Western Region Technical Attachment
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THE WARM RAIN PROCESS AND WSR-88D

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Introduction

As stated by Heymsfield (1992), "Cloud physics is a discipline in meteorology concerned with the properties of atmospheric clouds and the processes that operate within them, the diversity of phenomena intrinsic to natural clouds, and the interactions of clouds with the atmosphere." The suite of numerical models now run operationally at NMC do not contain explicit microphysical processes leading to precipitation in the model. Mesoscale models being tested in the research community only parameterize the complicated microphysical processes that have been observed in clouds. However, the complicated mechanisms leading to the formation and growth of precipitation in clouds can be critical to our ability to quantitatively estimate precipitation amounts and, as will be shown, to observe the proper amounts with the WSR-88D radar. In this Technical Attachment, an example is given for the failure of the Monterey WSR-88D (KMUX) to properly estimate precipitation during record 24-hour rains in the San Francisco Bay Area that occurred on November 5 and 6, 1994. It will be shown that this serious underestimation is a combination of the radar siting, the precipitation algorithm, and the precipitation mechanism operating within this cloud system.

Synoptic Setting

The synoptic pattern for 5 November at 1200 UTC showed a vigorous shortwave trough located near 45°N/145°W digging into the mean long-wave trough located along 120°W. Ahead of this shortwave trough was a southwest to northeast oriented region of warm overrunning associated with the warm conveyor belt ahead of the surface cold front (Browning 1985). The 0730 UTC 6 November infrared satellite image (Fig. 1) shows the southwestward extent of this conveyor belt to subtropical latitudes. The stalling of this warm conveyor belt over the San Francisco Bay region was a substantial contributor to the heavy precipitation.

NMC model output did a fairly good job of highlighting the strength and the slow moving nature of this band of precipitation. The 1200 UTC 5 November Eta model run forecasted significant vertical motion (Omega) just north of San Francisco Bay by 0000 UTC on the 6th, with a maximum of 15 μb s^{-1}, (Fig. 2). An analysis of two of the major terms in the quasigeostropic omega equation showed that most of this upward motion was likely due to the forcing provided by the laplacian of temperature advection term, mainly between the surface and 700 mb. There was very little contribution from differential vorticity advection during the heaviest precipitation. A five-panel time-height analysis produced over San Francisco using FAIS (Forecaster Applications and Imagery Software) shows the winds aloft veering with height in response to this warm advection (Fig. 3). As seen, a portion of the graphics were missing. The model indicates moderate to heavy precipitation expected from 1800 UTC on the 5th to 0000 UTC on the 7th. Both the NGM and aviation model (AVN) produced similar patterns, though amounts were substantially less.

Figure 3 indicates two separate periods of precipitation; the heaviest associated with frontal passage at 36 hrs. These model results can be compared to the temporal plot of precipitation from Mission Dolores, (Fig. 4). Another interesting comparison is the Eta model produced sounding for San Francisco (Fig. 5) versus the observed Oakland sounding for the same time (Fig. 11). The model sounding does a good job in predicting the atmospheric conditions in the lowest 10,000 ft but overestimates cloud top by almost 13,000 ft.

KMUX WSR-88D Analysis

Figure 6 is the storm total precipitation (STP) product for the period from 2207 UTC (1407 PST) 4 November to 2258 UTC (1458 PST) 6 November. Annotated over the radar derived amounts are the storm total rainfall amounts as observed by either cooperative observers or by ALERT telemetered gauges. Obviously there is a glaring discrepancy between the radar derived and observed precipitation amounts. In fact, for the region near San Rafael, the radar underestimated precipitation by a factor of 100! Note that the radar was down from 0145 UTC to 1030 UTC on 5 November. During this period, 2 inches of rain fell north of San Francisco and a few tenths fell in downtown San Francisco. Thus, this outage was not considered to be a substantial contributor to the radar underestimation.

Figure 7 shows the 0.5° elevation reflectivity pattern for 0000 UTC 6 November (1600 PST 5 November). The highest reflectivities (35 to 40 dBZ) are over Marin County where the gauge at Ross (near Mill Valley) was observing rainfall rates of .2 inches per hour. Figure 8 shows the echo tops for the same time period as Fig. 7. Note the highest tops may be as high as 15,000 to 20,000 ft. over this area. It would appear the radar was at least observing moderate rain over Marin County. So why did the radar do such a poor job of calculating precipitation?

If we look at the location of the radar beam over Marin County at 55 to 60 nm from the radar, (Fig. 9) (Barker, 1994), we see the bottom of the 0.5° beam is at 6000 ft with the top of the beam at 12000 ft. Thus, this lowest scan is sampling most of the precipitating cloud. Based on a preliminary discussion with the Norman OSF Algorithm Section, it appears the tilt test portion of the bi-scan maximization precipitation algorithm failed (Shedd et al., 1989). This portion of the algorithm tests for a 50 percent or greater reduction in echo coverage (> 1 dBZ) between the first two tilt scans (0.5° and 1.5° elevation scans) at a range beyond 50 km If this test is positive, the lowest tilt angle is considered anomalous propagation and is eliminated from the Z-R calculation! Figure 10 is a four panel display showing the lowest three elevation scans for 0000 UTC on the 6th plus the storm total precipitation up to this time. It is apparent that there is at least a 50 percent reduction in areal coverage of reflectivity between 0.5° and 1.5°.

Precipitation Formation Mechanism

The next question is, "How did a shallow, warm cloud system (cloud-top temperatures > -10° C) produce 5 to 11 inches of rainfall?" One can look at the Oakland sounding to address this question (Fig. 11). The 0000 UTC sounding shows that 80 percent of the precipitating cloud is warmer than 0° C. Thus, the warm rain process or coalescence growth must play a dominant role in precipitation formation. It is critical in the coalescence process that a broad cloud droplet spectrum exists (Mason 1971). Since these are maritime clouds the cloud droplet distribution is rather broad, usually spread equally between 10 and 50 μm. Figure 12 shows the collision efficiency (ability of larger drops to collect smaller drops and grow to precipitation size) of cloud droplets as a function of the largest drops in the cloud. In maritime clouds, the collision efficiency becomes very high leading to the rapid onset of coalescence growth and the warm rain process. Given that drops greater than 30 μm are present in this cloud and the cloud top temperature is near -5 °C, it is safe to assume that ice multiplication may be occurring (Hallet and Mossop 1974). This is the process whereby the freezing of these large drops as they accrete onto existing ice leads to ice splintering which produces hundreds of crystals per liter when normal ice nucleation processes would suggest less than .1 crystal per liter. This mechanism was observed many times in the Sierra Nevada (Reynolds 1988). Thus, it is hypothesized that a combination of coalescence growth and secondary ice production contributed to the formation of a large number of precipitation embryos which grew quite rapidly by coalescence growth in this relatively shallow cloud. The duration of precipitation was extended by the lack of southward movement of the cloud band for almost 12 hours.

If one looks at the distribution of precipitation in Fig. 5, it is obvious that precipitation was enhanced by orographic lift. The windward side of the Coast Range experienced a factor of 2 to 3 increase in precipitation over both the immediate coast and the interior coastal valleys. This indicates that the additional condensate formed by the lift from the Coast Range was immediately brought to the surface by enhanced coalescence in these large liquid water regions. These regions would be located well below the radar sampling elevations (lowest 1000 to 2000 ft MSL) as seen in Fig. 9. Thus, even if the lowest elevation slice had not been eliminated, it is likely that the radar would have seriously underestimated precipitation in the orographically enhanced regions.

Rhea Orographic Precipitation Model

It is possible to calculate a precipitation rate based on the condensate supply rate using the Rhea orographic precipitation model (Rhea, 1978). This model is currently being developed for use at the California-Nevada River Forecast Center. Briefly, this model is a simple 2 dimensional steady state multi-layer model with a Lagrangian framework. The model has 5 km horizontal resolution and uses terrain that has been smoothed to about 2 by 2 km. This does impact the models ability to simulate the appropriate lift for small but prominent topographic features. The model assumes that parcels follow model grid lines aligned along the 700 mb wind flow and are parallel to the model terrain. As parcels go up and down the model terrain, condensate precipitates if saturation is reached during lift or evaporates during descent.

The model can be initialized using either a sounding or using model gridded data. For this case, the 0000 UTC 6 November Oakland sounding was used as input. Using the original Oakland sounding, the model output for the period 1800 UTC on the 5th to 0600 on the 6th is shown in Fig. 13. For this period approximately 3.86 inches of rain fell at Mission Dolores. The model indicates no precipitation in downtown San Francisco (SFO) and only a few tenths near Kentfield (KEN) in Marin County. The model output is dry because the Oakland sounding indicated subsaturation below 650 mb and less than 70 percent relative humidity up to 500 mb. This required substantial lift before the airmass saturated thus severely reducing total precipitation. The sounding was taken during moderate precipitation in the Bay Area so it is not obvious why it was so dry. Most likely it is due to subsidence downwind of the first range of coastal mountains (rain shadow).

Obviously from satellite and radar data, the upwind layer from the surface to 650 mb was near or at saturation. To allow for this the sounding was modified to saturate the layer from the surface to 650 mb and then increase the relative humidity to 85 percent up to 500 mb. In addition, it was assumed that precipitation existed upwind of the coast. Thus, an additional 2 in of equivalent condensate was advected into the region. The model output for this run is shown in Fig. 14. Over 2 in of rain is predicted for San Francisco and over 3 in near KEN. Obviously, even with this "tweaking" the model underestimates precipitation. The lack of certain physical processes is contributing to the models poor performance.

Summary and Conclusions

During November 5 and 6, a record 24 hour rainfall of 6.16 inches occurred in downtown San Francisco. Over 10 inches fell to the north in Marin County. The clouds associated with this event were part of a warm conveyor belt ahead of a Pacific cold front. The origin of these clouds was maritime and subtropical, associated with an enhanced cloud droplet spectra and the onset of an efficient warm rain process. In addition, ice multiplication is suspected of enhancing the number of collectors increasing precipitation. The slow moving nature of this relatively narrow conveyor belt and enhanced orographic lift contributed to the large rainfall amounts. This storm is typical of the type of storms that produce flooding in the Bay Area.

The KMUX WSR-88D failed to estimate the magnitude of precipitation over the Bay Area by up to a factor of 100. A contributing factor was the tilt test in the bi-scan maximization which eliminated the lowest elevation scan. The radar location at over 1 km contributed to the undersampling of precipitation. Unfortunately, without Archive Level II data it is not possible to reprocess this case to see what the algorithm would have calculated if the lowest elevation scan was retained.

The current suite of NMC numerical models did predict a major precipitation event for the Bay Area but significantly underestimated rainfall amounts. This is related to both the inability of the model grid spacing to represent local topographic effects and the lack of any microphysical processes in the model.

The simple two dimensional Rhea orographic model with relatively high spatial resolution was also unable to simulate the magnitude of precipitation, even after accounting for the unrepresentativeness of the Oakland sounding. This can be related to both the lack of detailed terrain and microphysical processes in this model.

Possible solutions to the above mentioned problems are limited at the present time. A Change Request has been approved by the OSF to change the adaptable parameter controlling the change in echo areal coverage between the first two elevation scans. This may help in precipitation estimation but is not expected to resolve all the problems. A tilt scan near 0° would be needed to significantly improve precipitation estimates in shallow warm cloud systems.

Numerical models grid lengths are being reduced. The soon to be operational Meso-Eta has a grid length of 29 km. However this will not provide sufficient detail to resolve orographic effects within individual river basins. Microphysical parameterizations are also not being implemented in this revised model. The Rhea orographic model is undergoing testing using model gridded data. This may improve its performance but this model will continue to have serious limitations over low-lying areas because of its basic design. Sophisticated mesoscale models (Kim et al., 1995) with grid lengths of 5 km are now being tested in California. These will provide even further improvements. Not until explicit microphysical processes are modeled can we expect to obtain detailed fine-scale quantitative precipitation forecasts.

References

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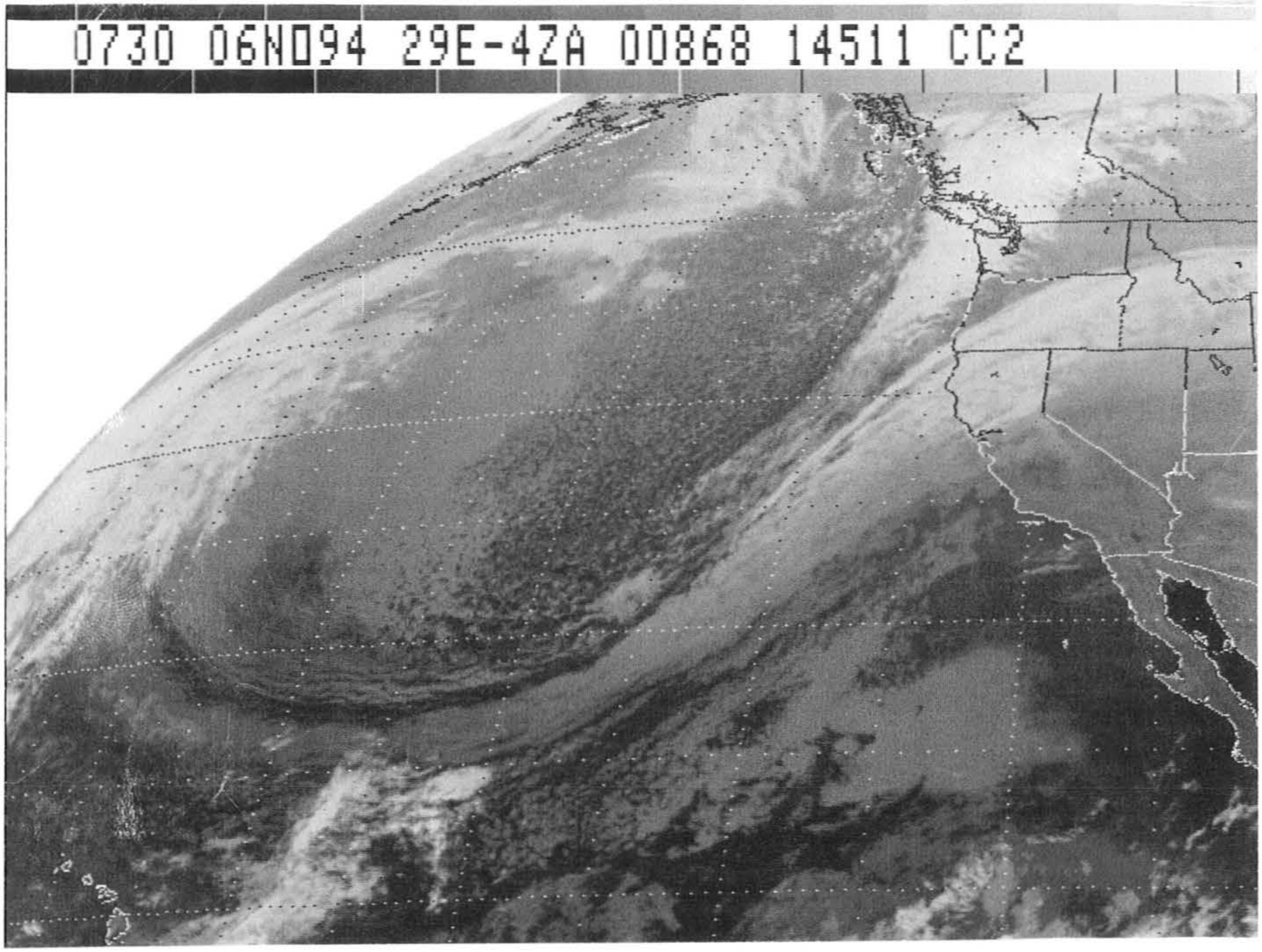


Figure 1 - Goes 7 infrared satellite image for 0730 UTC 6 November 1994. Warm conveyor belt seen as long narrow cloud band extending southwest into the subtropics.

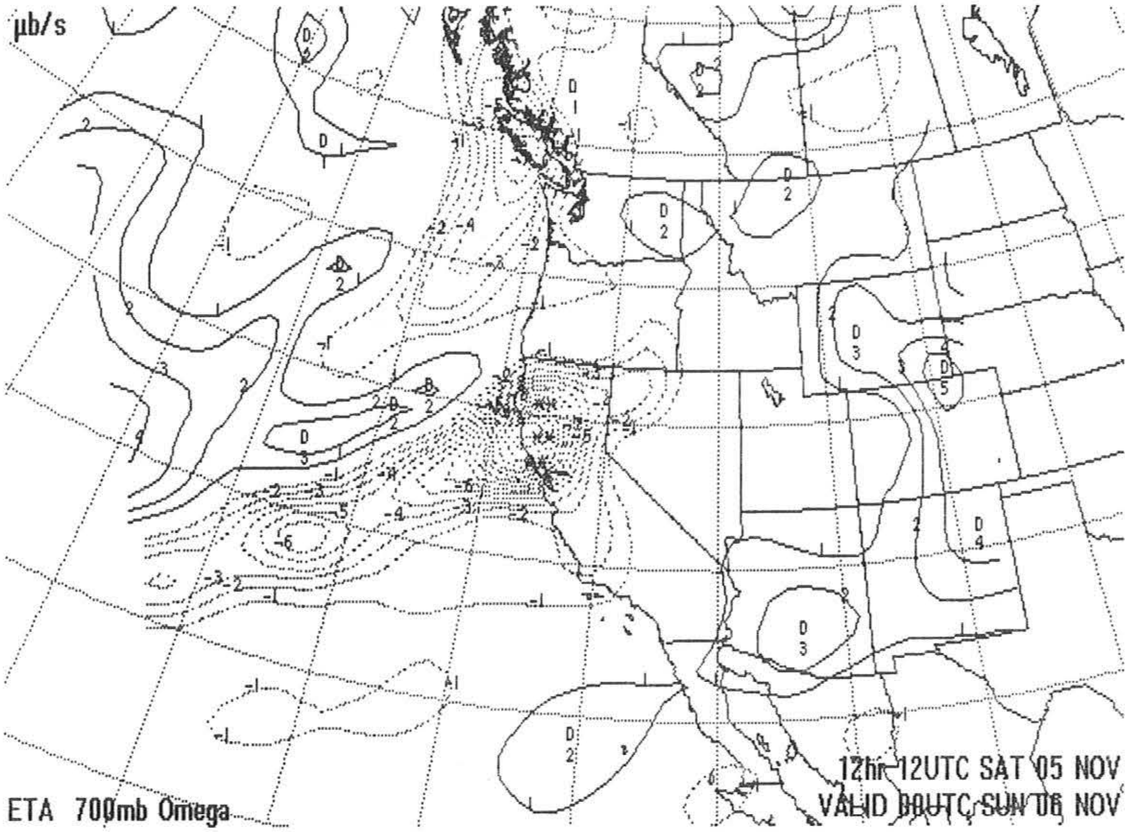


Figure 2 - Map showing 700 mbar vertical motion field. Maximum upward vertical motion is centered on the northwest coast of California with a maximum value of 15 ub/s.

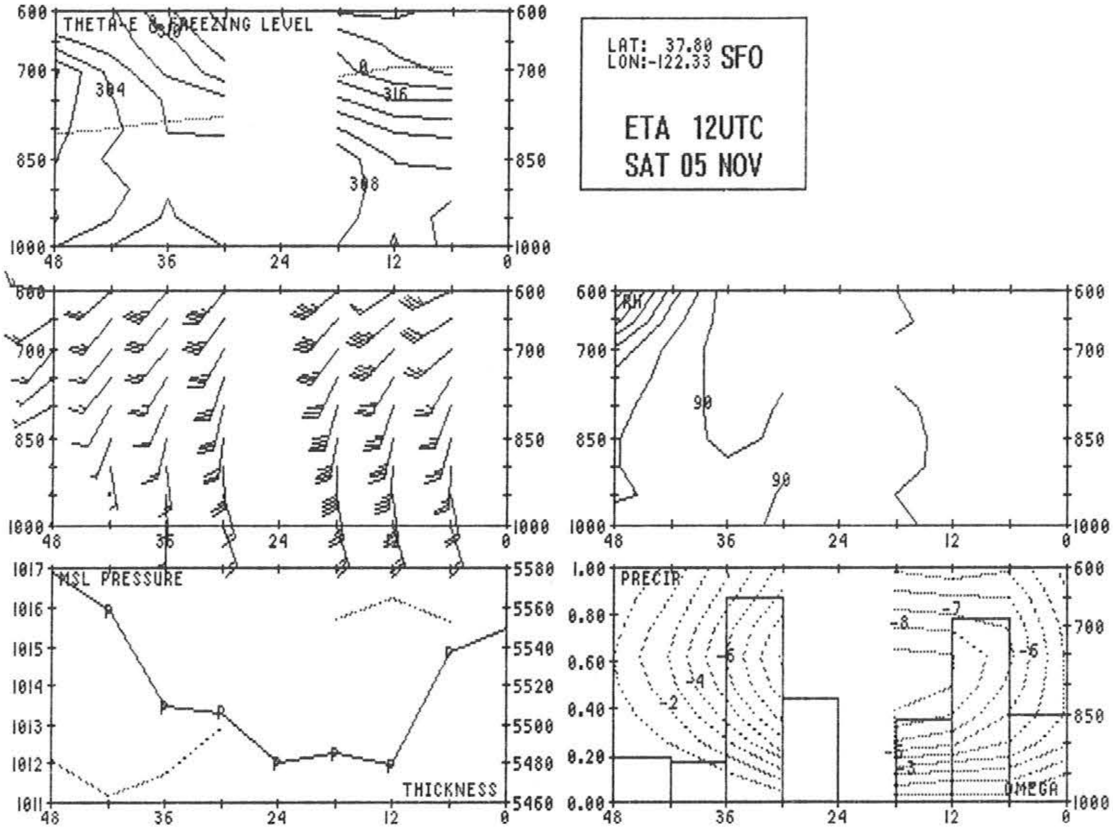


Figure 3 - Time-height cross-section over San Francisco produced from the 1200 UTC ETA. Fields are identified in upper right hand corner of each frame. The 24 hr analysis is missing.

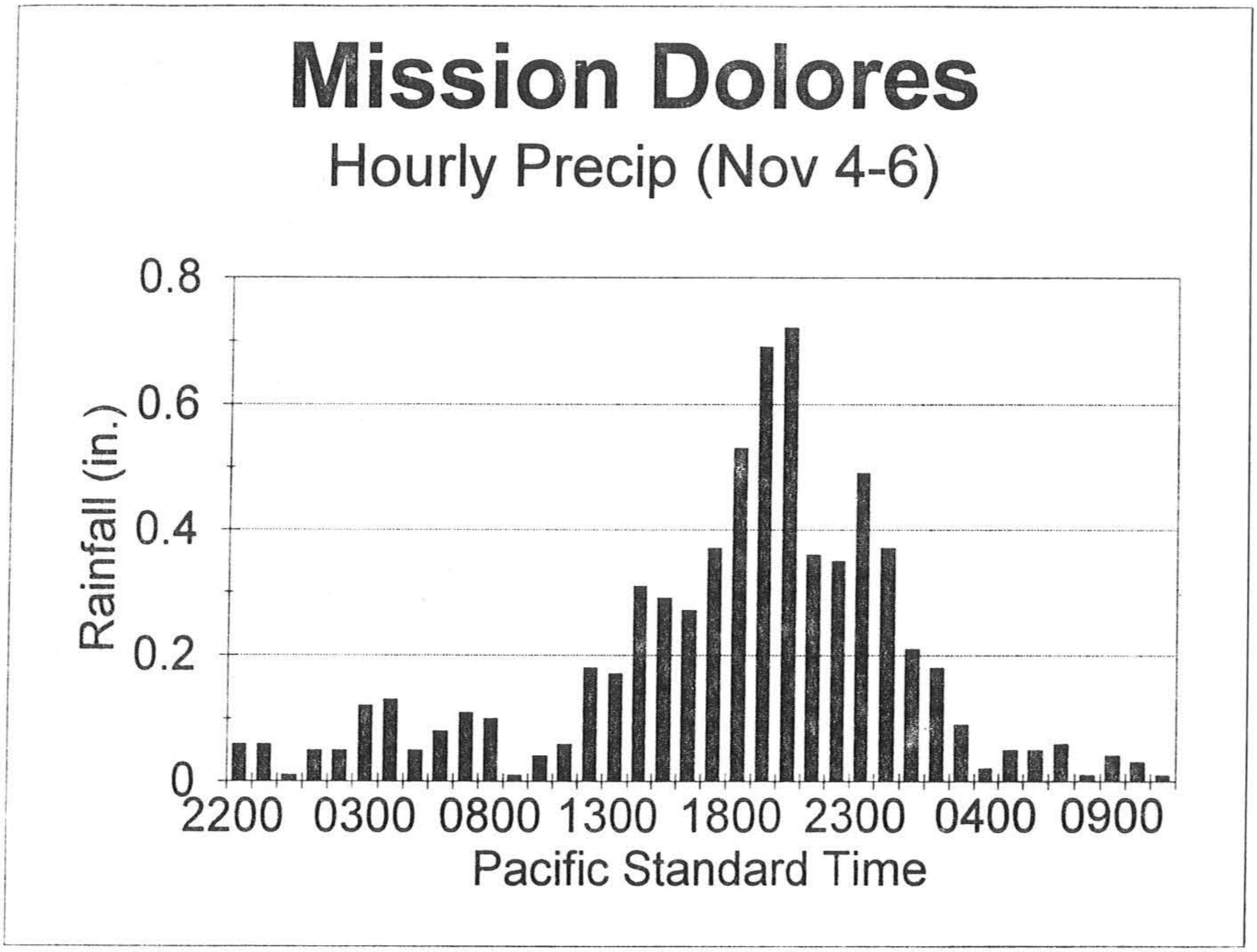


Figure 4 - Hourly plot of precipitation as measured at the Mission Dolores gauge in downtown San Francisco starting 2200 PST (0600 UTC) on the November 4th to 1100 PST (1900 UTC) on November 6th.

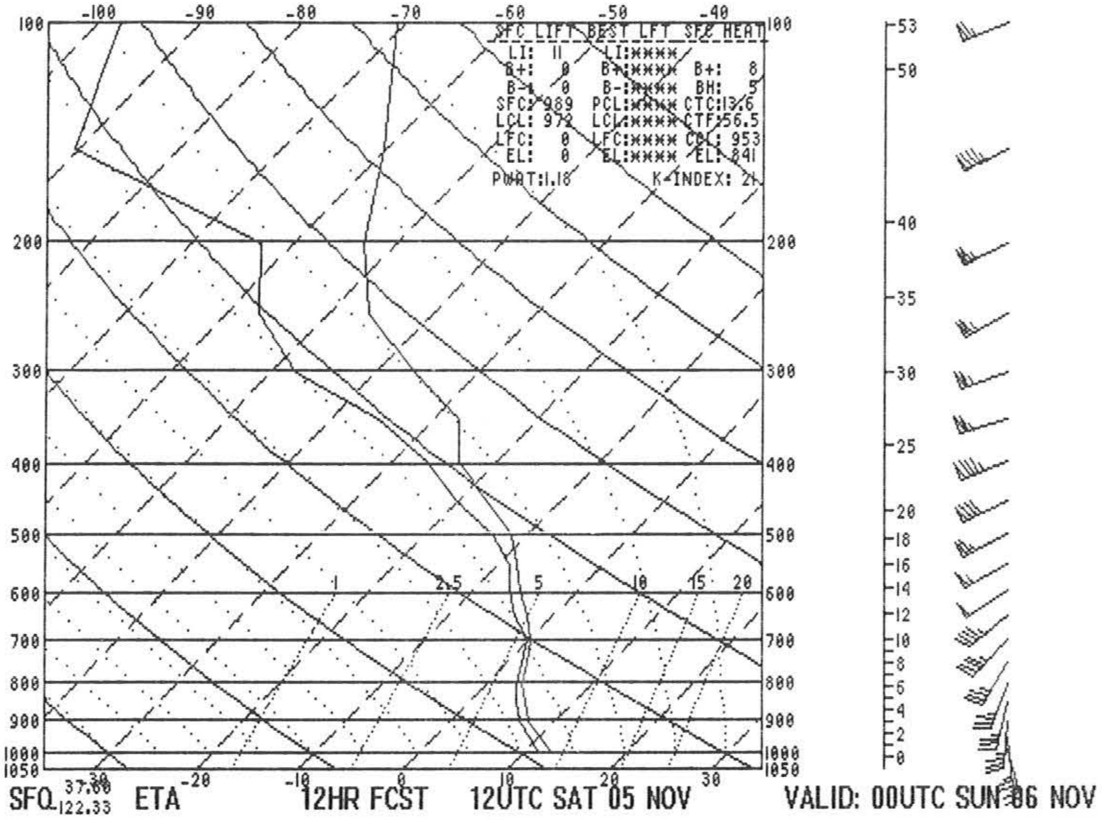
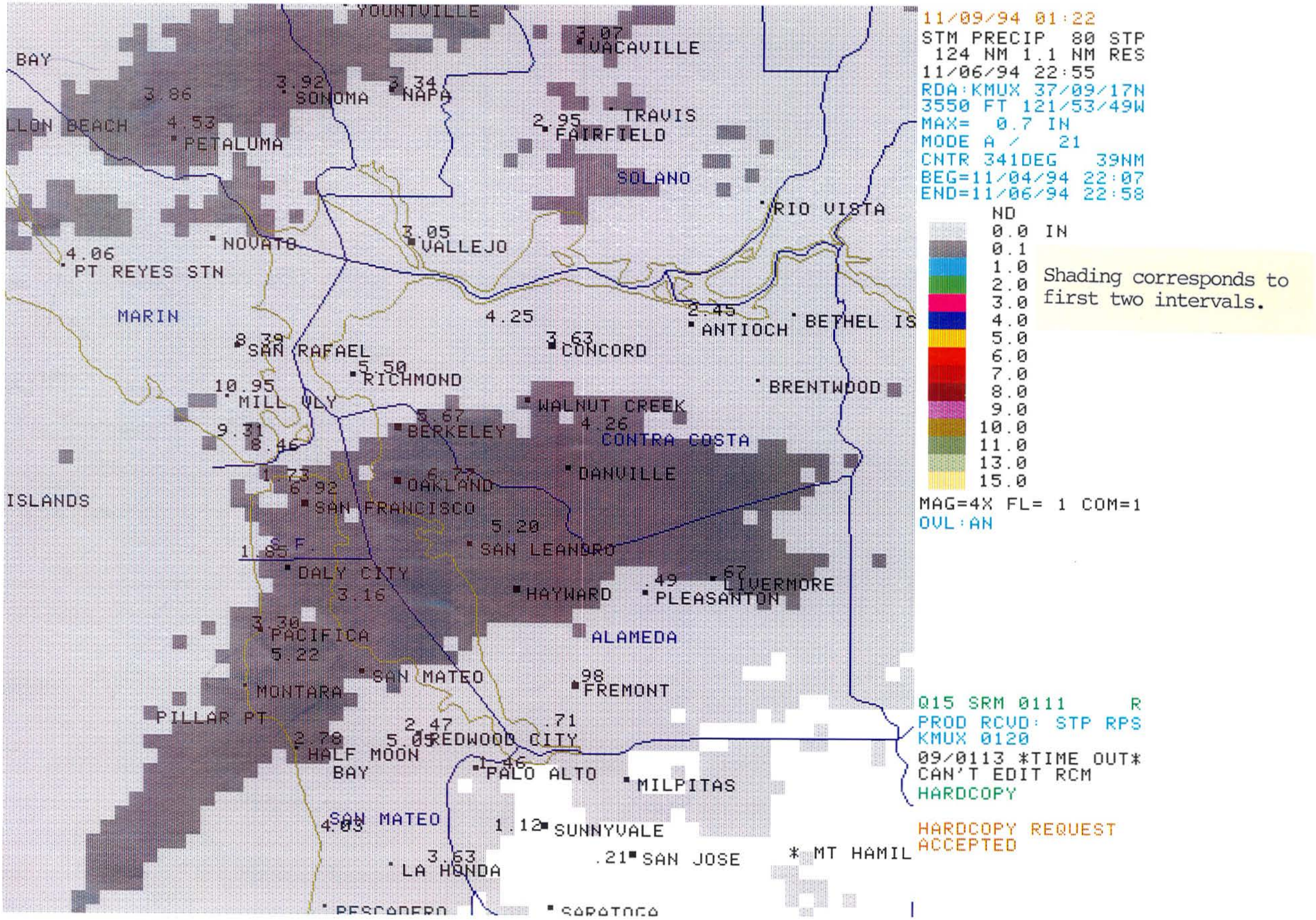


Figure 5 - ETA model produced 12 hr sounding valid 0000 UTC 06 November for San Francisco.



Shading corresponds to first two intervals.

Figure 6 - KMUX 88D Storm Total Precipitation product with observed storm total precipitation amounts annotated for the period 2207 UTC on November 4th to 22:58 UTC on November 6th. The radar was down from 0145 UTC to 1030 UTC on the 5th.

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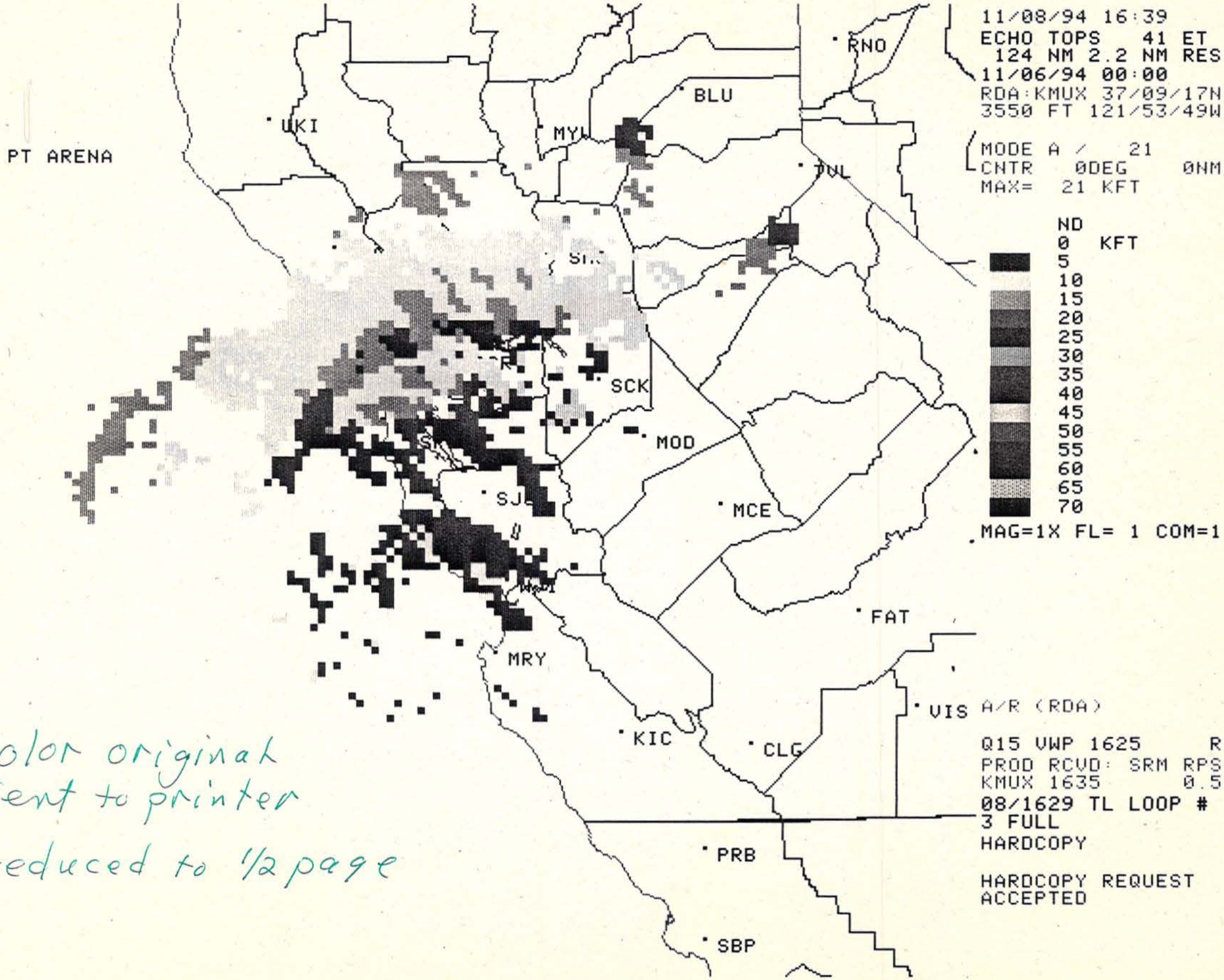
Figure 7 - KMUX 88D 0.5 ° elevation **6 November, 1994. Major precipit** **Francisco at this time. Note the rai** **(SJO).**



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ECHO TOPS    41 ET
 124 NM 2.2 NM RES
11/06/94 00:00
RDA:KMUX 37/09/17N
3550 FT 121/53/49W

MODE A /    21
CNTR   0DEG     0NM
MAX=  21 KFT

MAG=1X FL= 1 COM=1

A/R (RDA)

Q15 VWP 1625       R
PROD RCVD: SRM RPS
KMUX 1635        0.5
08/1629 TL LOOP #
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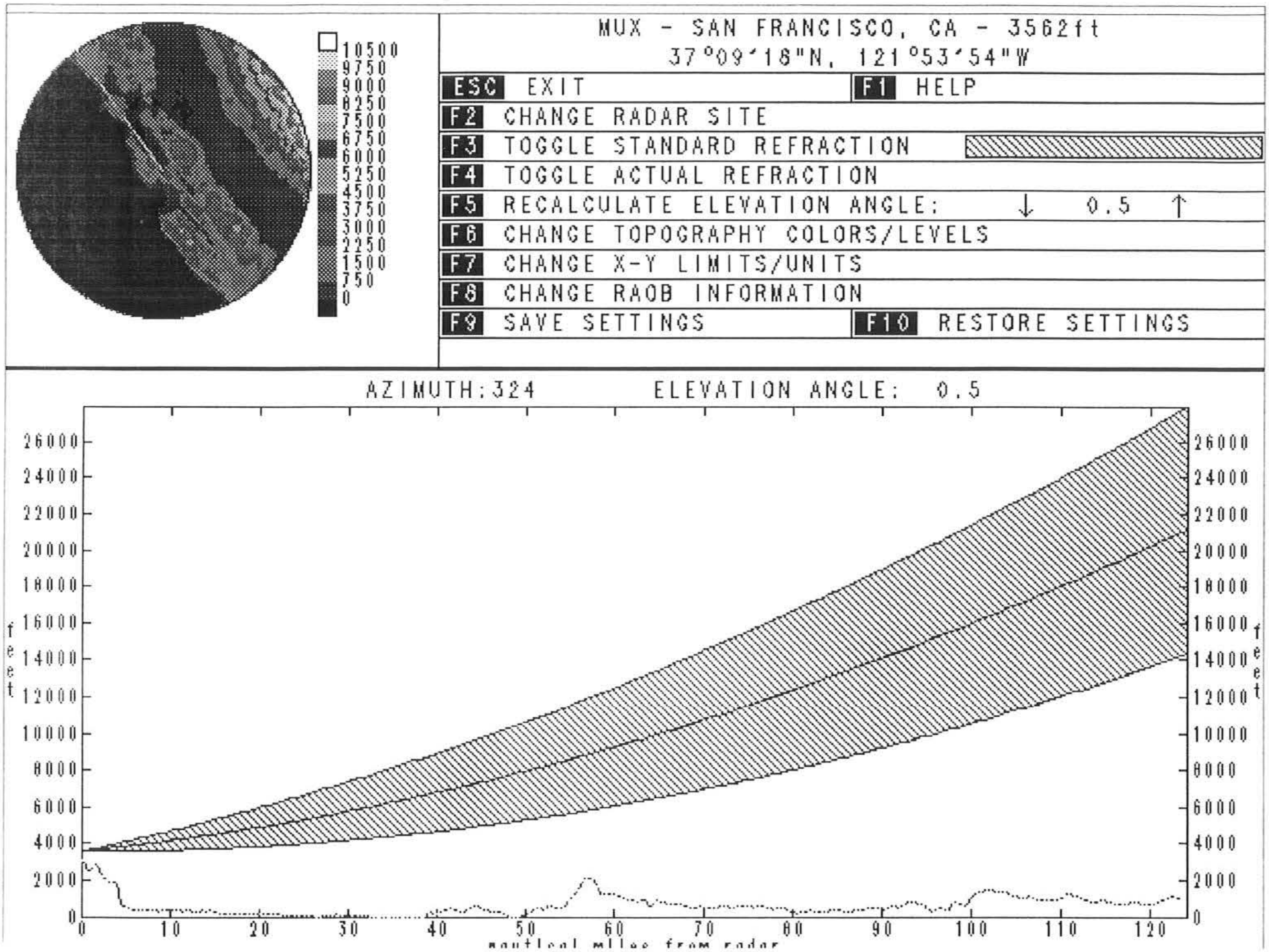
Figure 8 - Echo tops corresponding to Figure 7.



MUX - SAN FRANCISCO, CA - 3562ft
37°09'18"N, 121°53'54"W

AZIMUTH:324 ELEVATION ANGLE: 0.5

Figure 9 - Plot of 0.5 ° beam displayed along the azimuth over San Francisco and Marin County. The highest terrain shown at 57 nmi is Mt. Tamalpais where over 10 in of rain fell.

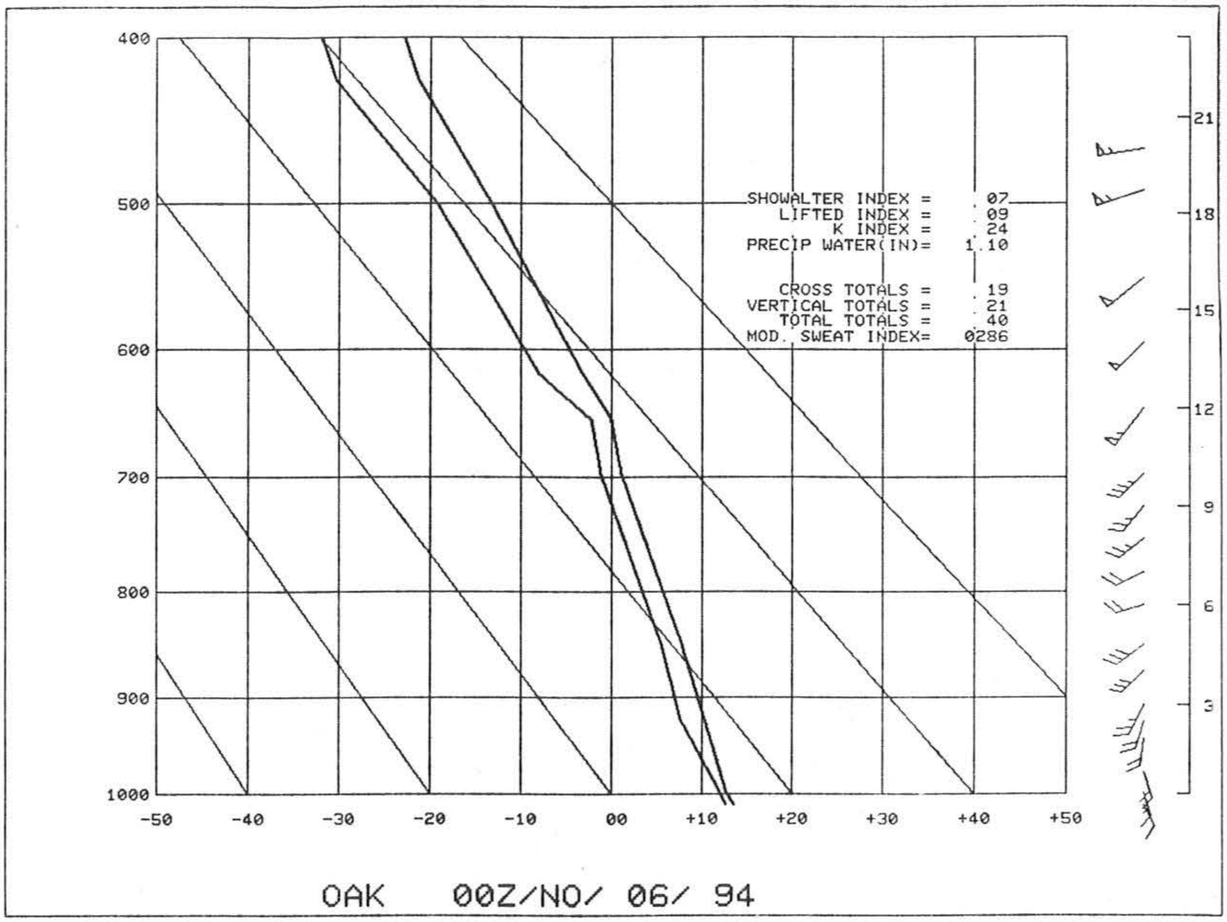


Figure 11 - Oakland 0000 UTC 6 November sounding. Shallow warm cloud layer is observed below 650 mbar.

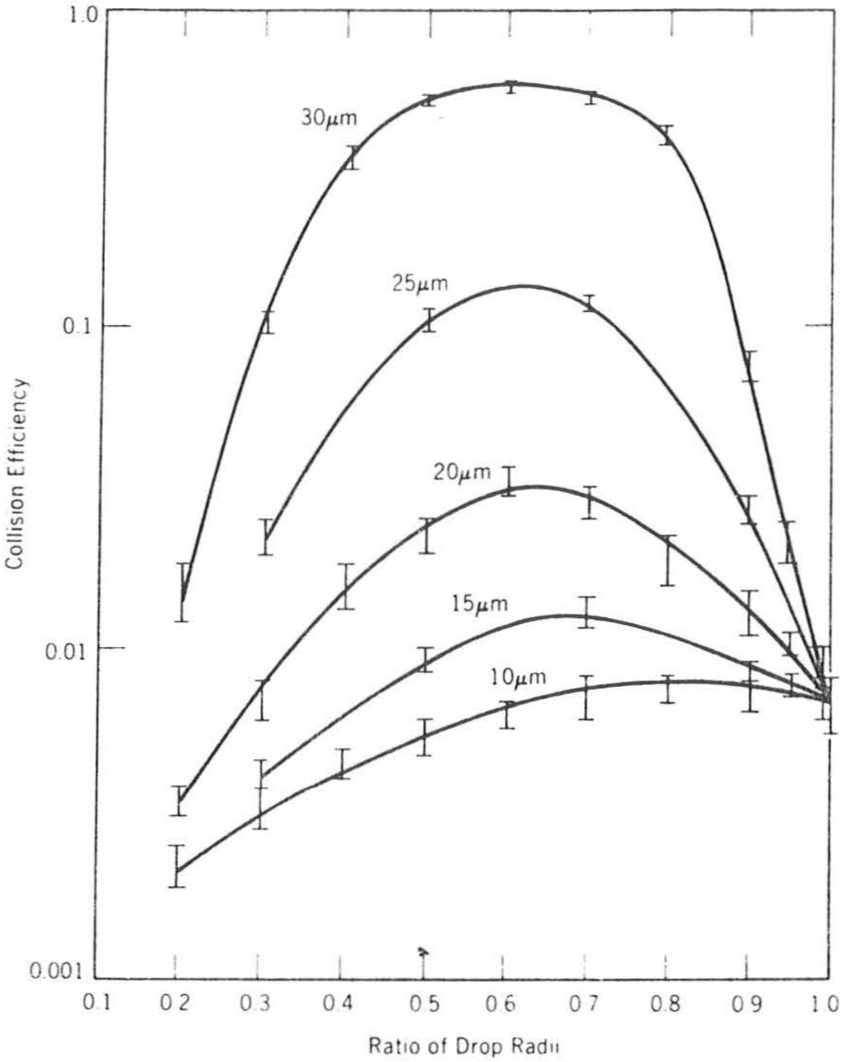


Figure 12 - Collision efficiency for several collector drops (10 - 30 um) as a function of the size ratio of the collector to the drop collected.

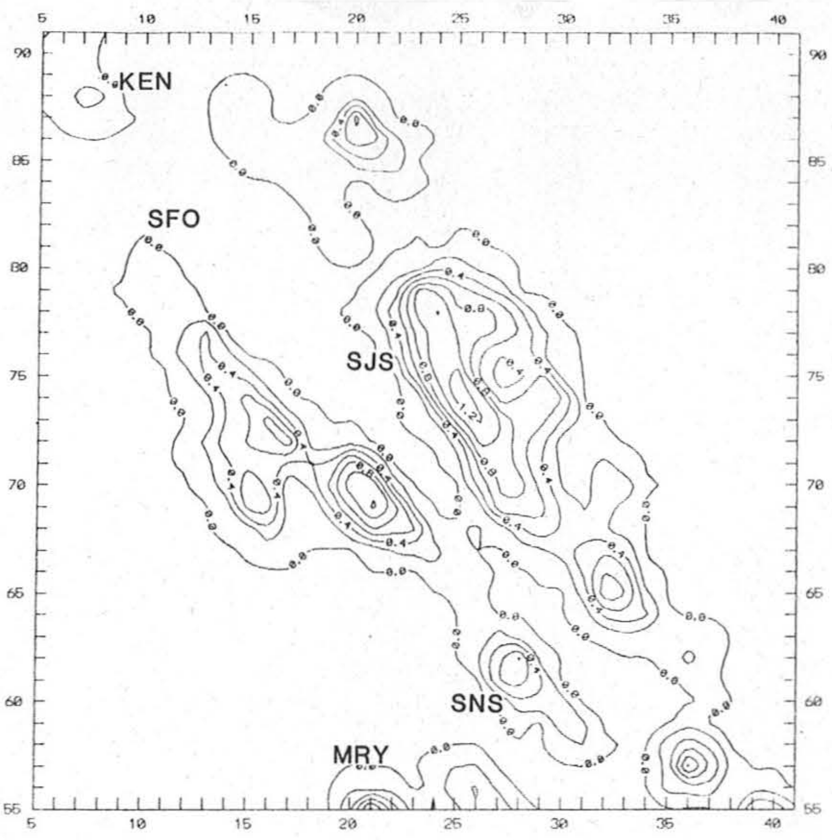


Figure 13 - Output from the Rhea orographic precipitation model for the 12 hr period centered on 0000 UTC 06 November. Contours are every .2 in. Various locations are identified.

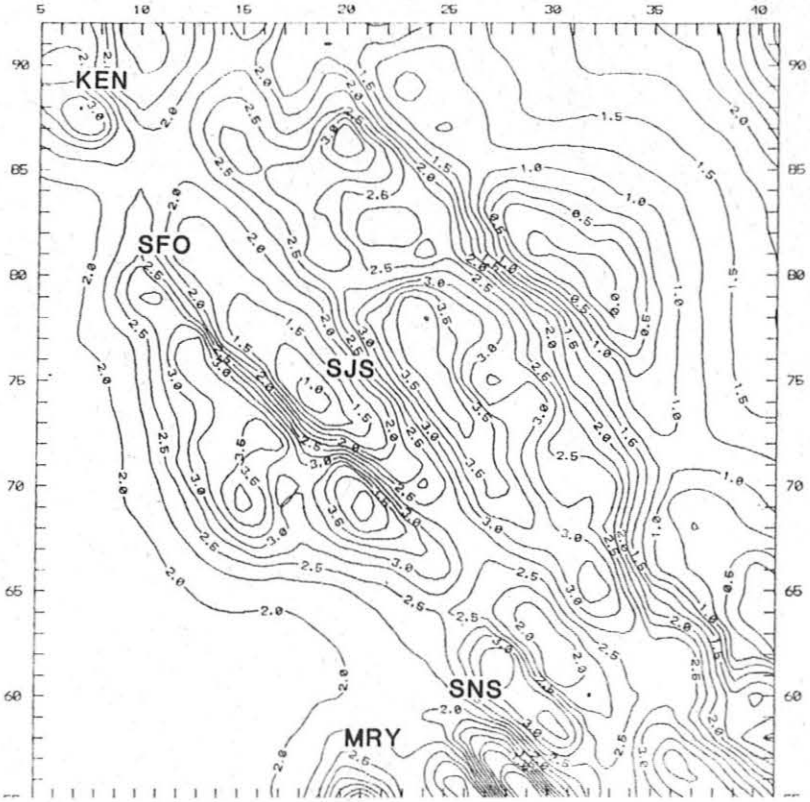
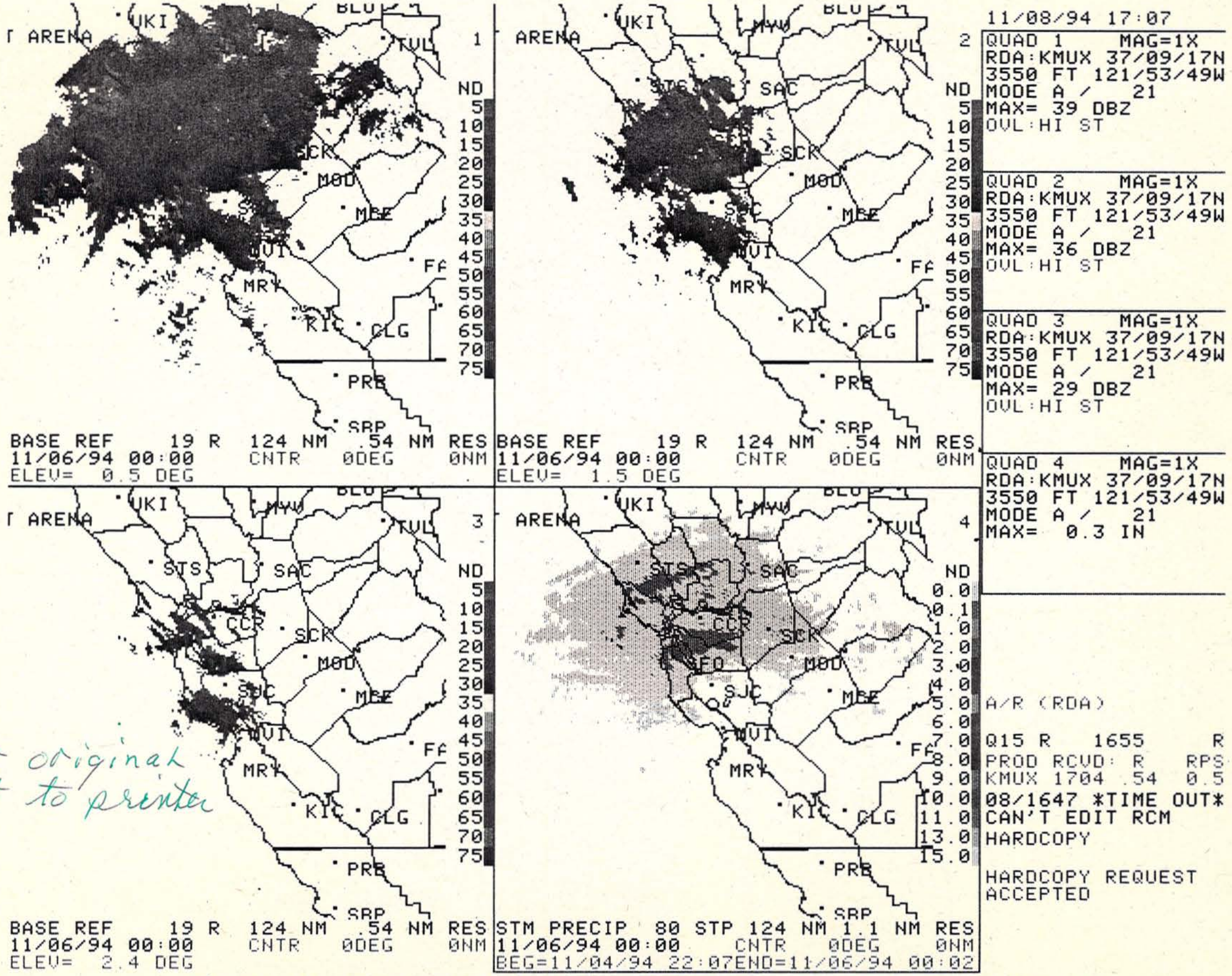


Figure 14 - Same as Figure 13 but after saturating the lowest 650 mbar of the Oakland sounding and advecting in an additional 2 in of equivalent condensate into the area.



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ELEV=  0.5 DEG

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11/06/94 00:00       CNTR    0DEG    0NM
ELEV=  1.5 DEG

BASE REF      19 R   124 NM   .54 NM RES
11/06/94 00:00       CNTR    0DEG    0NM
ELEV=  2.4 DEG

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11/08/94 17:07
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RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /      21
MAX= 39 DBZ
OVL:HI ST

QUAD 2      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /      21
MAX= 36 DBZ
OVL:HI ST

QUAD 3      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /      21
MAX= 29 DBZ
OVL:HI ST

QUAD 4      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /      21
MAX=  0.3 IN

A/R (RDA)

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08/1647 *TIME OUT*
CAN'T EDIT RCM
HARDCOPY

HARDCOPY REQUEST
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Figure 10 - Four panel section of KMUX data for 0000 UTC on the 6th showing various elevation tilts along with the STP product valid up to that time. Note change in areal reflectivity coverage between the 0.5 and 1.5 ° elevation scans.

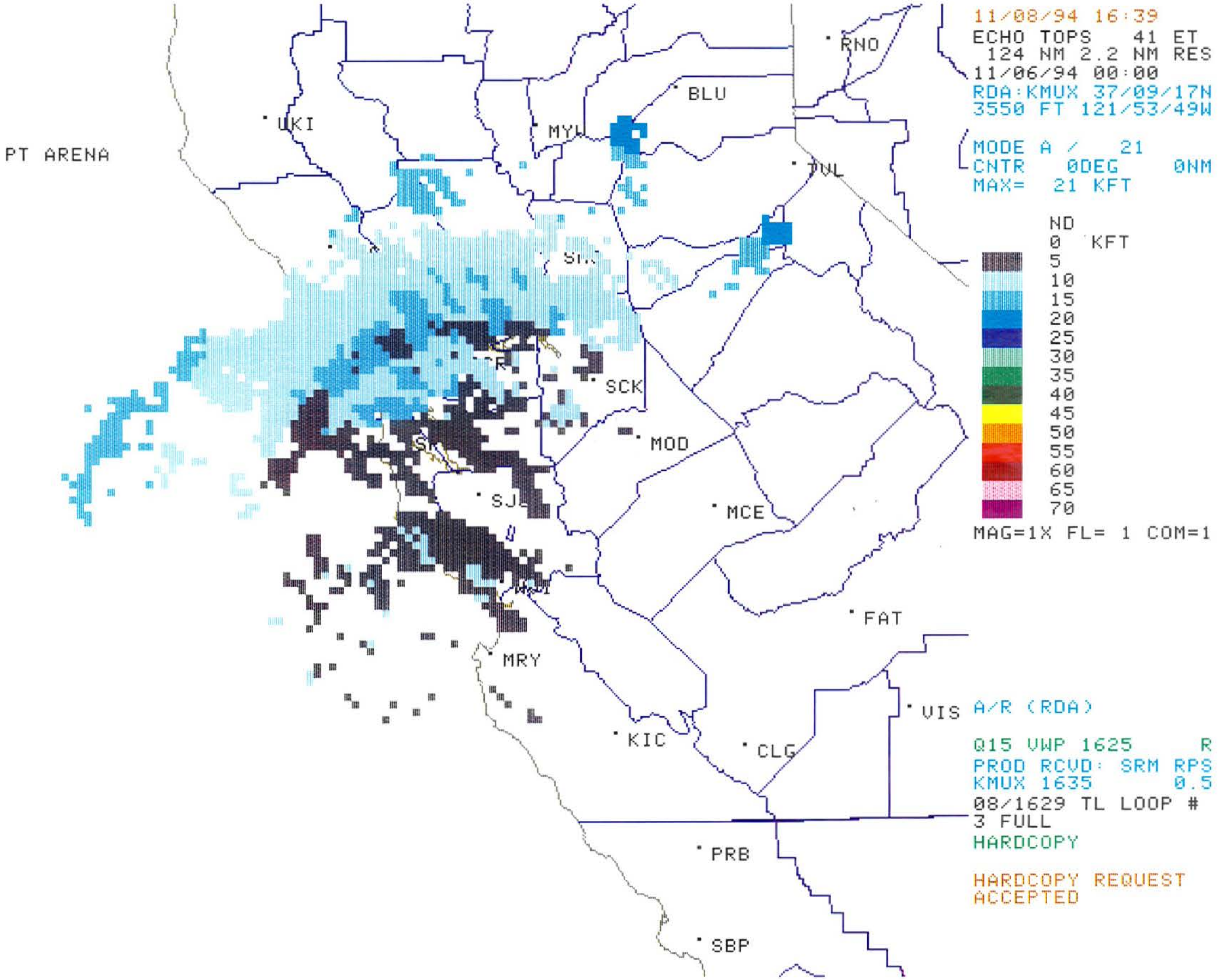


Figure 8 - Echo tops corresponding to Figure 7.

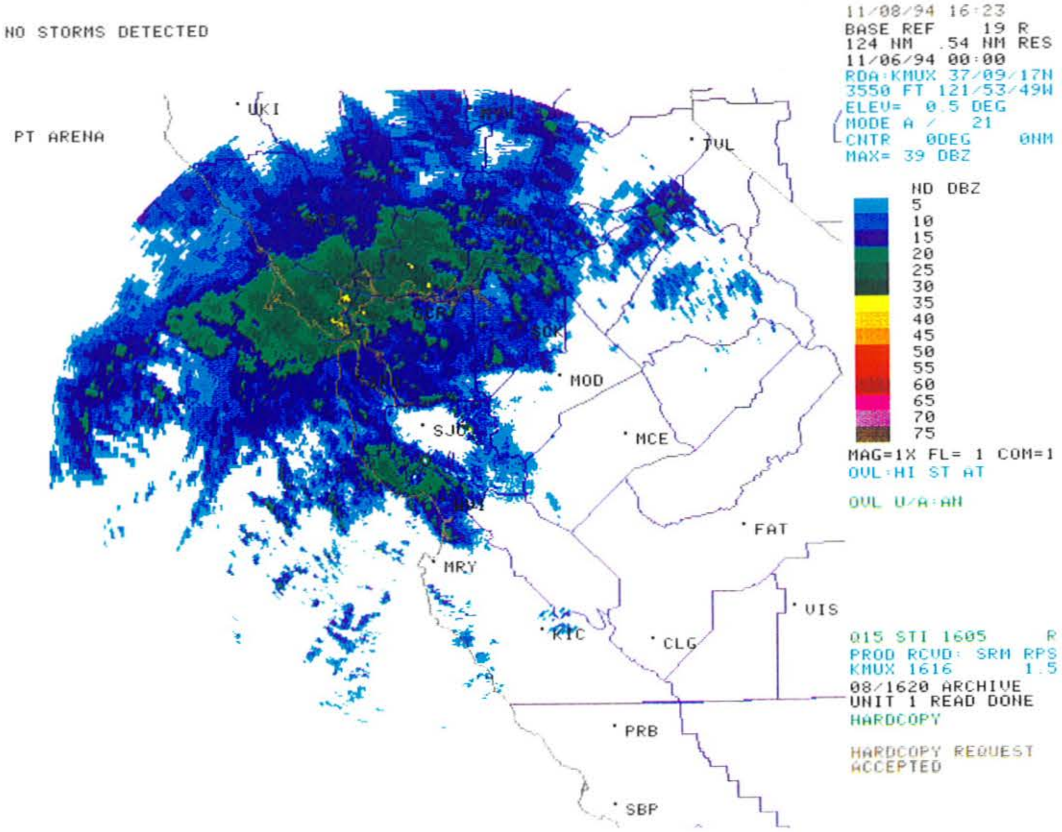


Figure 7 - KMUX 88D 0.5 ° elevation reflectivity data for 0000 UTC 6 November, 1994. Major precipitation is just north of San Francisco at this time. Note the rain shadow effect over San Jose (SJO).

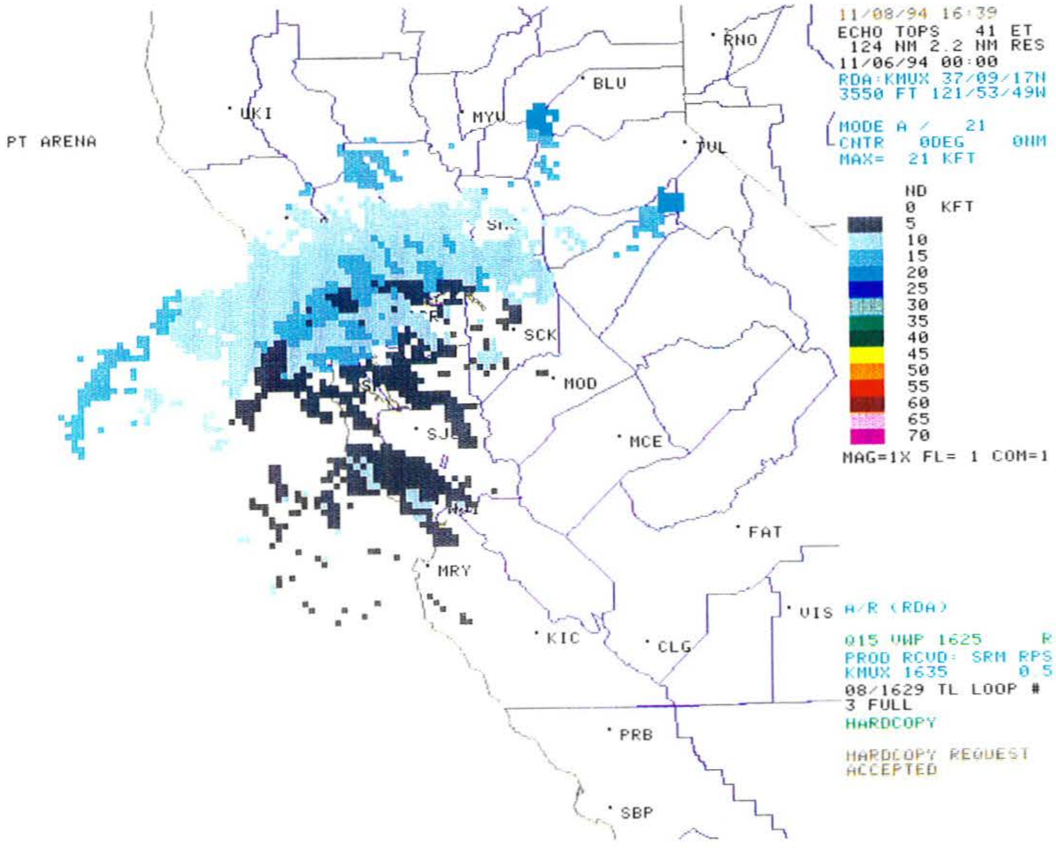
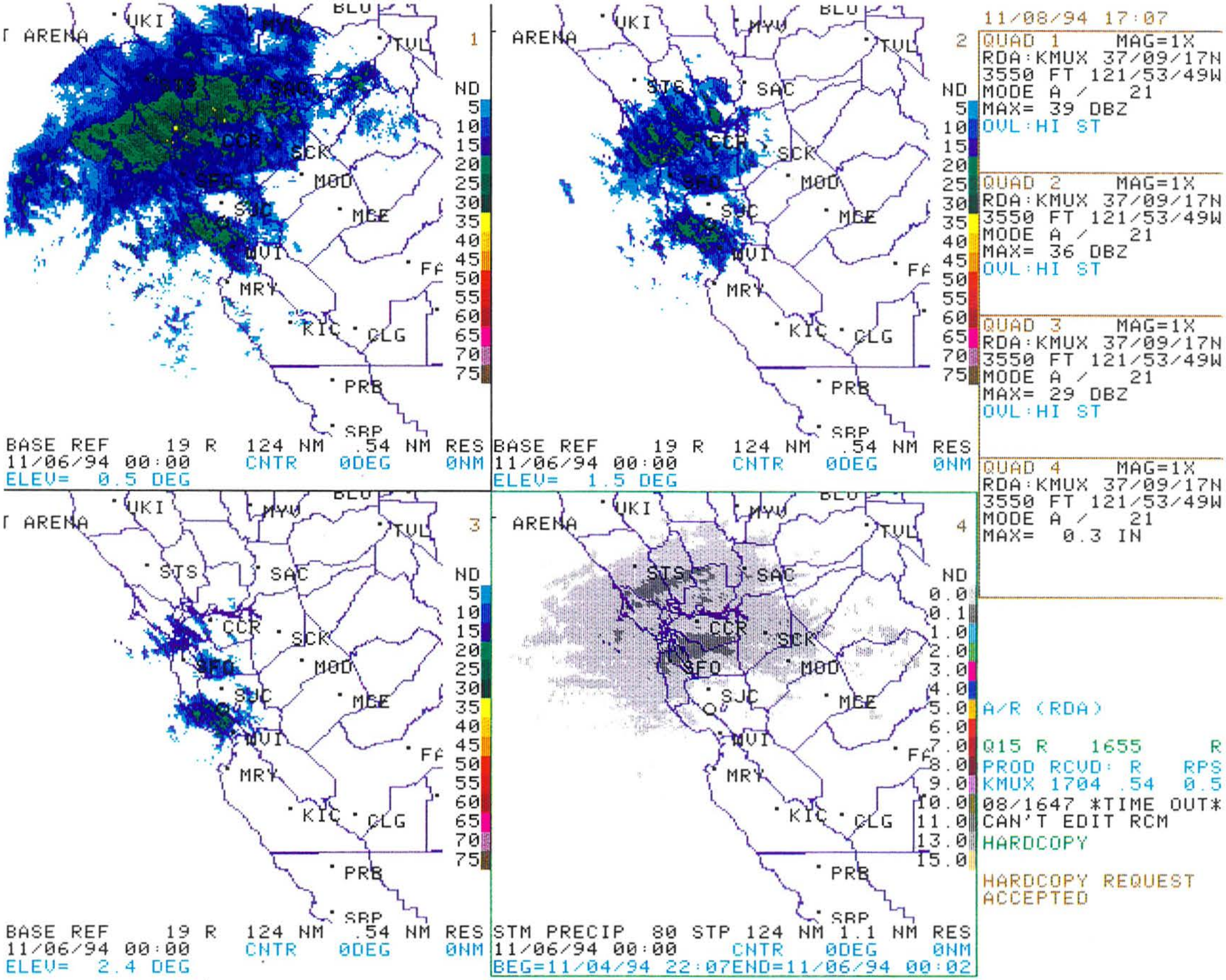


Figure 8 - Echo tops corresponding to Figure 7.



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ELEV=  0.5 DEG

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11/06/94 00:00       CNTR     0DEG    0NM
ELEV=  1.5 DEG

BASE REF      19 R   124 NM   .54 NM RES
11/06/94 00:00       CNTR     0DEG    0NM
ELEV=  2.4 DEG

STM PRECIP  80 STP 124 NM 1.1 NM RES
11/06/94 00:00       CNTR     0DEG    0NM
BEG=11/04/94 22:07END=11/06/94 00:02
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11/08/94 17:07
QUAD 1      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /       21
MAX= 39 DBZ
OVL:HI ST

QUAD 2      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /       21
MAX= 36 DBZ
OVL:HI ST

QUAD 3      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /       21
MAX= 29 DBZ
OVL:HI ST

QUAD 4      MAG=1X
RDA:KMUX 37/09/17N
3550 FT 121/53/49W
MODE A /       21
MAX=  0.3 IN

A/R (RDA)

Q15 R    1655      R
PROD RCVD: R    RPS
KMUX 1704 .54   0.5
08/1647 *TIME OUT*
CAN'T EDIT RCM
HARDCOPY

HARDCOPY REQUEST
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Figure 10 - Four panel section of KMUX data for 0000 UTC on the 6th showing various elevation tilts along with the STP product valid up to that time. Note change in areal reflectivity coverage between the 0.5 and 1.5 ° elevation scans.