface wind direction between 210° and 330° , and (c) large dewpoint depressions (see acknowledgments). The values at the top of the solid bars show the number of downslope events per month having multiple gusts of 45 kt or greater for the period 1977–1986. Data are from Lee et al. (1990).

would follow passage of the short-wave trough. Also, a strong west to east sea level pressure gradient was expected to set up across the Front Range behind a Pacific cold front that was already pushing into the state by dawn. This synoptic pattern matches that described by Lee et al. (1989) as being most favorable for strong downslope winds in Fort Collins.

3. Mesoscale evolution

Throughout the morning hours, NMC surface analyses showed the Pacific cold front moving rapidly into northeastern Colorado (Fig. 4). Temperatures across the front differed by as much as 20°F (11°C), with the only indication of a developing mesoscale feature being a hint of a wave on the front in east-central Colorado. Other data sources clearly show that an even more complex situation was evolving.

One such data source was imagery from the U.S. Geostationary Operational Environmental Satellite (GOES-7). Both visible and infrared (IR) imagery showed an extensive mass of thick cloud cover near the jet maximum, just north of the surface front (Fig. 5). This cloud cover was increasing in areal coverage and advecting eastward. As the clouds reached the Continental Divide, the first author (who was hiking in the area west of Fort Collins at the time) observed the arrival of what appeared to be relatively thick, Chinook arch clouds with bases at approximately 15 000 ft (4600 m) AGL. Shortly after this cloud cover moved in, light-moderate precipitation, in the form of rain mixed with

snow, began falling. About 2 h later, another hiker reported heavy snow and strong winds roughly 60 km west of Fort Collins. Officially, up to 15 cm of snow was reported in the northern and central mountains of Colorado by National Weather Service observers for the 24-h period. When the same clouds moved into Fort Collins later in the day, the second author noted thick clouds with some virga, but no precipitation. As we will show below, these precipitation observations will play a crucial role in understanding the geographically isolated nature of the most severe winds.

Mesoscale surface observations [available from a 22 site mesonetwork operated in northeastern Colorado by National Oceanic and Atmospheric Administration's (NOAA's) Forecast Systems Laboratory] showed westerly winds behind the front along the Front Range, becoming more northerly out on the Plains (Fig. 6). Satellite imagery suggests that the Pacific front was developing a wave in western Nebraska (Fig. 7). At the immediate cusp of the wave an intense thunderstorm developed, which produced several incidents of 7–10-cm diameter hail and strong winds in many Nebraska locations (NOAA 1993). West of that cusp, a line of cumulus clouds formed marking the leading edge of a surge of colder air being driven southward behind the developing wave. A meteorologist traveling north of Greeley, Colorado, (GLY) at the time of frontal passage reported a “wall of dust” approaching from the north, followed by very strong north winds (estimated >50 kt, or 25 m s^{-1}) and restricted visibility (estimated <0.6 mi, or ~ 1 km).

These apparently diverse observations are important to understanding the localized nature of significant events that are analyzed below utilizing the mesoscale model. Furthermore, they clearly show how observational data can enhance the forecaster's ability to stay ahead of an evolving situation. Indeed, from the short-range forecaster's point of view, this case illustrates several important points. For example, recall that the NGM had predicted a single, deep low in North Dakota by late afternoon. The low pressure area in western Nebraska and the subsequent mesoscale, northerly surge was unexpected. Analyzing this mesoscale surge as a separate entity (Fig. 8), having as it did a different source region than the air advecting into the state from the west, provides important additional forecast insight. For example, knowing the winds at Greeley, Colorado, (GLY, Fig. 6) would shift from light and variable, to strong northerly, then to strong westerly would be extremely important information to those involved with aircraft operations or agricultural burns.

4. A localized extreme

Notice that both the sustained winds and wind gusts shown in Fig. 9 increase steadily from midday (approximately 1800 UTC) throughout the entire afternoon. This was typical of most locations along the

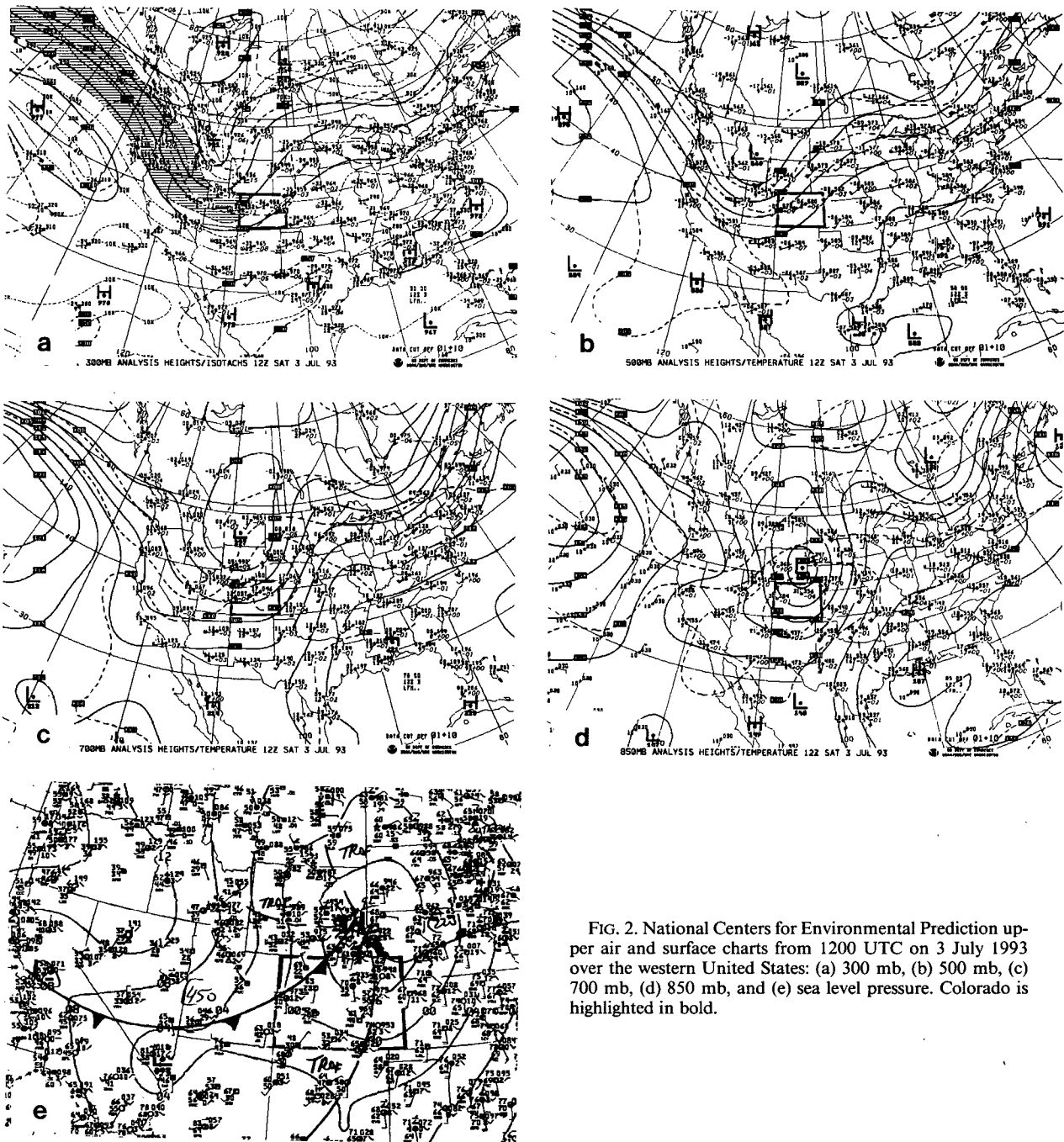


FIG. 2. National Centers for Environmental Prediction upper air and surface charts from 1200 UTC on 3 July 1993 over the western United States: (a) 300 mb, (b) 500 mb, (c) 700 mb, (d) 850 mb, and (e) sea level pressure. Colorado is highlighted in bold.

northern Front Range. At most locations, maximum gusts were limited to a range of between 52 and 62 kt ($26\text{--}32\text{ m s}^{-1}$) throughout the period. Unlike these other locations, however, at about 2300 UTC Fort Collins suddenly experienced nearly an hour of much stronger flow with some gusts approaching, and occasionally exceeding, 80 kt (41 m s^{-1}).

The late afternoon synoptic situation was close to that suggested by the morning NGM, with most of the

minor differences working against severe downslope winds. For example, both the 700-mb height gradient and the sea level pressure gradient were a little weaker than expected. When an expert system, used by the National Weather Service to forecast severe downslope wind gusts for northeast Colorado (Weaver and Phillips 1990), was run after the fact using actual evening observations, the result for Fort Collins suggested maximum gusts of 52 kt (26 m s^{-1}).

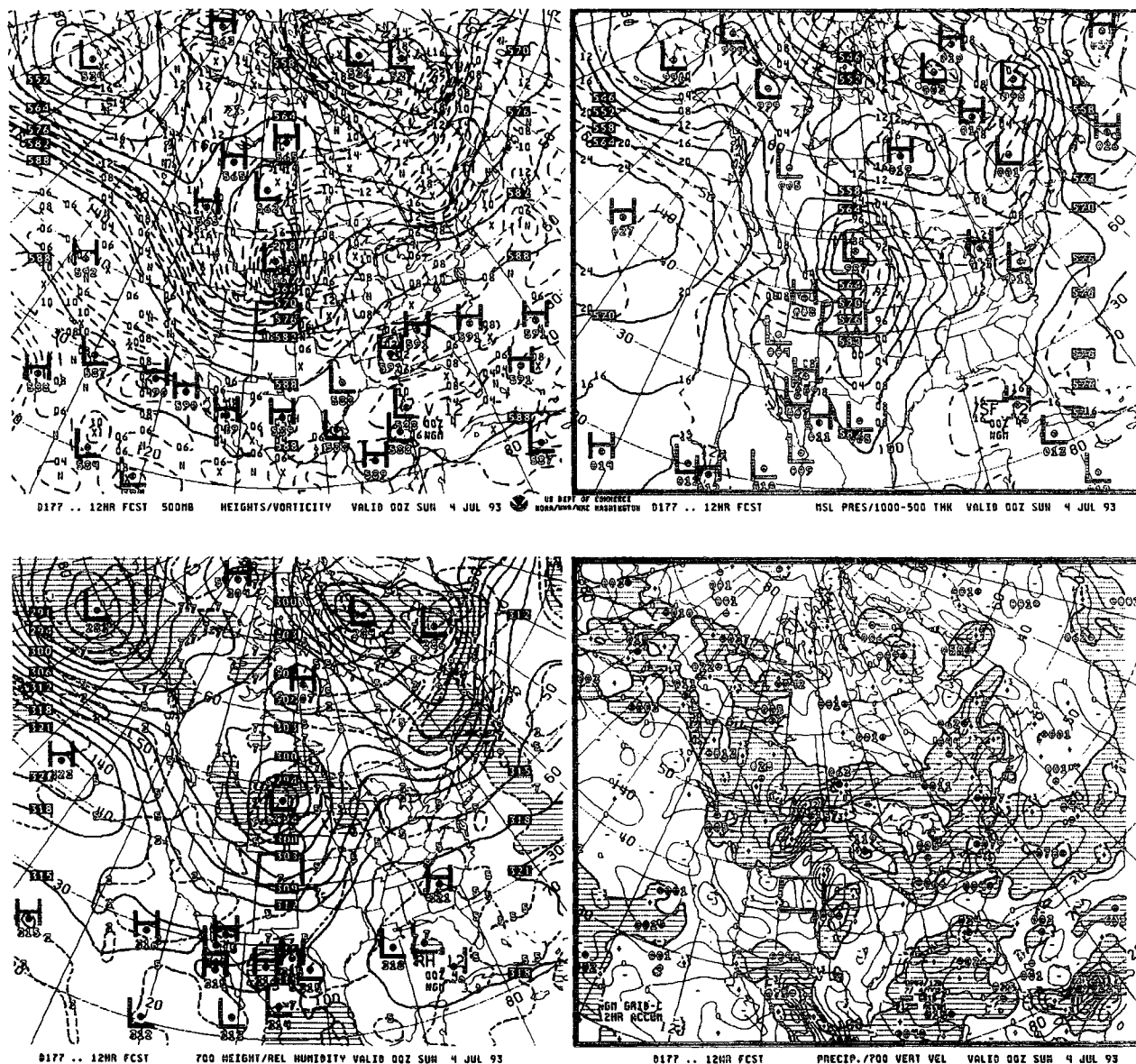


FIG. 3. NGM 12-h forecast, valid at 0000 UTC on 4 July 1993. Panels shown are 500-mb heights and vorticity (upper left), MSL pressure/1000–500-mb thickness (upper right), 700-mb heights and relative humidity (lower left), and precipitation and 700-mb vertical velocity (lower right).

5. Mesoscale model simulation

a. RAMS mesoscale forecast model setup

The Regional Atmospheric Modeling System (RAMS) was run in real time during the summer of 1993, as it has been for the previous two winters (Cotton et al. 1994). In this setup, RAMS was initialized off the 0000 UTC eta model initial fields and produced a 36-h forecast running on an IBM RS6000/370 workstation. The summertime setup contained two interactive grids. Grid No. 1 had 80-km grid spacing and covered the western two-thirds of the United States;

grid No. 2 had 16-km grid spacing and covered central and northeastern Colorado and adjacent portions of Kansas, Nebraska, and Wyoming (see Fig. 10). The location of the summer grid is shifted northeastward from the winter position used by Cotton et al. (1994) and Beitler (1994) in order to capture severe storms over the High Plains and the genesis of mesoscale convective systems. Vertical grid spacing varied from 200 m near the surface to 1 km near the model top at 17 km.

The physics used in the real-time forecast version of RAMS is rather simple. It consists of the forecast of

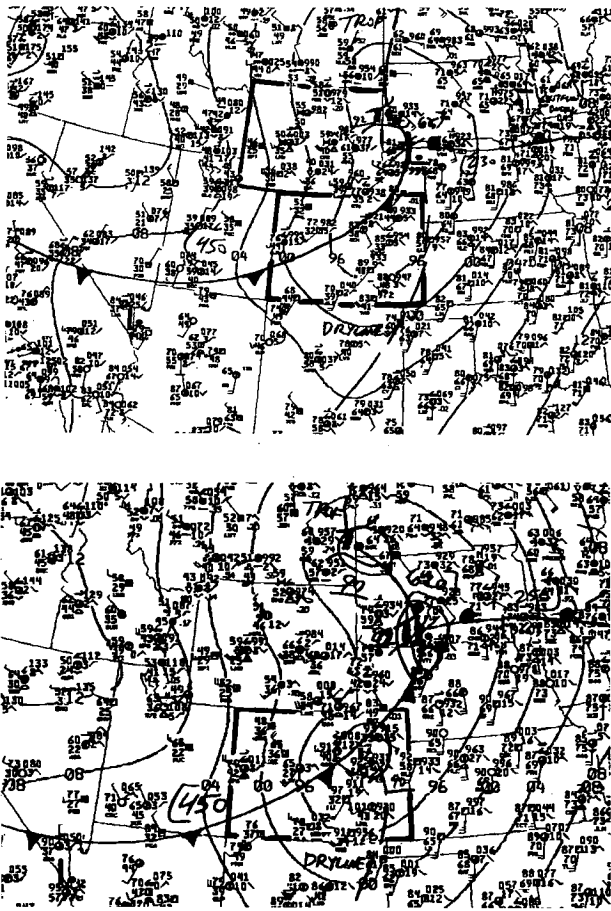


FIG. 4. NMC sea level pressure analysis from 1500 UTC (top) and 1800 UTC (bottom) on 3 July 1993. All plotting is done using conventional U.S. units and symbols.

total water mixing ratio (called level 1 microphysics) with any liquid water in excess of water saturation “dumped into a bucket” using a precipitation removal algorithm in which the amount precipitated is a function of temperature (see Cotton et al. 1994). For the summer season, this scheme was augmented with a simple Kuo-type (1965) convective parameterization scheme as implemented by Tremback (1990). This is somewhat of an abuse of the Kuo scheme, since it was not designed to be run at grid spacings as small as 16 km. Nonetheless, deep convection was not an important factor in this wind storm situation. The more appropriate scheme for such grid spacing, developed by Weissbluth and Cotton (1993), however, was not available in the real-time version of RAMS at that time.

A soil-vegetation model developed by Lee (1992) was used with the soil moisture values and vegetation parameters hand-tuned at the beginning of the summer season and left unadjusted for the summer. This surface model is complemented with the simple Mahrer and Pielke (1975) surface radiation model, which, in its initial implementation, does not respond to clouds. Thompson (1993) modified the scheme to allow the presence of “pseudo” clouds, in which a threshold relative humidity is used to identify the presence of clouds. Neiburger’s (1949) curve is used to relate cloud depth to cloud albedo for shortwave radiation. For longwave radiation, the presence of pseudoclouds produces the addition of a downward blackbody radiative flux equal to σT^4 , where T is the temperature of the base of the relative humidity-determined cloud. This yields more realistic forecasts of surface temperatures than the unmodified Mahrer–Pielke scheme.

During the summer of 1993, RAMS was initialized with the 0000 UTC surface airways observations

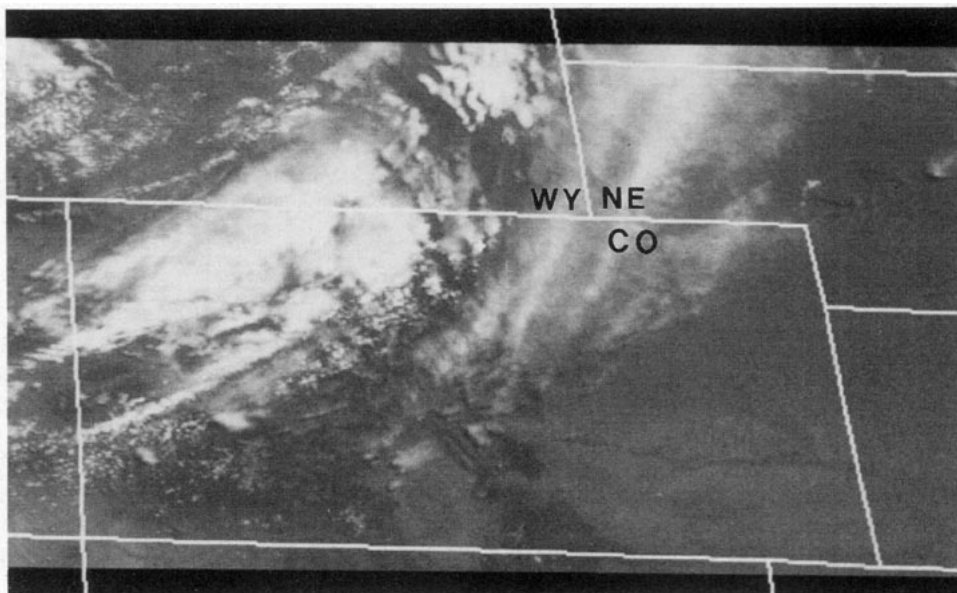


FIG. 5. GOES-7 visible satellite image from 1800 UTC on 3 July 1993 centered over Colorado with portions of surrounding states included.

FRONT RANGE MESONET

UTC TIME : 1800

LAST TIME AVAILABLE : 0455

07/03/93

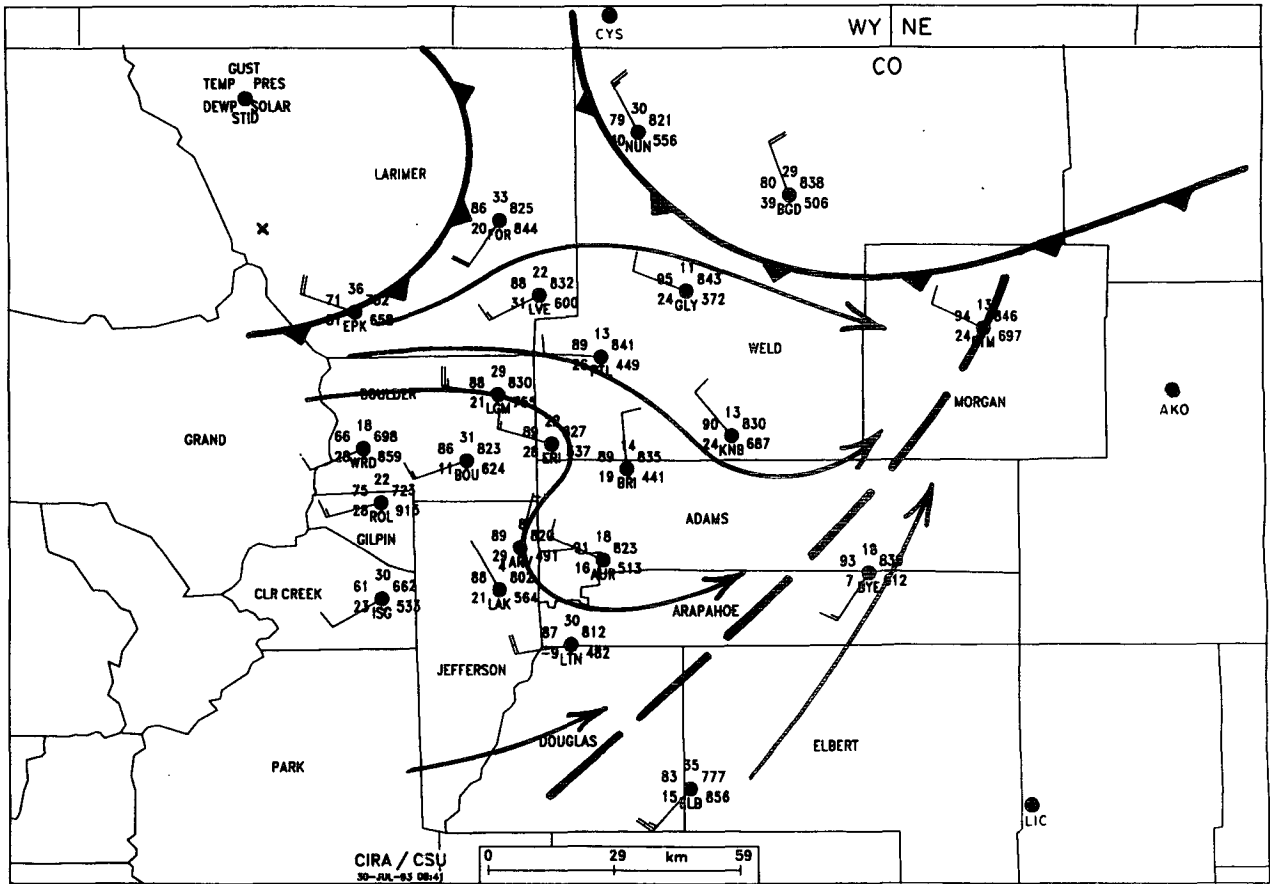


FIG. 6. Mesonet observations from NOAA/FSL's surface mesonet network over north-central Colorado for 1800 UTC 3 July 1993. Plotting uses conventional U.S. units and symbols. FOR is Fort Collins, AUR is Denver, and GLY is Greeley.

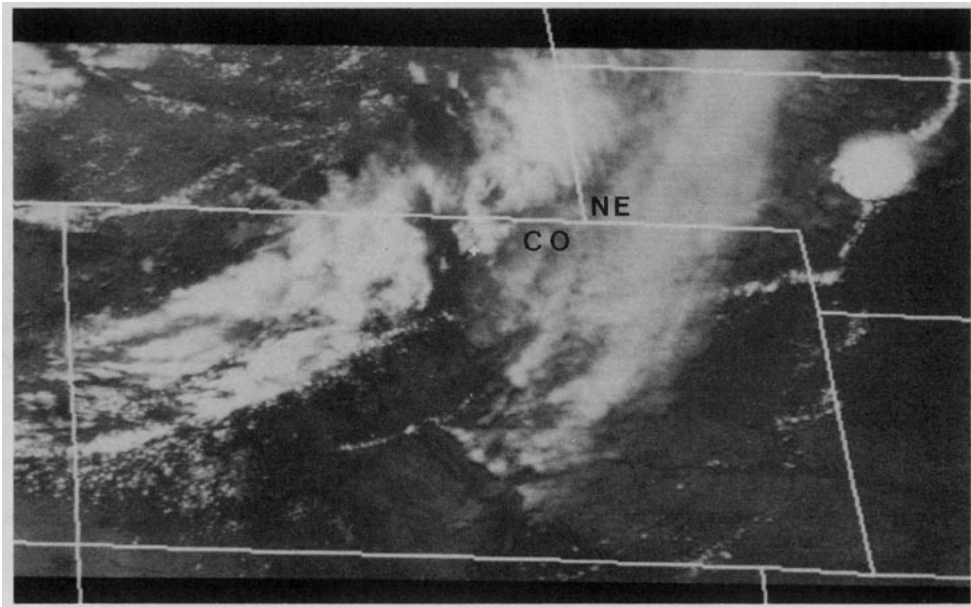


FIG. 7. GOES-7 visible satellite image from 2000 UTC on 3 July 1993 centered over Colorado with portions of surrounding states included. Note large thunderstorm at wave cusp in western Nebraska.

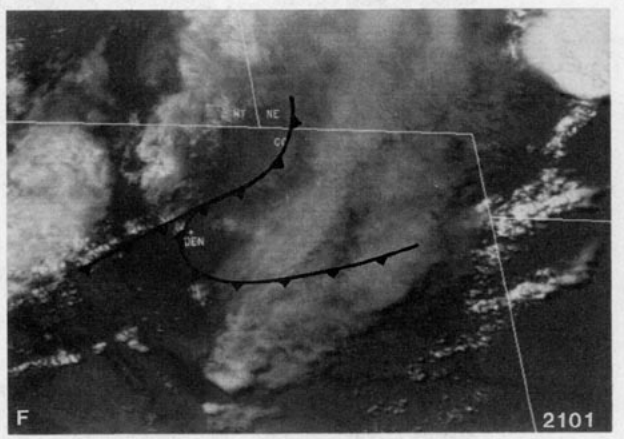
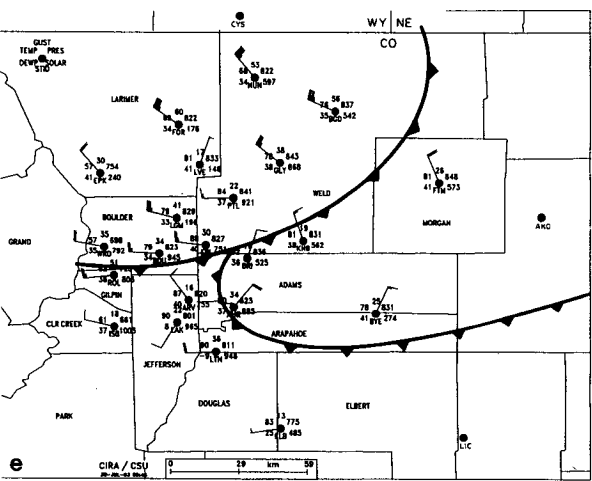
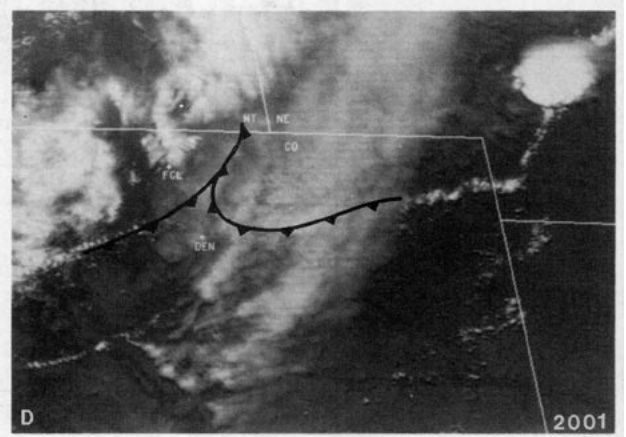
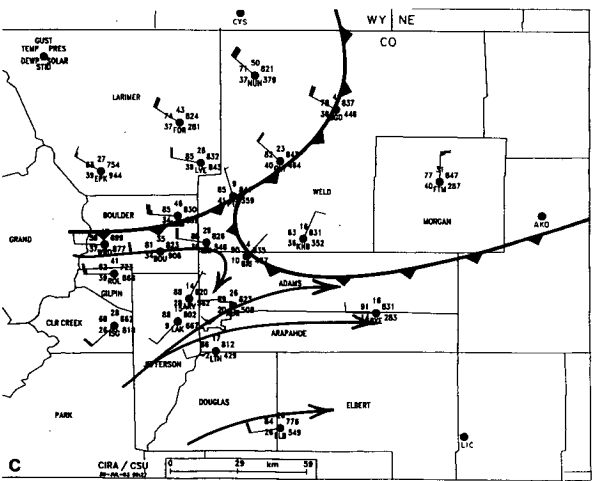
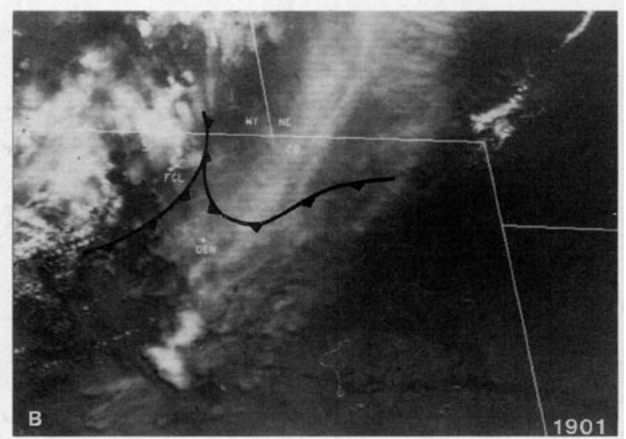
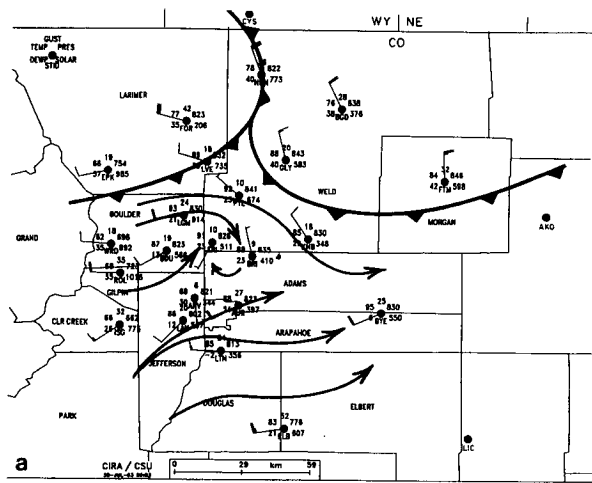


FIG. 8. Series of analyzed mesonet plots with accompanying GOES-7 visible satellite imagery for various times. Shown are (a)–(b) 1900 UTC, (c)–(d) 2000 UTC, and (e)–(f) 2100 UTC.

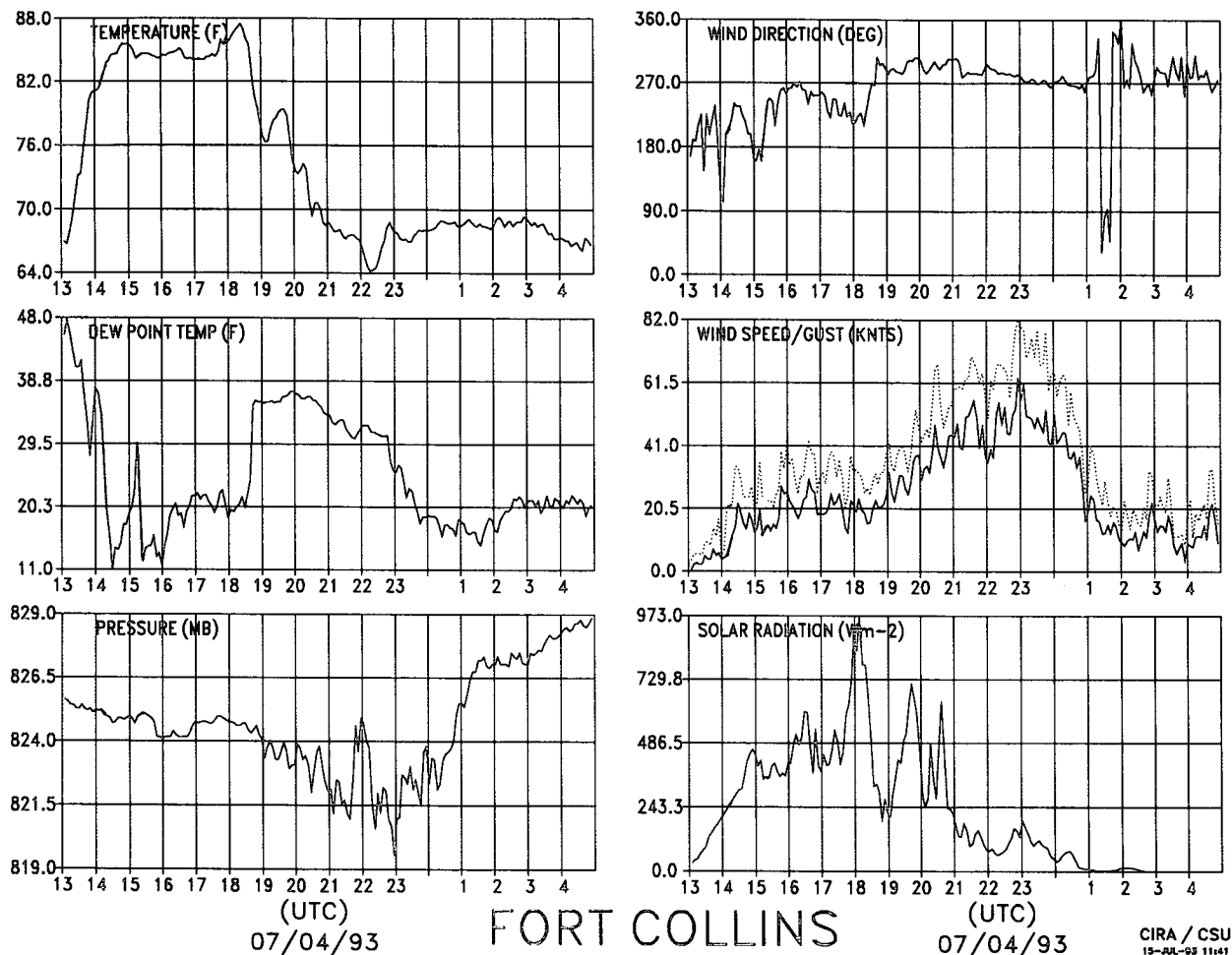


FIG. 9. Time-series plots of various surface parameters for Fort Collins, Colorado, from 1300 UTC 3 July 1993 through 0500 UTC 4 July 1993.

(SAOs) and standard upper-air sounding data. Using the ISAN analysis package developed by Tremback (1990), these data were interpolated onto isentropic surfaces using a Barnes (1973) objective analysis scheme. The observed, nongridded data were then blended with the eta model initialization datasets over data-sparse regions to form a complete initial field that was then interpolated onto the RAMS coarse grid. The eta model forecast fields at the 12-, 18-, 24-, 30-, and 36-h points of the forecasts were nudged to the lateral boundary region of the coarse grid of RAMS using a Davies (1979) nudging procedure. Because the conditions looked favorable for strong winds, RAMS was also run from the 1200 UTC observations and eta model initial data.

b. RAMS forecasts

A comparison between wind observations at the NOAA Mesonet site in Fort Collins (hourly average)

and model forecasts (shown in Fig. 11) shows that the model fails to reproduce observed winds during its entire run, with the exception of initial indications of strengthening flow. To add more realism to the simulation, the moisture complexity was changed from level 1 to level 2, in which cloud water is allowed, and run again. This change had no effect on surface wind speed. The model was also run a third time at a moisture complexity of level 3 or with the explicit bulk microphysics module including rain- and ice-phase hydrometeors (Cotton et al. 1986) activated. This also had no effect on surface winds. It was quite clear that RAMS was unable to forecast the windstorm in its normal real-time forecasting configuration.

6. Sensitivity experiments with RAMS

According to Durran (1986), the two theories that describe the development of strong lee slope winds are the linear theory and the hydraulic theory. Both these

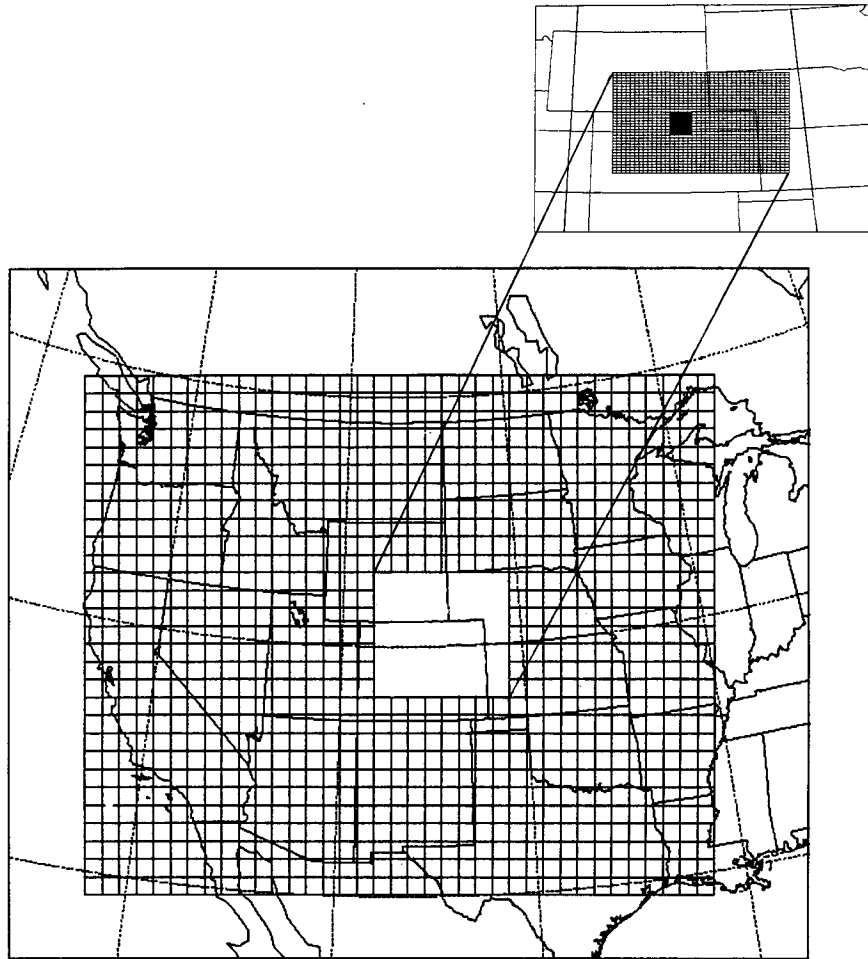


FIG. 10. Real-time grid No. 1 setup with 80-km horizontal grid spacing. Inset: real-time grid No. 2 setup (winter position) with 16-km horizontal grid spacing. Grid No. 3 along the eastern slopes of the Colorado Front Range is shown with 4-km grid spacing.

theories (and Durran's theory, which links these two theories), along with previous modeling results, show pronounced perturbations in the wind field along the



FIG. 11. Observed (solid) versus two-grid forecast winds (dashed) at Fort Collins. Speed in meters per second.

leeward slope. In the regular 16-km horizontal grid-spacing, forecasting version of RAMS, this region was only represented by three grid points; therefore, a third, finer grid was added in this area for the entire simulation (Fig. 10). Grid No. 3 has a horizontal grid spacing of 4 km, which extends along the Front Range from the Colorado–Wyoming border to Denver and has the same vertical dimensions as the other two grids. Within the first two hours of the simulation, the effects of the third grid produced strong winds descending along the lee slope of the mountains, low-level descent of 2.5 m s^{-1} , and a wave pattern just east of the mountain crest that is typical of a downslope windstorm.

As the simulation continues, the winds strengthen. A strong resemblance exists between the simulated θ field and wind field at the time of maximum observed winds shown in Figs. 12 and 13 at 10 h after model initialization and those analyzed by Lilly and Zipser (1972) in the 11 January 1972 windstorm. The most striking similarity between the two fields is the injection

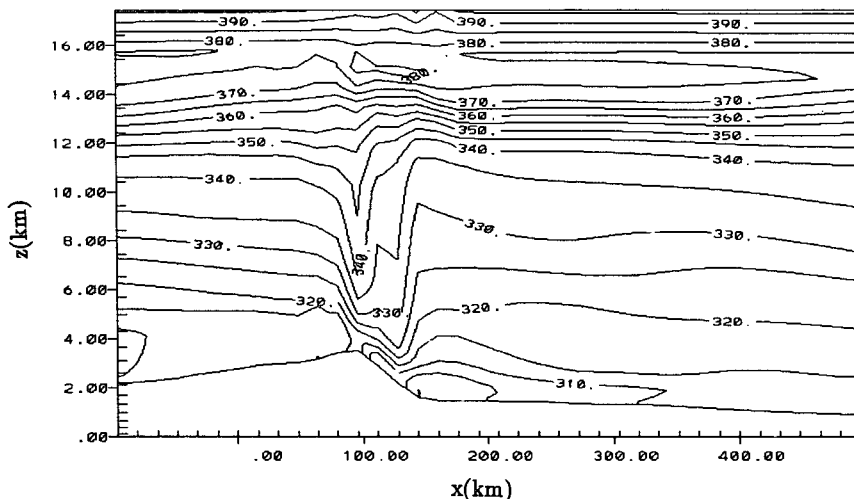


FIG. 12. RAMS-generated θ field (K) at 10 h for 3 July 1993 windstorm valid at 2200 UTC. Contour interval is 5 K. Grid No. 2 of a three-grid run is displayed.

of high stratospheric air into the lower troposphere in the vicinity of the mountain top. A wave pattern in the field can also be seen on the east side of the ridge. Like Lilly and Zipser's observation, a wind maximum of 60 m s^{-1} just to the east of the lee slope and a wind minimum in the mid- and upper-troposphere of 10 m s^{-1} in a narrow area directly above mountain top is simulated.

As with the two-grid simulations, the three-grid simulations were run at level 1 through level 3 moisture complexity. Unlike the two-grid simulations, the three-grid bulk microphysics run (level 3) differed considerably from the level 2 run (see Fig. 14). Although both three-grid simulations exhibited high initial winds

due to spinup, the level 3 run matched wind speed observations fairly well after 6 hours, whereas the level 2 microphysics run overpredicted wind speeds throughout the simulation. Also, recall that the observed precipitation matches the level 3 conditions.

This is probably due to the existence of precipitating hydrometeors in the level 3 run and only cloud water in level 2. In the spinup of the model, it takes a few hours to fully develop hydrometeors to their proper concentrations. At a given time, there is comparable water mass in the level 2 and level 3 runs. The main difference, however, is the form this water takes. The level 2 runs have many small cloud droplets, while the level 3 runs have fewer, large rain drops and ice particles

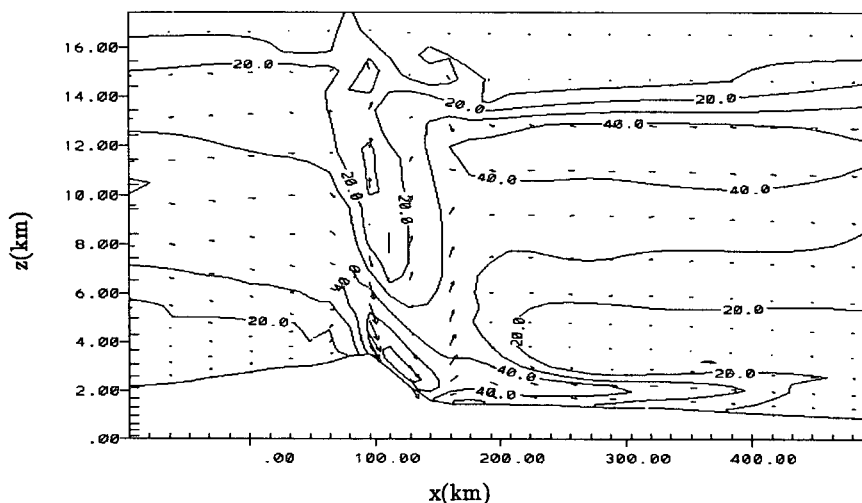


FIG. 13. RAMS-generated u -component wind field (m s^{-1}) at 10 h for 3 July 1993 windstorm valid at 2200 UTC. Contour interval is 10 m s^{-1} . Grid No. 2 of a three-grid run is displayed.

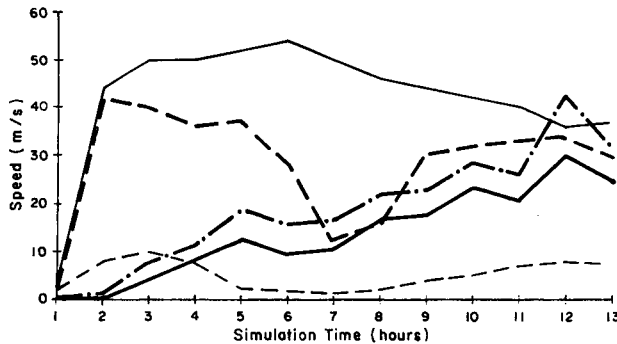


FIG. 14. Observed wind speed (dark thick solid) and gusts (dash-dot) for Fort Collins versus RAMS forecast winds for two grid simulations (thin dashed) and three grid simulations at level 2 (thin solid) and level 3 (thick dashed) microphysics options for 1200 UTC initialization. Speed in meters per second.

along the slope. Because the full microphysics option is in use, the thermodynamic consequences of explicitly resolving hydrometeors must be considered.

In the case of the level 2 microphysics, as the air ascends over the windward slope, cloud water is condensed, and as it descends over the lee slope the condensed water immediately evaporates, causing localized strong cooling and a pronounced dip in the isotherms. With the level 3 explicit microphysics version, however, a fraction of the water that is condensed during ascent precipitates to the ground, leaving smaller amounts of condensate to evaporate on the lee slope. In addition, the rate of evaporation of raindrops and other large hydrometeors is less than a comparable amount of liquid water residing in cloud droplets. This is principally due to the reduction in surface to volume ratio with increasing hydrometeor size. This results in a smaller downward displacement of the isotherms on the leeward side. Therefore, the winds will not be as strong as in the cases that do not consider the thermodynamics of the precipitation physics.

The one remaining problem in these simulations is the spinup effects. There is virtually no accuracy in the wind forecasts within the first 6 hours of the simulation. One way to counter these effects is to start the model 12 hours earlier. Figure 15 compares the observed wind and gusts and the 1200 UTC initialized three-grid level 3 forecast to a level 3 forecast using 0000 UTC initial conditions. Starting the model 12 hours earlier removes the spinup effects and produces better results 12 hours later.

7. Summary

An unseasonal, summertime downslope windstorm, similar to winter season windstorms along the Front Range of Colorado, is described. In addition to being out of season, the storm was also unusual in that it was characterized by having its strongest wind gusts limited to a small geographical region in and near the city of

Fort Collins. The synoptic pattern associated with the 3 July outbreak resembled that of a typical wintertime downslope windstorm, with a strong south-southwest-oriented height gradient at 700 mb and a strong west to east sea level pressure gradient across the Front Range. The pattern evolved into one even stronger than anticipated due to the development of an unforecasted, deep surface low in western Nebraska. Also, during the period of strongest winds in Fort Collins, deep clouds were observed on satellite imagery to the west of the Fort Collins area. These clouds were producing significant snowfall at higher elevations but only virga in and around Fort Collins.

From the results of simulating the 3 July 1993 windstorm with RAMS, the most important factor in obtaining a good wind forecast is the grid spacing along the leeward slope. To resolve a particular feature in a numerical model, the grid spacing must be at least four times smaller than the characteristic length of the feature. In this case, the spacing must be smaller than one-quarter wavelength of the high θ air injected from the lower stratosphere. If the grid spacing is bigger, the model cannot resolve this feature and the strong winds will not develop.

A secondary, but extremely important, factor seems to be in the use of explicit bulk cloud microphysics. The manner in which the microphysics is used in the model is also critical. Level 2 microphysics allows all the moisture to make it over the Front Range. The strong evaporation that occurs on the leeward slope as a result causes a pronounced kink in the isotherms and an overprediction of the strength of the surface winds on the lee slope. When level 3 microphysics is used, the moist air flows up and over the Front Range, and much of the precipitation forms and falls out on the windward side and near the summit. Cooling on the lee slope is reduced and, consequently, so is the amplitude of the kink in the isotherms on the lee slope. This reduces the magnitude of surface winds so that a better forecast is produced. The model findings are

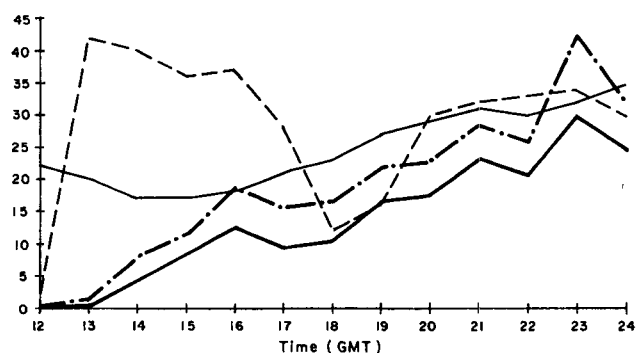


FIG. 15. Observed wind speed (thick solid) and gusts (dash-dot) for Fort Collins versus RAMS forecast winds for three grid simulations at level 3 complexity for 0000 UTC initialization (thin solid) and 1200 UTC initialization (thin dashed). Speed in meters per second.

confirmed by the observational data. The deep cloudiness observed on satellite was limited to a region in north-central Colorado where the strongest winds occurred. An in situ observation reported virga, but no precipitation, in Fort Collins. Finally, copious precipitation did occur near the Front Range summit as verified by National Weather Service observers and hikers in the area.

In summary, then, to forecast this type of downslope windstorm accurately over the Colorado Front Range with a mesoscale numerical prediction model, grid spacing of approximately 4 km and the use of explicit bulk microphysics is required. With the advent of even faster computers or use of clusters of workstations (see Cotton et al. 1994), the hardware requirements needed to forecast this type of mesoscale phenomenon will be available in the very near future.

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REFERENCES

- Barnes, S. L., 1973: Mesoscale objective map analysis using weighted time series observations. NOAA Tech. Memo. ERL NSSL-62, 60 pp. [NTIS COM-73-10781.]
- Beitler, B. A., 1994: Mesoscale numerical prediction of Colorado snowfall and winds. M.S. thesis, Dept. of Atmospheric Science, Colorado State University, 83 pp.
- Cotton, W. R., G. J. Tripoli, R. M. Rauber, and E. A. Mulvihill, 1986: Numerical simulation of the effects of varying ice crystal nucleation rates and aggregation processes on orographic snowfall. *J. Climate Appl. Meteor.*, **25**, 1658–1680.
- , G. Thompson, and P. W. Mielke Jr., 1994: Real-time mesoscale prediction on workstations. *Bull. Amer. Meteor. Soc.*, **75**, 349–362.
- Davies, H. C., 1979: Phase-lagged wave-CISK. *Quart. J. Roy. Meteor. Soc.*, **105**, 325–353.
- Durran, D. R., 1986: Another look at downslope windstorms. Part I: The development of analogs to supercritical flow in an infinitely deep, continuously stratified fluid. *J. Atmos. Sci.*, **43**, 2527–2543.
- Kuo, H. L., 1965: On formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.*, **22**, 40–63.
- Lee, T. J., 1992: The impact of vegetation on the atmospheric boundary layer and convective storms. Ph.D. dissertation, Colorado State University, 137 pp.
- , R. A. Pielke, R. C. Kessler, and J. Weaver, 1989: Influence of cold pools downstream of mountain barriers on downslope winds and flushing. *Mon. Wea. Rev.*, **117**, 2041–2058.
- , J. F. Weaver, and R. A. Pielke, 1990: Numerical predictions and nowcasting of downslope windstorms along the Colorado Front Range. Preprints, *Fifth Conf. on Mountain Meteorology*, Boulder, CO, Amer. Meteor. Soc., 81–84.
- Lilly, D. K., and E. J. Zipser, 1972: The front range windstorm of 11 January 1972: A meteorological narrative. *Weatherwise*, **25**, 56–63.
- Mahrer, Y., and R. A. Pielke, 1975: A numerical study of the air flow over mountains using the two-dimensional version of the University of Virginia mesoscale model. *J. Atmos. Sci.*, **32**, 2144–2155.
- NOAA, 1993: Storm data and unusual weather phenomena with late reports and corrections, 35(7), NESDIS, National Climatic Data Center, 300 pp.
- Neuburger, M., 1949: Reflection, absorption, and transmission of insolation by stratus cloud. *J. Appl. Meteor.*, **6**, 98–104.
- Thompson, G., 1993: Prototype real-time mesoscale prediction during 1991–92 winter season and statistical verification of model data. M.S. thesis, Dept. of Atmospheric Science, Colorado State University, 105 pp.
- Tremback, C. J., 1990: Numerical simulation of a mesoscale convective complex: Model development and numerical results. Ph.D. dissertation, Colorado State University, 247 pp.
- Weaver, J. F., and R. S. Phillips, 1990: An expert system application for forecasting severe downslope winds at Fort Collins, CO, U.S.A. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, AB, Canada, Amer. Meteor. Soc., 13–15.
- Weissbluth, M. J., and W. R. Cotton, 1993: The representation of convection in mesoscale models. Part I: Scheme fabrication and calibration. *J. Atmos. Sci.*, **50**, 3852–3872.