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A CASE STUDY OF MESOSCALE OROGRAPHIC ENHANCEMENT OF PRECIPITATION IN THE SANTA CATALINA MOUNTAINS OF ARIZONA

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Introduction

During the early morning hours of January 5, 1995 (LST), a vigorous short-wave trough was over southern California approaching Arizona. As the system approached southeast Arizona, synoptic scale ascent developed in conjunction with a strong, moist low-level jet. Intense rainfall (and snowfall above 2550 meters) over the Santa Catalina Mountains just north of Tucson was observed between 0600 UTC and 1200 UTC. As a result of 20 inches of wet snow, roads to the ski area were closed for several days. Precipitation on Mount Lemmon (40 km north of Tucson at an elevation of 2791 meters) was from 2 to 4 inches in the period 0000 UTC to 1200 UTC on the 5th, while rainfall at the National Weather Service office in Tucson was only 0.13 inches. The exact precipitation on Mount Lemmon is somewhat ambiguous due to estimated measurements from a local ski area and a frozen automated precipitation gage near the summit.

The south facing slopes of the Santa Catalina Mountains drain into the Tucson valley where widespread flooding problems occurred during the morning hours of the 5th as numerous washes and normally dry rivers experienced swift runoff, prompting several road closures in and around Tucson. The regional scale numerical models (which for the purposes of this paper consists of only the NGM and Eta) handled the synoptic evolution satisfactorily, but were not capable of resolving the meso-beta scale (Orlanski 1975) processes which produced the heavy rainfall over the mountains north of Tucson. The deficiency of these models primarily resulted from the poor resolution of the small topographic features (on the order of 25 to 50 km) that pepper the southeast Arizona landscape. See Dunn and Horel (1994) for a literature review regarding the NGM and Eta models, as well as previous precipitation studies utilizing these models. To illustrate the capability of mesoscale models employing high resolution terrain data, and to better understand the mesoscale processes associated with this precipitation event, a PSU-NCAR Mesoscale Model (MM5) version 1 (Grell et al. 1995) simulation was performed.

Synoptic Analysis and the Regional Models Forecast

The 0000 UTC and 1200 UTC January 5, 1995 Eta and NGM operational forecasts were revisited to determine the accuracy of their 6 to 12 hour guidance, and also to provide synoptic scale analysis of the event. Generally, the synoptic scale forecast produced by these models was of high quality and quasi-geostrophic diagnostics (Hoskins et al. 1978; Sanders and Hoskins 1990; Durran and Snellman 1987) would have benefited the forecaster in analyzing synoptic scale vertical motions. However, besides the poor terrain resolution, there were two notable weaknesses in both the NGM and Eta model forecasts which contributed to the heavy precipitation. First, the 12 hour forecast low-level wind field (below 700 hPa) was under-forecast by 30 to 50 percent. A southwesterly low-level jet forecast by the 0000 UTC models in the 20 to 30 knot range over the southern Arizona verified in the 40 to 50 knot range. The verifying 1200 UTC 850 hPa wind field is shown in Fig. 1. Second, the stronger than expected low-level jet was very effective at advecting low-level moisture northward into southern Arizona. Both the NGM and Eta under-forecast the low-level moisture flux into southern Arizona.

Figure 2 shows the surface pressure (as a proxy for model terrain) from the NGM model (horizontal resolution of approximately 80 km) and the 12 hour NGM QPF ending at 1200 UTC January 5. The NGM 12 hour QPF is less than 0.50 inch across southern Arizona with the greatest precipitation amounts over the higher model terrain.

Conceptualization of the Precipitation Event

Figure 3 shows the Tucson sounding from 1200 UTC on the 5th of January, 1995. Compared to the 0000 UTC sounding from the evening before (not shown), temperatures cooled at middle and upper levels about 3 degrees Celsius, and warmed 2 to 3 degrees below 700 hPa. Figure 4 shows 500 hPa quasi-geostrophic vertical velocity valid at 1200 UTC January 5, 1995 from the 00 hour Eta model forecast, indicating upward motion of 3 to 5 microbars/second over eastern Arizona. Time-height cross sections from the numerical models centered on Tucson showed slight mid-level warm air advection through the 0000 UTC to 1200 UTC period. Calculations based on the quasi-geostrophic thermodynamic equation (Holton 1979) (neglecting temperature advection and using a static stability derived from the 1200 UTC Tucson sounding) indicate that a time averaged omega of 1.5 microbars/second for a period of 12 hours is sufficient to cool temperatures by approximately 3 degrees Celsius. Thus, despite the weak warm air advection in the middle levels of the atmosphere, cooling due to synoptic scale upward vertical motion dominated the local temperature tendency resulting in destabilization of the atmosphere. At lower levels, both the warm air advection and positive moisture advection contributed to the destabilization.

Errors in the forecast low-level moisture and wind field become significant when the mountains of southeast Arizona, whose horizontal resolution are on the order of 25 to 50 km, are considered. Computation of the up-slope flow over the steep south facing slopes of the Santa Catalina Mountains assuming a 50 knot low-level jet yields an upward vertical velocity of roughly 1.2 m/s. Analysis of the sounding in Fig. 3 shows that parcels lifted from the 700 to 850 hPa layer (i.e. the layer of air forced to ascend over the Santa Catalina Mountains) are slightly unstable to moist adiabatic ascent. The strong low-level jet not only created forced ascent in excess of 1 m/s allowing parcels to reach their level of free convection, but also served as a continuous source of moisture. Infrared satellite pictures (not shown) showed occasional localized convection over the Santa Catalina's during the 0600 UTC to 1200 UTC period.

Mesoscale Model Simulation

a. Model description

To better understand this particular rainfall event, as well as explore the capability of high resolution mesoscale models for operational use, a 12 hour MM5 simulation was performed. The authors would like to thank Jordan Powers of NCAR for his support and assistance in the modeling effort. The initial conditions of the atmosphere and sea surface temperature fields were obtained by interpolation of the NMC operational global analyses to the model grid. These course resolution fields were then enhanced through a Cressman-type objective analysis scheme (Manning and Haagenson 1992) of surface and rawinsonde data. In order to simulate a real-time operational run of the MM5, no additional processing of the initial data were performed (i.e. no data not routinely available through automated procedures by operational run time were utilized). The simulation was carried out for a period of 12 hours in order to capture the heavy precipitation event which occurred primarily within the 0600 UTC to 1200 UTC window. This also allowed sufficient time for the model to "spin-up" and generate cloud water during the first few hours of the simulation (Powers, personal communication). For this particular run of the MM5, an explicit moisture scheme (Hsie et al. 1984) for grid-resolvable precipitation was used in conjunction with a convective parameterization (Grell et al. 1995) for subgrid-scale convective precipitation processes. The grid resolution utilized a 15 km course grid and a 5 km nested fine grid with 27 vertical levels. The size and location of these grids are shown in Fig. 5a. The fine grid terrain is shown in Fig. 5b and captures many of the detailed terrain features of southern Arizona, including the Santa Catalina Mountains.

b. Model results

Prior to the heavy rainfall, the MM5 showed blocked flow and a meso-high immediately upstream of Mt. Lemmon over the Tucson area through 0700 UTC. National Weather Service (NWS) surface observations from Tucson International Airport showed light easterly winds out of this meso-high (through 0600 UTC) prior to southwesterly momentum mixing downward to the surface. As the stability decreased and the southwesterly low-level jet intensified, up-slope flow developed over the windward slopes of the Santa Catalina's. Figure 6 shows a cross section (see Fig. 5b for location of the cross section) of vertical velocity (m/s) and equivalent potential temperature at forecast hour 10 of the simulation (valid time: 1000 UTC January 5, 1995). The model simulation shows 1.22 m/s up-slope flow just above the south slopes of the Santa Catalina's. In the 500 hPa to 800 hPa layer, equivalent potential temperature is nearly constant implying very weak to neutral stability for moist parcel displacement. Figure 7a-c shows the MM5 total precipitation (explicit and convective precipitation combined) ending at 0600 UTC, 0900 UTC, and 1200 UTC, respectively. In Fig. 7d, the MM5 12 hour accumulated convective precipitation (ending at 1200 UTC). The MM5 simulation maintains intense orographic precipitation over the Santa Catalina Mountains during the 0600 UTC to 1200 UTC period producing a 12 hour QPF of 68.9 mm (2.71 inches) on Mt. Lemmon. Note that the convective parameterization did turn on, but the convective scheme contributed less than 1 mm to the total Mt. Lemmon precipitation. Based on satellite imagery (not shown), it is believed that brief convective bursts did occur over the mountain despite the fact that the model did not simulate significant convective precipitation. The detailed gravity wave fields produced by the MM5 and their role in the orographic precipitation event, as well as the significance of the feeder-seeder process (Bluestein 1993) remain to be investigated for this case.

Summary

Regional scale numerical weather prediction models (in this case the NGM and Eta) did a reasonable job forecasting the synoptic scale evolution of the trough which moved across Arizona on January 5, 1995. Notable model deficiencies included an under-forecast low-level jet and under-forecast low- level moisture flux into southern Arizona. But, despite the meteorological deficiencies in the regional scale models forecasts, it is believed that the most significant deficiency resulted from poor terrain resolution.

An MM5 simulation utilizing a fine grid of 5 km over southern Arizona was run to investigate the mesoscale processes and aid in determining the usefulness of high resolution mesoscale models during a significant orographic precipitation event in southern Arizona. The MM5 results further suggest that the primary deficiency of the regional scale numerical models in a southern Arizona orographic precipitation event is their poor terrain resolution.

In order for future events of this magnitude to be better forecast, either (1) mesoscale numerical models capable of resolving the small but significant mountain ranges of southeast Arizona must be employed, or (2) techniques must be derived which allow forecasters to recognize and anticipate the development of similar conditions based on available regional scale numerical model guidance.

Acknowledgments

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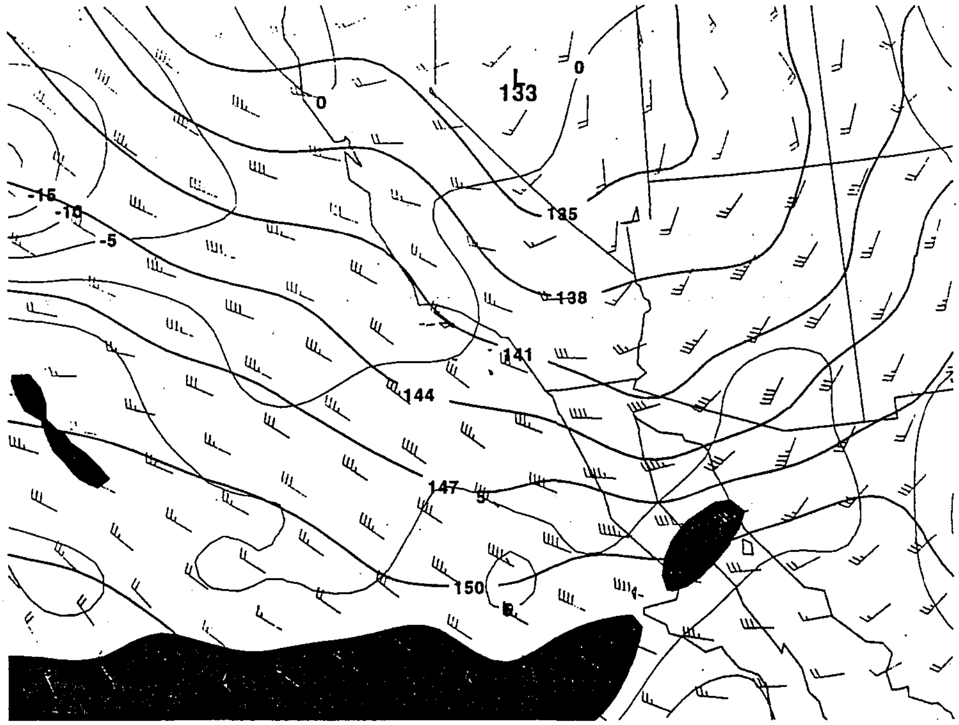


Fig. 1. Eta 00 hour forecast 850 hPa height (bold solid; contour interval 3 dam), wind (knots), and dew point (thin solid; contour interval 5 celsius) valid 1200 UTC January 5, 1995. Dew points greater than 10 celsius are shaded.

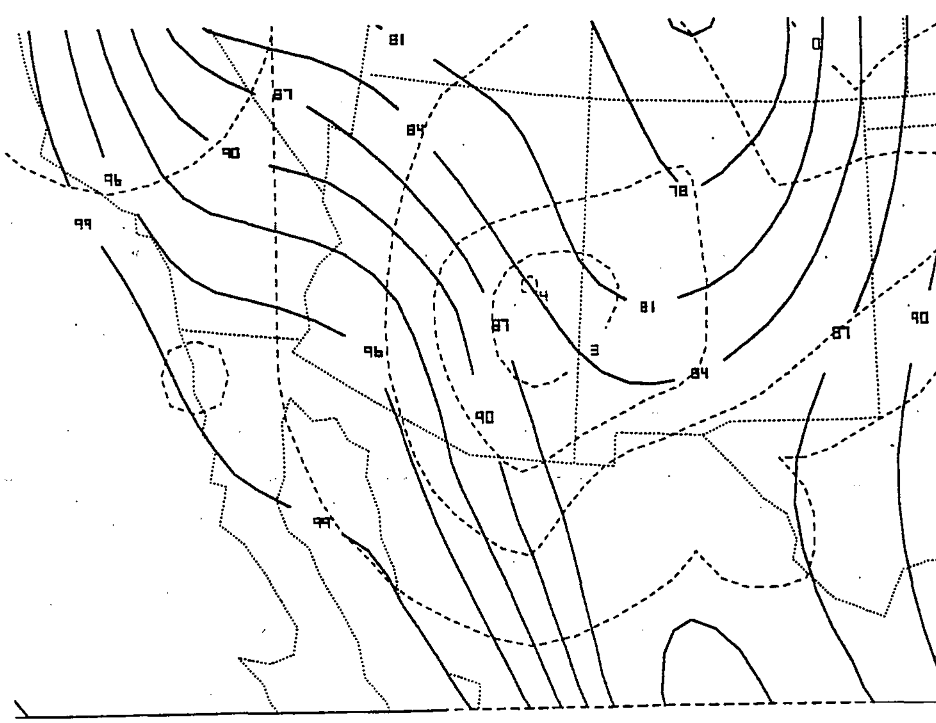


Fig. 2. NGM surface pressure (bold solid; contour interval 3 kPa) and NGM 12 hour QPF (dashed; contour interval in tenths of inches) valid 1200 UTC January 5, 1995.

(a)

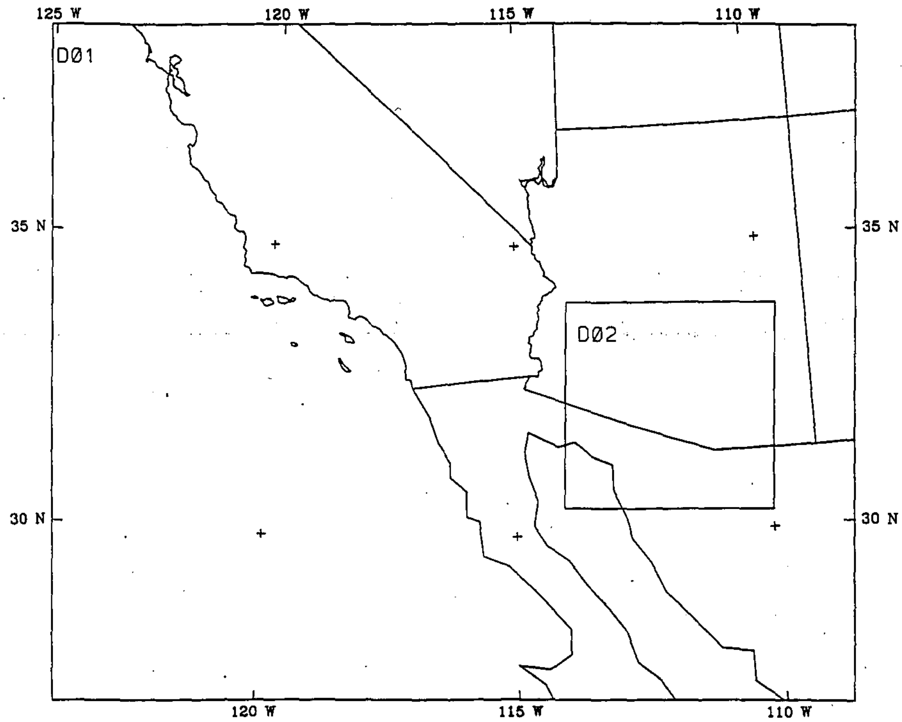


Fig. 5. (a) The course domain (labeled D01) and the fine domain (labeled D02) used in the MM5 simulation of the January 5, 1995 heavy precipitation event. Horizontal resolution of the course domain is 15 km, and the fine domain 5 km.

(b)

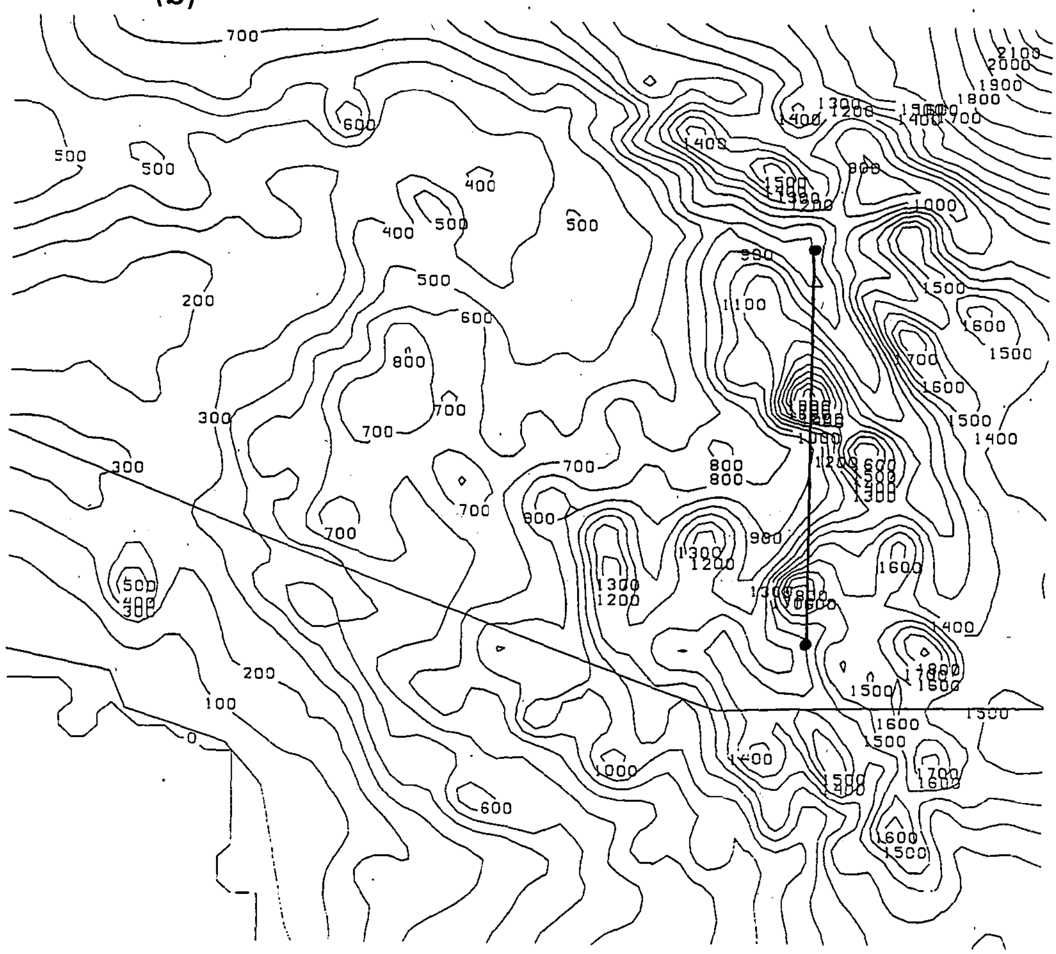


Fig. 5. (b) Model fine grid terrain (horizontal resolution of 5 km; contour interval 100 meters). The solid line represents the cross section referenced in Fig. 6.

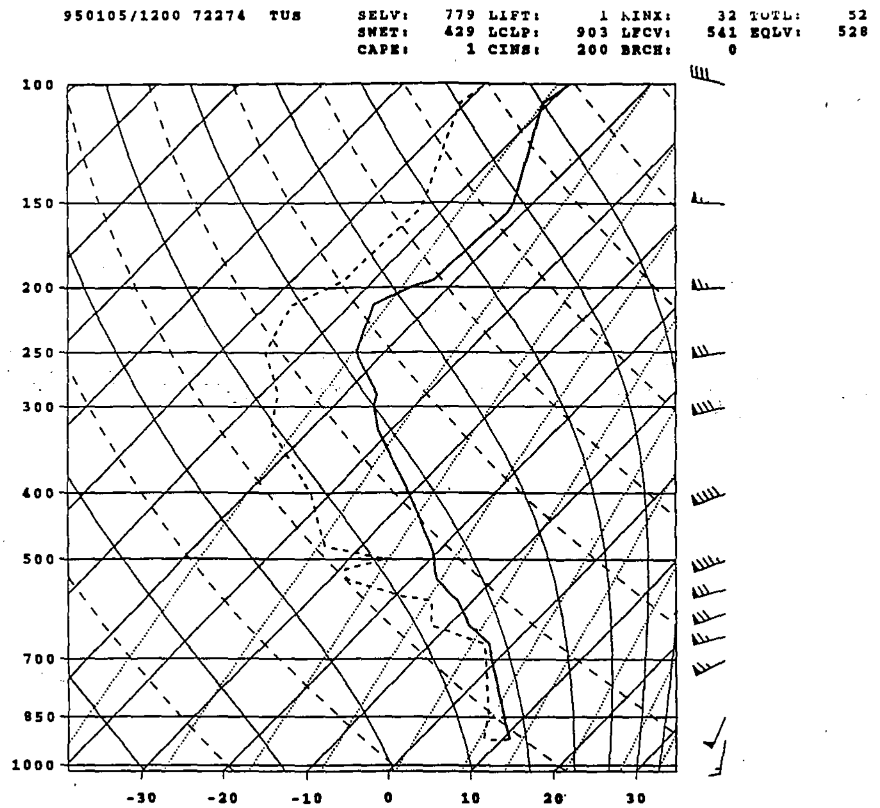


Fig. 3. NWS Tucson sounding valid 1200 UTC January 5, 1995.

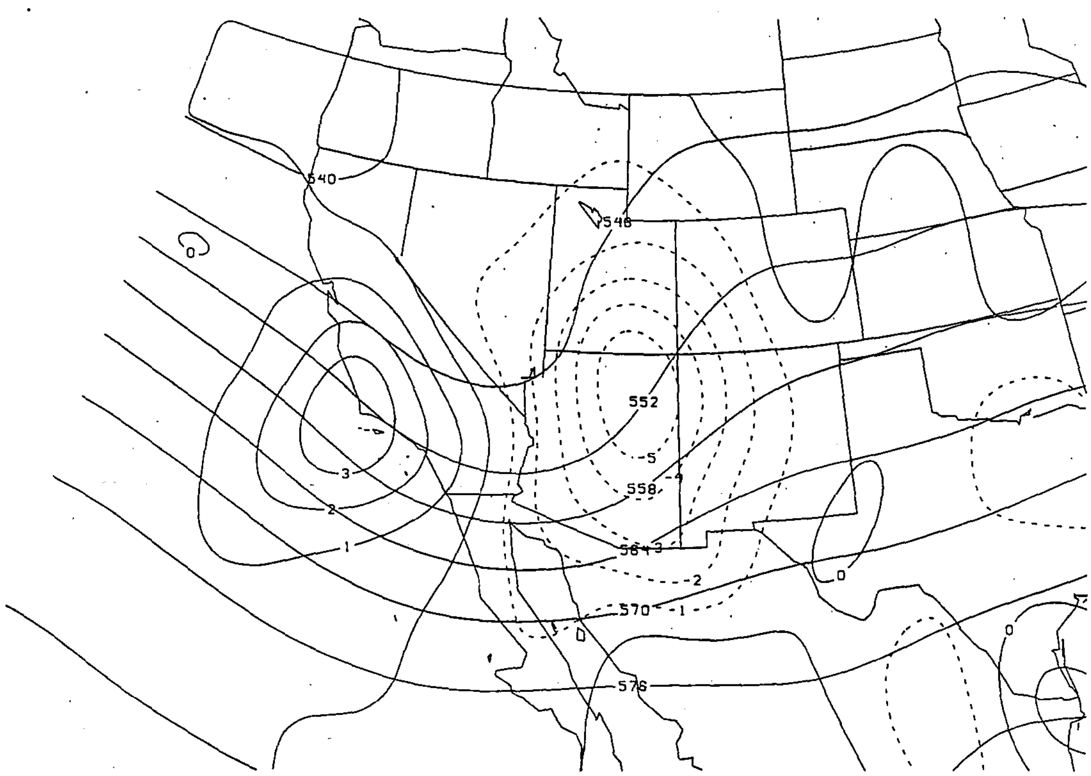


Fig. 4. Eta 00 hour forecast 500 hPa height (solid; contour interval 6 dam) and Eta 00 hour forecast 500 hPa quasi-geostrophic omega (dashed/solid; contour interval 1 microbar/second) valid 1200 UTC January 5, 1995.

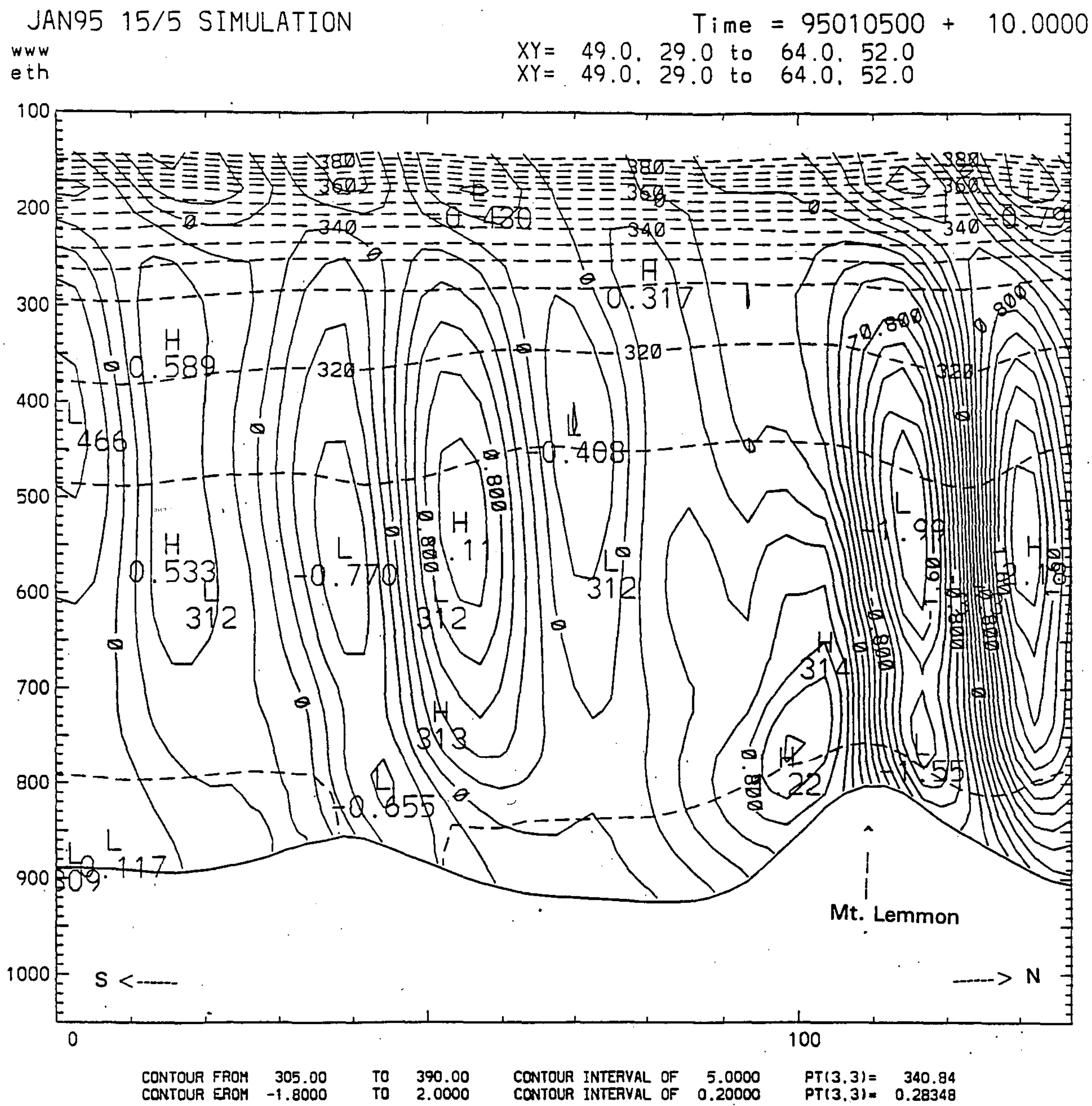
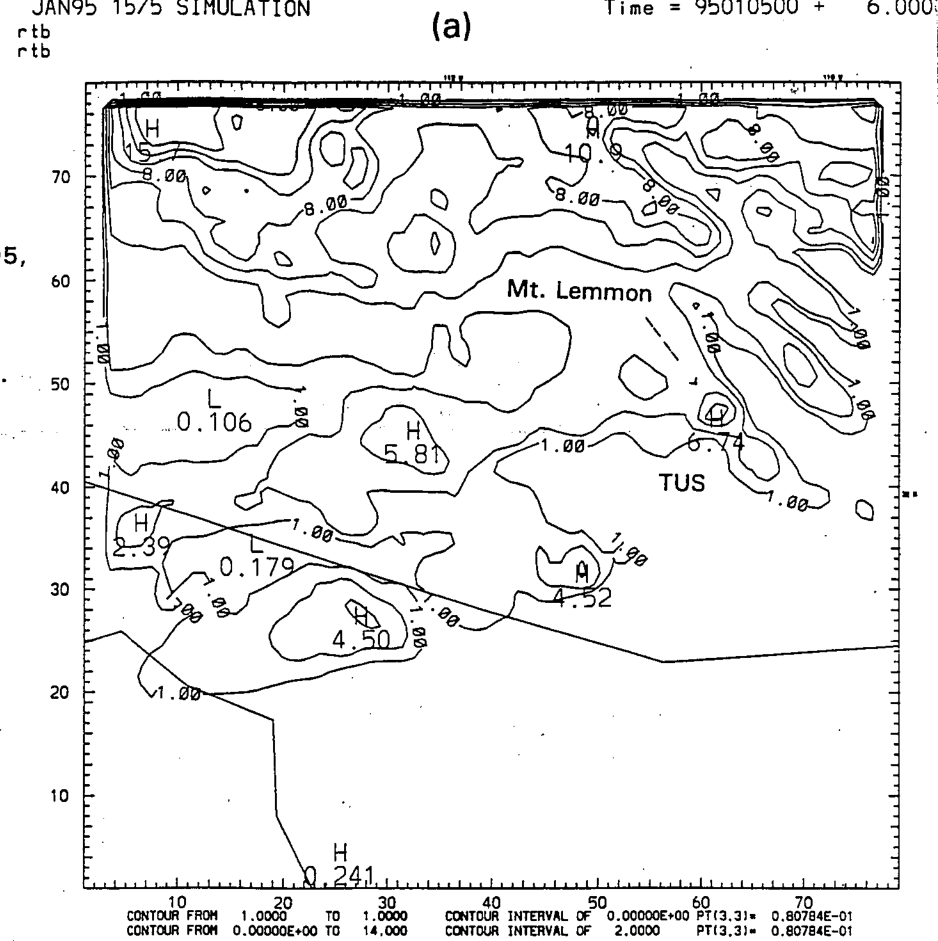
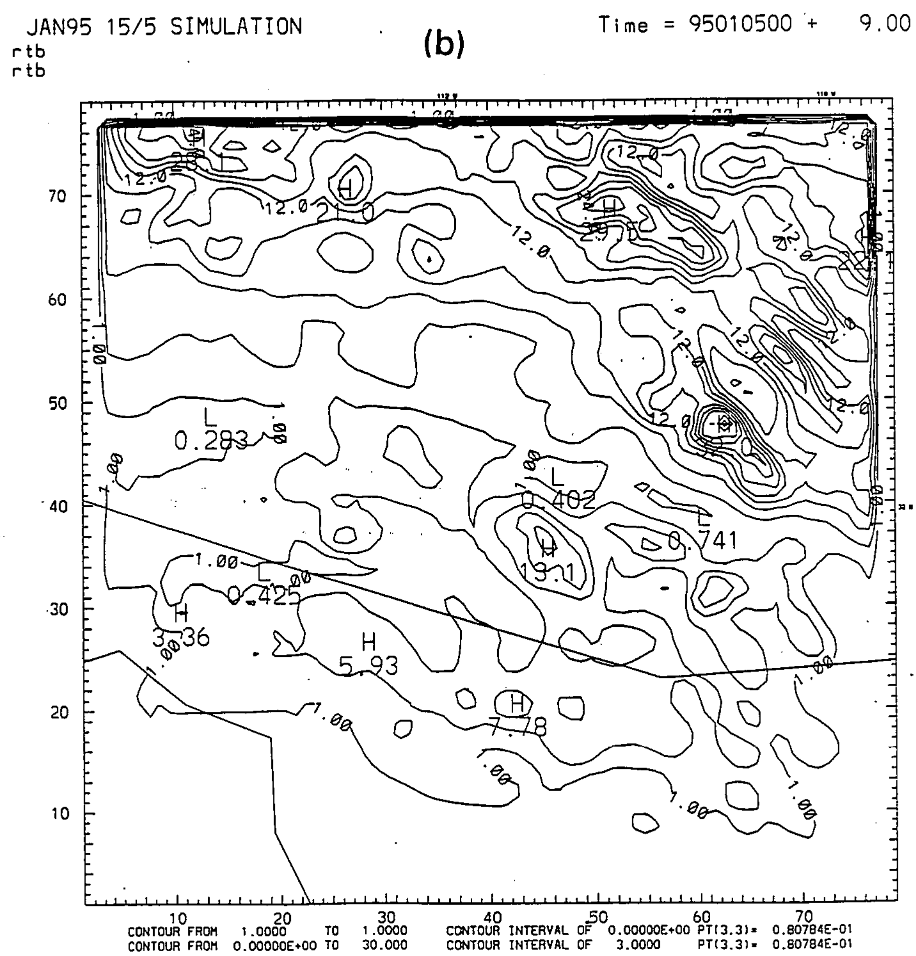


Fig. 6. Cross section (see Fig. 5b for location) running North to South through heavy precipitation over Mt. Lemmon. Vertical velocity (solid; contour interval 0.2 m/s) and equivalent potential temperature (dashed; contour interval 5K).

Fig. 7. (a)-(c) MM5 fine grid total (explicit and convective combined) QPF ending at 0600 UTC, 0900 UTC, and 1200 UTC January 5, 1995, respectively. (Contours interval in (a): 1, 2, 4, 6 mm...; Contour interval in (b) and (c): 1, 3, 6, 9 mm ...). Location of Mt. Lemmon and Tucson (TUS) are shown in (a). (d) MM5 fine grid convective QPF ending at 1200 UTC January 5, 1995. (Contour interval 0.5 mm).



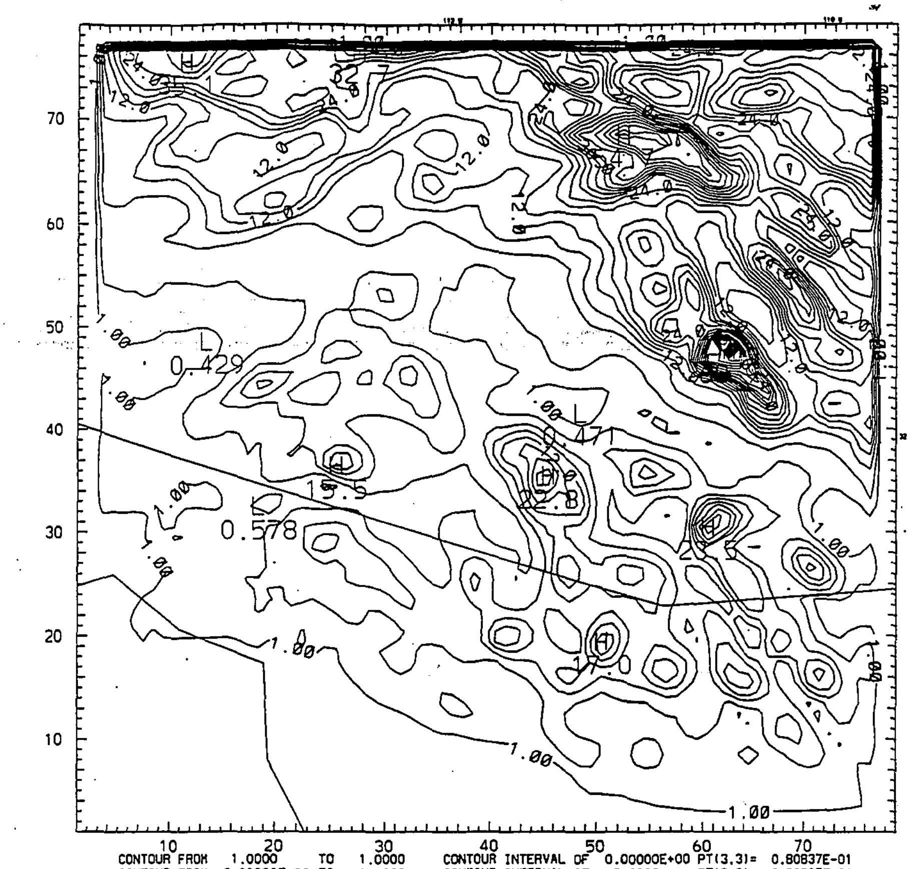


JAN95 15/5 SIMULATION

rtb
rtb

(c)

Time = 95010500 + 12.0000



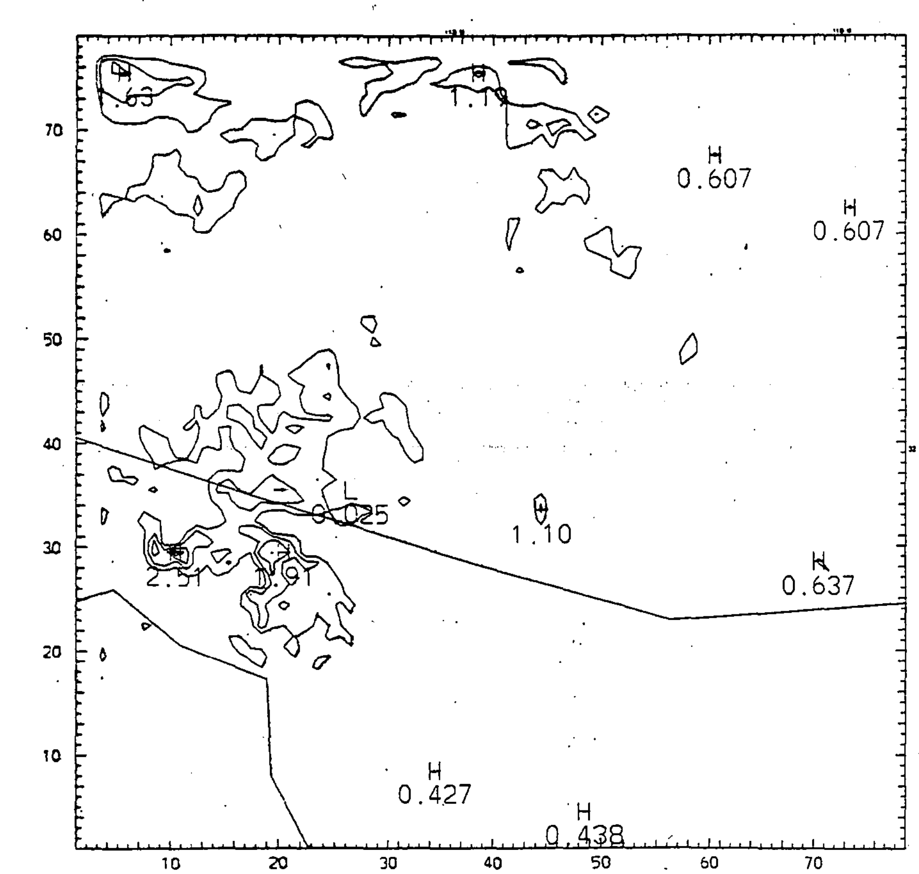
CONTOUR FROM 1.0000 TO 1.0000 CONTOUR INTERVAL OF 0.00000E+00 PT(3,3)= 0.80837E-01
CONTOUR FROM 0.00000E+00 TO 66.000 CONTOUR INTERVAL OF 3.0000 PT(3,3)= 0.80837E-01

JAN95 15/5 SIMULATION

rtc

(d)

Time = 95010500 + 12.0000



CONTOUR FROM 0.00000E+00 TO 2.5000 CONTOUR INTERVAL OF 0.50000 PT(3,3)= 0.80784E-01